Control System Toolbox™

Reference

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R2015a

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Control System Toolbox™ Reference

Revision History

June 2001	Online only	New for Version 5.1 (Release 12.1)
July 2002	Online only	Revised for Version 5.2 (Release 13)
June 2004	Online only	Revised for Version 6.0 (Release 14)
March 2005	Online only	Revised for Version 6.2 (Release 14SP2)
September 2005	Online only	Revised for Version 6.2.1 (Release 14SP3)
March 2006	Online only	Revised for Version 7.0 (Release 2006a)
September 2006	Online only	Revised for Version 7.1 (Release 2006b)
March 2007	Online only	Revised for Version 8.0 (Release 2007a)
September 2007	Online only	Revised for Version 8.0.1 (Release 2007b)
March 2008	Online only	Revised for Version 8.1 (Release 2008a)
October 2008	Online only	Revised for Version 8.2 (Release 2008b)
March 2009	Online only	Revised for Version 8.3 (Release 2009a)
September 2009	Online only	Revised for Version 8.4 (Release 2009b)
March 2010	Online only	Revised for Version 8.5 (Release 2010a)
September 2010	Online only	Revised for Version 9.0 (Release 2010b)
April 2011	Online only	Revised for Version 9.1 (Release 2011a)
September 2011	Online only	Revised for Version 9.2 (Release 2011b)
March 2012	Online only	Revised for Version 9.3 (Release 2012a)
September 2012	Online only	Revised for Version 9.4 (Release 2012b)
March 2013	Online only	Revised for Version 9.5 (Release 2013a)
September 2013	Online only	Revised for Version 9.6 (Release 2013b)
March 2014	Online only	Revised for Version 9.7 (Release 2014a)
October 2014	Online only	Revised for Version 9.8 (Release 2014b)
March 2015	Online only	Revised for Version 9.9 (Release 2015a)

Contents

Functions — Alphabetical List

abs

Entrywise magnitude of frequency response

Syntax

```
absfrd = abs(sys)
```

Description

`absfrd = abs(sys)` computes the magnitude of the frequency response contained in the FRD model `sys`. For MIMO models, the magnitude is computed for each entry. The output `absfrd` is an FRD object containing the magnitude data across frequencies.

See Also

`bodemag` | `fnorm` | `sigma`

absorbDelay

Replace time delays by poles at $z = 0$ or phase shift

Syntax

```
sysnd = absorbDelay(sysd)
[sysnd,G] = absorbDelay(sysd)
```

Description

`sysnd = absorbDelay(sysd)` absorbs all time delays of the dynamic system model sysd into the system dynamics or the frequency response data.

For discrete-time models (other than frequency response data models), a delay of `k` sampling periods is replaced by `k` poles at $z = 0$. For continuous-time models (other than frequency response data models), time delays have no exact representation with a finite number of poles and zeros. Therefore, use `pade` to compute a rational approximation of the time delay.

For frequency response data models in both continuous and discrete time, `absorbDelay` absorbs all time delays into the frequency response data as a phase shift.

`[sysnd,G] = absorbDelay(sysd)` returns the matrix G that maps the initial states of the `ss` model sysd to the initial states of the sysnd.

Examples

Example 1

Create a discrete-time transfer function that has a time delay and absorb the time delay into the system dynamics as poles at $z = 0$.

```
z = tf('z',-1);
sysd = (-.4*z -.1)/(z^2 + 1.05*z + .08);
sysd.InputDelay = 3
```

These commands produce the result:

```
Transfer function:
             -0.4 z - 0.1
z^(-3) * -------------------
          z^2 + 1.05 z + 0.08

Sample time: unspecified
```

The display of `sysd` represents the `InputDelay` as a factor of `z^(-3)`, separate from the system poles that appear in the transfer function denominator.

Absorb the delay into the system dynamics.

```
sysnd = absorbDelay(sysd)
```

The display of `sysnd` shows that the factor of `z^(-3)` has been absorbed as additional poles in the denominator.

```
Transfer function:
      -0.4 z - 0.1
-------------------------
z^5 + 1.05 z^4 + 0.08 z^3

Sample time: unspecified
```

Additionally, `sysnd` has no input delay:

```
sysnd.InputDelay

ans =

     0
```

Example 2

Convert "nk" into regular coefficients of a polynomial model.

Consider the discrete-time polynomial model:

```
m = idpoly(1,[0 0 0 2 3]);
```

The value of the B polynomial, m.b, has 3 leading zeros. Two of these zeros are treated as input-output delays. Consequently:

```
sys = tf(m)
```

creates a transfer function such that the numerator is [0 2 3] and the IO delay is 2. In order to treat the leading zeros as regular B coefficients, use absorbDelay:

```
m2 = absorbDelay(m);
sys2 = tf(m2);
```

`sys2's` numerator is `[0 0 0 2 3]` and `IO` delay is `0`. The model `m2` treats the leading zeros as regular coefficients by freeing their values. `m2.Structure.b.Free(1:2)` is `TRUE` while `m.Structure.b.Free(1:2)` is `FALSE`.

See Also

`totaldelay` | `hasdelay` | `pade`

allmargin

Gain margin, phase margin, delay margin and crossover frequencies

Syntax

```
S = allmargin(sys)
S = allmargin(mag,phase,w,ts)
```

Description

`S = allmargin(sys)` computes the gain margin, phase margin, delay margin and the corresponding crossover frequencies of the SISO open-loop model `sys`. The `allmargin` command is applicable to any SISO model, including models with delays.

The output `S` is a structure with the following fields:

- `GMFrequency` — All –180° (modulo 360°) crossover frequencies in `rad/TimeUnit`, where `TimeUnit` is the time units of the input dynamic system, specified in the TimeUnit property of sys.
- `GainMargin` — Corresponding gain margins, defined as `1/G`, where `G` is the gain at the –180° crossover frequency. Gain margins are in absolute units.
- `PMFrequency` — All 0 dB crossover frequencies in `rad/TimeUnit`, where `TimeUnit` is the time units of the input dynamic system, specified in the TimeUnit property of sys).
- `PhaseMargin` — Corresponding phase margins in degrees.
- `DMFrequency` and `DelayMargin` — Critical frequencies and the corresponding delay margins. Delay margins are specified in the time units of the system for continuous-time systems and multiples of the sample time for discrete-time systems.
- `Stable` — 1 if the nominal closed-loop system is stable, 0 otherwise.

  Where stability cannot be assessed, `Stable` is set to `NaN`. In general, stability cannot be assessed for an `frd` system.

`S = allmargin(mag,phase,w,ts)` computes the stability margins from the frequency response data `mag`, `phase`, `w`, and the sample time, `ts`. Provide magnitude values `mag` in absolute units, and phase values `phase` in degrees. You can provide the frequency vector `w` in any units; `allmargin` returns frequencies in the same units. `allmargin` interpolates between frequency points to approximate the true stability margins.

See Also

`linearSystemAnalyzer` | `margin`

AnalysisPoint

Points of interest for linear analysis

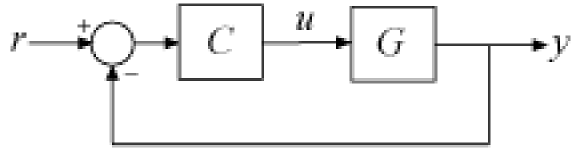
Syntax

```
AP = AnalysisPoint(name)
AP = AnalysisPoint(name,N)
```

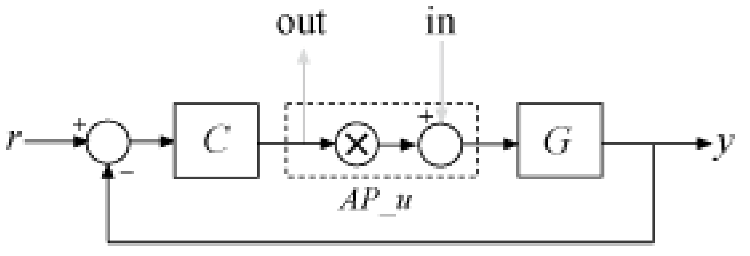
Description

`AnalysisPoint` is a Control Design Block for marking a location in a control system model as a point of interest for linear analysis and controller tuning. You can combine an `AnalysisPoint` block with numeric LTI models, tunable LTI models, and other Control Design Blocks to build tunable models of control systems. `AnalysisPoint` locations are available for analysis with commands such as `getIOTransfer` or `getLoopTransfer`. Such locations are also available for specifying design goals for control system tuning.

For example, consider the following control system.



Suppose that you are interested in the effects of disturbance injected at u in this control system. Inserting an `AnalysisPoint` block at the location u associates an implied input, implied output, and the option to open the loop at that location, as in the following diagram.



Suppose that T is a model of the control system including the AnalysisPoint block, AP_u. In this case, the command getIOTransfer(T,'AP_u','y') returns a model of the closed-loop transfer function from u to y. Likewise, the command getLoopTransfer(T,'AP_u',-1) returns a model of the negative-feedback open-loop response, CG, measured at the location u.

AnalysisPoint blocks are also useful when tuning a control system using Robust Control Toolbox™ tuning commands such as systune. You can use an AnalysisPoint block to mark a loop-opening location for open-loop tuning requirements such as TuningGoal.LoopShape or TuningGoal.Margins. You can also use a AnalysisPoint block to mark the specified input or output for tuning requirements such as TuningGoal.Gain. For example, Req = TuningGoal.Margins('AP_u',5,40) constrains the gain and phase margins at the location u.

You can create AnalysisPoint blocks explicitly using the AnalysisPoint command and connect them with other block diagram components using model interconnection commands. For example, the following code creates a model of the system illustrated above. (See “Construction” on page 1-10 and “Examples” on page 1- below for more information.)

```
G = tf(1,[1 2]);
C = ltiblock.pid('C','pi');
AP_u = AnalysisPoint('u');
T = feedback(G*AP_u*C,1);       % closed loop r->y
```

You can also create analysis points implicitly, using the `connect` command. The following syntax creates a dynamic system model with analysis points, by interconnecting multiple models `sys1,sys2,...,sysN`:

```
sys = connect(sys1,sys2,...,sysN,inputs,outputs,APs);
```

The string vector `APs` lists the signal locations at which to insert analysis points. The software automatically creates and inserts an `AnalysisPoint` block with channels corresponding to these locations. See `connect` for more information.

Construction

`AP = AnalysisPoint(name)` creates a single-channel analysis point. Insert `AP` anywhere in the generalized model of your control system to mark a point of interest for linear analysis or controller tuning. name specifies the block name.

`AP = AnalysisPoint(name,N)` creates a multi-channel analysis point with N channels. Use this block to mark a vector-valued signal as a point of interest or to bundle together several points of interest.

Input Arguments

`name`

Analysis point name, specified as a string. This input argument sets the value of the `Name` property of the `AnalysisPoint` block. (See "Properties" on page 1-10.) When you build a control system model using the block, the `Name` property is what appears in the `Blocks` list of the resulting `genss` model.

`N`

Number of channels for a multichannel analysis point, specified as a scalar integer.

Properties

`Location`

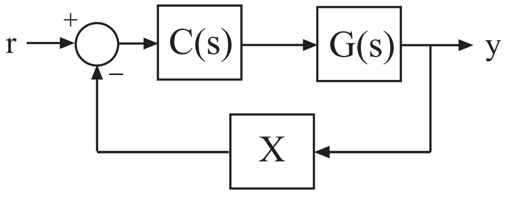
Names of channels in the `AnalysisPoint` blocks, specified as a string or a cell array of strings.

By default, the analysis-point channels are named after the name argument. For example, if you have a single-channel analysis point, `AP`, that has name `'AP'`, then `AP.Location = 'AP'` by default. If you have a multi-channel analysis point, then `AP.Location = {'AP(1)','AP(2)',...}` by default. Set `AP.Location` to a different value if you want to customize the channel names.

Open

Loop-opening state, specified as a logical value or vector of logical values. This property tracks whether the loop is open or closed at the analysis point.

For example, consider the feedback loop of the following illustration.



You can model this feedback loop as follows.

```
G = tf(1,[1 2]);
C = ltiblock.pid('C','pi');
X = AnalysisPoint('X');
T = feedback(G*C,X);
```

You can get the transfer function from *r* to *y* with the feedback loop open at *X* as follows.

```
Try = getIOTransfer(T,'r','y','X');
```

In the resulting generalized state-space (`genss`) model, the `AnalysisPoint` block `'X'` is marked open. In other words, `Try.Blocks.X.Open = 1`.

For a multi-channel analysis point, then `Open` is a logical vector with as many entries as the analsysis point has channels.

Default: 0 for all channels

Ts

Sample time. For `AnalysisPoint` blocks, the value of this property is automatically set to the sample time of other blocks and models you connect it with.

Default: `0` (continuous time)

`TimeUnit`

String representing the unit of the time variable. This property specifies the units for the time variable, the sample time `Ts`, and any time delays in the model. Use any of the following values:

- `'nanoseconds'`
- `'microseconds'`
- `'milliseconds'`
- `'seconds'`
- `'minutes'`
- `'hours'`
- `'days'`
- `'weeks'`
- `'months'`
- `'years'`

Changing this property has no effect on other properties, and therefore changes the overall system behavior. Use `chgTimeUnit` to convert between time units without modifying system behavior.

Default: `'seconds'`

`InputName`

Input channel names. Set `InputName` to a string for single-input model. For a multi-input model, set `InputName` to a cell array of strings.

Alternatively, use automatic vector expansion to assign input names for multi-input models. For example, if `sys` is a two-input model, enter:

```
sys.InputName = 'controls';
```

The input names automatically expand to `{'controls(1)';'controls(2)'}`.

You can use the shorthand notation `u` to refer to the `InputName` property. For example, `sys.u` is equivalent to `sys.InputName`.

Input channel names have several uses, including:

- Identifying channels on model display and plots
- Extracting subsystems of MIMO systems
- Specifying connection points when interconnecting models

Default: Empty string `''` for all input channels

`InputUnit`

Input channel units. Use `InputUnit` to keep track of input signal units. For a single-input model, set `InputUnit` to a string. For a multi-input model, set `InputUnit` to a cell array of strings. `InputUnit` has no effect on system behavior.

Default: Empty string `''` for all input channels

`InputGroup`

Input channel groups. The `InputGroup` property lets you assign the input channels of MIMO systems into groups and refer to each group by name. Specify input groups as a structure. In this structure, field names are the group names, and field values are the input channels belonging to each group. For example:

```
sys.InputGroup.controls = [1 2];
sys.InputGroup.noise = [3 5];
```

creates input groups named `controls` and `noise` that include input channels 1, 2 and 3, 5, respectively. You can then extract the subsystem from the `controls` inputs to all outputs using:

```
sys(:,'controls')
```

Default: Struct with no fields

`OutputName`

Output channel names. Set `OutputName` to a string for single-output model. For a multi-output model, set `OutputName` to a cell array of strings.

Alternatively, use automatic vector expansion to assign output names for multi-output models. For example, if `sys` is a two-output model, enter:

```
sys.OutputName = 'measurements';
```

The output names automatically expand to
`{'measurements(1)';'measurements(2)'}`.

You can use the shorthand notation `y` to refer to the `OutputName` property. For example, `sys.y` is equivalent to `sys.OutputName`.

Output channel names have several uses, including:

- Identifying channels on model display and plots
- Extracting subsystems of MIMO systems
- Specifying connection points when interconnecting models

Default: Empty string `''` for all output channels

OutputUnit

Output channel units. Use `OutputUnit` to keep track of output signal units. For a single-output model, set `OutputUnit` to a string. For a multi-output model, set `OutputUnit` to a cell array of strings. `OutputUnit` has no effect on system behavior.

Default: Empty string `''` for all output channels

OutputGroup

Output channel groups. The `OutputGroup` property lets you assign the output channels of MIMO systems into groups and refer to each group by name. Specify output groups as a structure. In this structure, field names are the group names, and field values are the output channels belonging to each group. For example:

```
sys.OutputGroup.temperature = [1];
sys.InputGroup.measurement = [3 5];
```

creates output groups named `temperature` and `measurement` that include output channels 1, and 3, 5, respectively. You can then extract the subsystem from all inputs to the `measurement` outputs using:

```
sys('measurement',:)
```

Default: Struct with no fields

Name

System name. Set `Name` to a string to label the system.

Default: `''`

`Notes`

Any text that you want to associate with the system. Set `Notes` to a string or a cell array of strings.

Default: `{}`

`UserData`

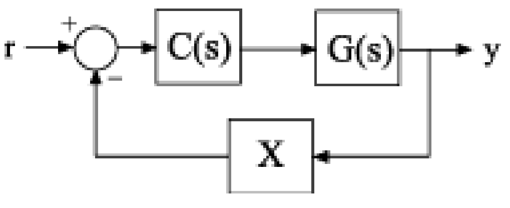
Any type of data you wish to associate with system. Set `UserData` to any MATLAB® data type.

Default: `[]`

Examples

Feedback Loop with Analysis Point

Create a model of the following feedback loop with an analysis point in the feedback path.



For this example, the plant model is $G = 1/(s+2)$. C is a tunable PI controller, and X is the analysis point.

```
G = tf(1,[1 2]);
C = ltiblock.pid('C','pi');
X = AnalysisPoint('X');
T = feedback(G*C,X);
T.InputName = 'r';
T.OutputName = 'y';
```

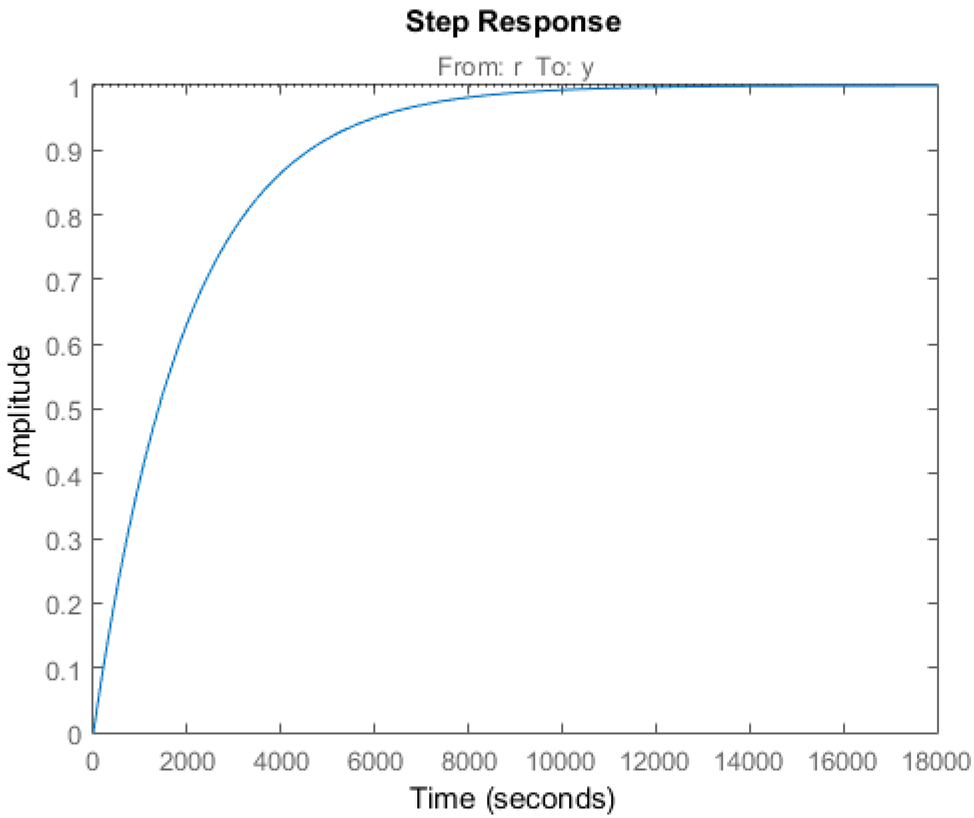
T is a tunable genss model. T.Blocks contains the Control Design Blocks of the model, which are the controller, C, and the analysis point, X.

```
T.Blocks
```

```
ans = 

    C: [1x1 ltiblock.pid]
    X: [1x1 AnalysisPoint]
```

Examine the step response of T.

```
stepplot(T)
```



The presence of the `AnalysisPoint` block does not change the dynamics of the model.

You can use the analysis point for linear analysis of the system. For instance, extract the system response at `'y'` to a disturbance injected at the analysis point.

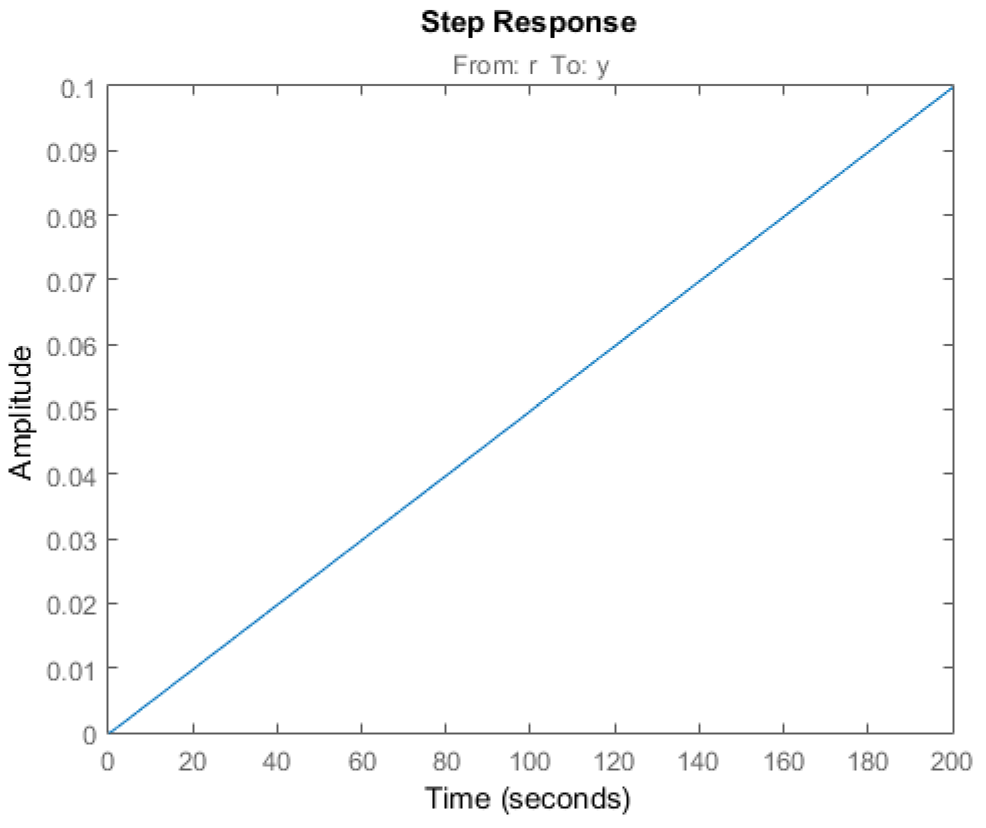
```
Txy = getIOTransfer(T,'X','y');
```

The `AnalysisPoint` block also allows you to temporarily open the feedback loop at that point. For example, compute the open-loop response from `'r'` to `'y'`.

```
Try_open = getIOTransfer(T,'r','y','X');
```

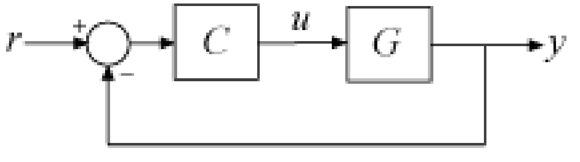
Specifying the analysis point name as the last argument to getIOTransfer extracts the response with the loop open at that point. Examine the step response of `Try_open` to verify that it is the open-loop response.

```
stepplot(Try_open);
```



Feedback Loop With Analysis Point Inserted by `connect`

Create a model of the following block diagram from r to y. Insert an analysis point at an internal location, u.



Create `C` and `G`, and name the inputs and outputs.

```
C = pid(2,1);
C.InputName = 'e';
C.OutputName = 'u';
G = zpk([],[-1,-1],1);
G.InputName = 'u';
G.OutputName = 'y';
```

Create the summing junction.

```
Sum = sumblk('e = r - y');
```

Combine `C`, `G`, and the summing junction to create the aggregate model, with an analysis point at u.

```
T = connect(G,C,Sum,'r','y','u')
```

```
T =

  Generalized continuous-time state-space model with 1 outputs, 1 inputs, 3 states, and
    AnalysisPoints_: Analysis point, 1 channels, 1 occurrences.

Type "ss(T)" to see the current value, "get(T)" to see all properties, and "T.Blocks" t
```

The resulting `T` is a `genss` model. The `connect` command creates the `AnalysisPoint` block, `AnalysisPoints_`, and inserts it into `T`. To see the name of the analysis point channel in `AnalysisPoints_`, use `getPoints`.

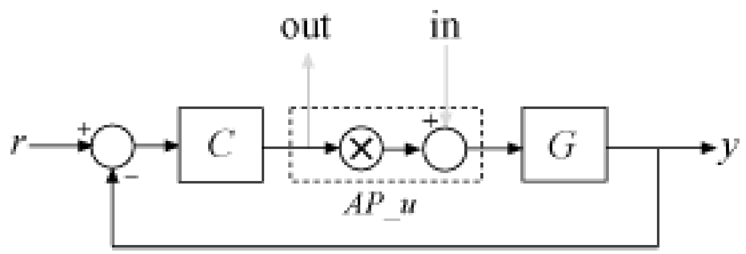
```
getPoints(T)
```

```
ans =

    'u'
```

The analysis point channel is named `'u'`. You can use this analysis point to extract system responses. For example, the following commands extract the open-loop transfer at u and the closed-loop response at y to a disturbance injected at u.

```
L = getLoopTransfer(T,'u',-1);
Tuy = getIOTransfer(T,'u','y');
```

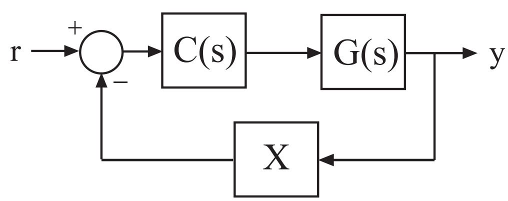
T is equivalent to the following block diagram, where *AP_u* designates the AnalysisPoint block AnalysisPoints_ with channel name *u*.



Multi-Channel Analysis Points

Create a block for marking two analysis points in a MIMO model.

In the control system of the following illustration, consider each signal a vector-valued signal of size 2. In other words, the signal *r* represents {r(1),r(2)}, *y* represents {y(1),y(2)}, and so on.



The feedback signal is therefore also a vector-valued signal of size 2.

Create a block for marking the two analysis points in the feedback path.

```
AP = AnalysisPoint('X',2)
```

```
AP =
```

```
Multi-channel analysis point at locations:
   X(1)
   X(2)

Type "ss(AP)" to see the current value and "get(AP)" to see all properties.
```

The `AnalysisPoint` block is stored as a variable in the MATLAB workspace called `AP`. In addition, the `Name` property of the block is set to `X`. When you interconnect the block with numeric LTI models or other Control Design Blocks, this analysis-point block is identified in the `Blocks` property of the resulting `genss` model as `X`. The block name `X` is automatically expanded to generate the channel names `X(1)` and `X(2)`.

It is sometimes convenient to change the channel names to match the names of the signals they correspond to in a block diagram of your model. For example, suppose the points of interest you want to mark in your model are signals named `L` and `V`. Change the `Location` property of `AP` to make the names match those signals.

```
AP.Location = {'L';'V'}
```

```
AP =

Multi-channel analysis point at locations:
   L
   V

Type "ss(AP)" to see the current value and "get(AP)" to see all properties.
```

Although the channel names have changed, the block name remains `X`.

```
AP.Name
```

```
ans =

X
```

Therefore, the `Blocks` property of a `genss` model you build with this block still identifies the block as `X`. Use `getPoints` to find the channel names of available analysis points in a `genss` model.

- “Control System with Multichannel Analysis Points”

More About

- “Control Design Blocks”

- “Models with Tunable Coefficients”
- “Marking Signals of Interest for Control System Analysis and Design”

See Also

`genss` | `getPoints` | `connect`

Introduced in R2014b

append

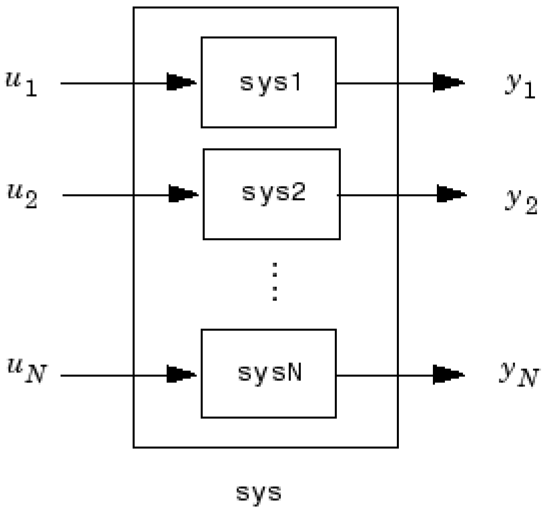
Group models by appending their inputs and outputs

Syntax

```
sys = append(sys1,sys2,...,sysN)
```

Description

`sys = append(sys1,sys2,...,sysN)` appends the inputs and outputs of the models `sys1`,...,`sysN` to form the augmented model `sys` depicted below.



For systems with transfer functions $H_1(s), \ldots, H_N(s)$, the resulting system `sys` has the block-diagonal transfer function

$$\begin{bmatrix} H_1(s) & 0 & \ldots & 0 \\ 0 & H_2(s) & \cdots & \vdots \\ \vdots & \vdots & \ddots & 0 \\ 0 & \cdots & 0 & H_N(s) \end{bmatrix}$$

For state-space models `sys1` and `sys2` with data (A_1, B_1, C_1, D_1) and (A_2, B_2, C_2, D_2), `append(sys1,sys2)` produces the following state-space model:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} A_1 & 0 \\ 0 & A_2 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} B_1 & 0 \\ 0 & B_2 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix}$$
$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} C_1 & 0 \\ 0 & C_2 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} D_1 & 0 \\ 0 & D_2 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix}$$

Arguments

The input arguments `sys1`,..., `sysN` can be model objects s of any type. Regular matrices are also accepted as a representation of static gains, but there should be at least one model in the input list. The models should be either all continuous, or all discrete with the same sample time. When appending models of different types, the resulting type is determined by the precedence rules (see "Rules That Determine Model Type" for details).

There is no limitation on the number of inputs.

Examples

The commands

```
sys1 = tf(1,[1 0]);
sys2 = ss(1,2,3,4);
sys = append(sys1,10,sys2)
```

produce the state-space model

```
a =
          x1   x2
    x1     0    0
    x2     0    1

b =
          u1   u2   u3
    x1     1    0    0
    x2     0    0    2
```

```
c =
        x1  x2
   y1    1   0
   y2    0   0
   y3    0   3

d =
        u1  u2  u3
   y1    0   0   0
   y2    0  10   0
   y3    0   0   4

Continuous-time model.
```

See Also

connect | feedback | parallel | series

augstate

Append state vector to output vector

Syntax

```
asys = augstate(sys)
```

Description

`asys = augstate(sys)` appends the state vector to the outputs of a state-space model.

Given a state-space model `sys` with equations

$$\begin{aligned}\dot{x} &= Ax + Bu \\ y &= Cx + Du\end{aligned}$$

(or their discrete-time counterpart), `augstate` appends the states x to the outputs y to form the model

$$\begin{aligned}\dot{x} &= Ax + Bu \\ \begin{bmatrix} y \\ x \end{bmatrix} &= \begin{bmatrix} C \\ I \end{bmatrix} x + \begin{bmatrix} D \\ 0 \end{bmatrix} u\end{aligned}$$

This command prepares the plant so that you can use the `feedback` command to close the loop on a full-state feedback $u = -Kx$.

Limitation

Because `augstate` is only meaningful for state-space models, it cannot be used with TF, ZPK or FRD models.

See Also

`feedback` | `parallel` | `series`

balreal

Gramian-based input/output balancing of state-space realizations

Syntax

```
[sysb, g] = balreal(sys)
[sysb, g] = balreal(sys,'AbsTol',ATOL,'RelTol',RTOL,'Offset',ALPHA)
[sysb, g] = balreal(sys, condmax)
[sysb, g, T, Ti] = balreal(sys)
[sysb, g] = balreal(sys, opts)
```

Description

`[sysb, g] = balreal(sys)` computes a balanced realization `sysb` for the stable portion of the LTI model `sys`. `balreal` handles both continuous and discrete systems. If `sys` is not a state-space model, it is first and automatically converted to state space using `ss`.

For stable systems, `sysb` is an equivalent realization for which the controllability and observability Gramians are equal and diagonal, their diagonal entries forming the vector G of Hankel singular values. Small entries in G indicate states that can be removed to simplify the model (use `modred` to reduce the model order).

If `sys` has unstable poles, its stable part is isolated, balanced, and added back to its unstable part to form `sysb`. The entries of `g` corresponding to unstable modes are set to `Inf`.

`[sysb, g] = balreal(sys,'AbsTol',ATOL,'RelTol',RTOL,'Offset',ALPHA)` specifies additional options for the stable/unstable decomposition. See the `stabsep` reference page for more information about these options. The default values are `ATOL = 0`, `RTOL = 1e-8`, and `ALPHA = 1e-8`.

`[sysb, g] = balreal(sys, condmax)` controls the condition number of the stable/unstable decomposition. Increasing `condmax` helps separate close by stable and unstable modes at the expense of accuracy. By default `condmax=1e8`.

`[sysb, g, T, Ti] = balreal(sys)` also returns the vector `g` containing the diagonal of the balanced gramian, the state similarity transformation $x_b = Tx$ used to convert `sys` to `sysb`, and the inverse transformation $Ti = T^{-1}$.

If the system is normalized properly, the diagonal `g` of the joint gramian can be used to reduce the model order. Because `g` reflects the combined controllability and observability of individual states of the balanced model, you can delete those states with a small `g(i)` while retaining the most important input-output characteristics of the original system. Use `modred` to perform the state elimination.

`[sysb, g] = balreal(sys, opts)` computes the balanced realization using the options specified in the `hsvdOptions` object `opts`.

Examples

Balanced Realization of Stable System

Consider the following zero-pole-gain model, with near-canceling pole-zero pairs:

```
sys = zpk([-10 -20.01],[-5 -9.9 -20.1],1)
```

```
sys =

     (s+10) (s+20.01)
  ----------------------
  (s+5) (s+9.9) (s+20.1)

Continuous-time zero/pole/gain model.
```

A state-space realization with balanced gramians is obtained by

```
[sysb,g] = balreal(sys);
```

The diagonal entries of the joint gramian are

```
g'
```

```
ans =

    0.1006    0.0001    0.0000
```

This indicates that the last two states of `sysb` are weakly coupled to the input and output. You can then delete these states by

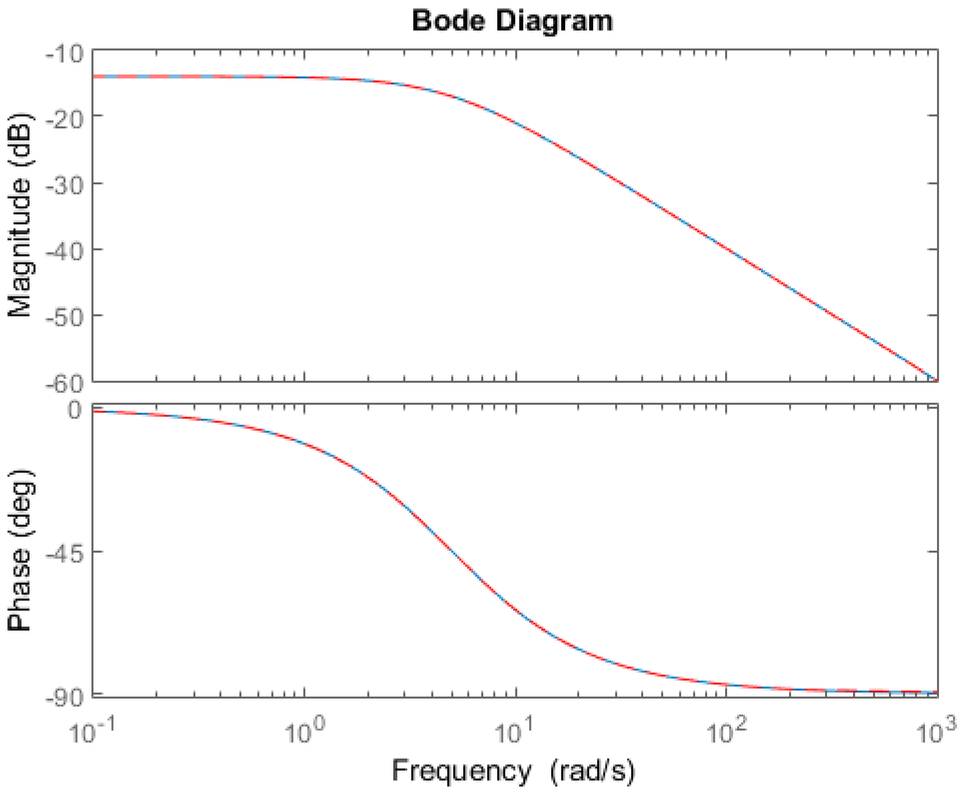
```
sysr = modred(sysb,[2 3],'del');
```

This yields the following first-order approximation of the original system.

```
zpk(sysr)


ans =

   1.0001
  --------
  (s+4.97)

Continuous-time zero/pole/gain model.
```

Compare the Bode responses of the original and reduced-order models.

```
bodeplot(sys,sysr,'r--')
```



The plots shows that removing the second and third states does not have much effect on system dynamics.

Balanced Realization of Unstable System

Create this unstable system:

```
sys1=tf(1,[1 0 -1])

Transfer function:
   1
-------
s^2 - 1
```

Apply `balreal` to create a balanced gramian realization.

```
[sysb,g]=balreal(sys1)

a =
       x1   x2
   x1   1    0
   x2   0   -1


b =
           u1
   x1  0.7071
   x2  0.7071


c =
            x1       x2
   y1   0.7071  -0.7071


d =
       u1
   y1   0

Continuous-time model.

g =

       Inf
    0.2500
```

The unstable pole shows up as `Inf` in vector g.

More About

Algorithms

Consider the model

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$

with controllability and observability gramians W_c and W_o. The state coordinate transformation $\bar{x} = Tx$ produces the equivalent model

$$\dot{\bar{x}} = TAT^{-1}\bar{x} + TBu$$
$$y = CT^{-1}\bar{x} + Du$$

and transforms the gramians to

$$\bar{W}_c = TW_cT^T, \quad \bar{W}_o = T^{-T}W_o T^{-1}$$

The function `balreal` computes a particular similarity transformation T such that

$$\bar{W}_c = \bar{W}_o = diag(g)$$

See [1], [2] for details on the algorithm.

References

[1] Laub, A.J., M.T. Heath, C.C. Paige, and R.C. Ward, "Computation of System Balancing Transformations and Other Applications of Simultaneous Diagonalization Algorithms," *IEEE® Trans. Automatic Control*, AC-32 (1987), pp. 115-122.

[2] Moore, B., "Principal Component Analysis in Linear Systems: Controllability, Observability, and Model Reduction," *IEEE Transactions on Automatic Control*, AC-26 (1981), pp. 17-31.

[3] Laub, A.J., "Computation of Balancing Transformations," *Proc. ACC*, San Francisco, Vol.1, paper FA8-E, 1980.

See Also

`hsvdOptions` | `ss` | `gram` | `modred`

balred

Model order reduction

Syntax

```
rsys = balred(sys,ORDERS)
rsys = balred(sys,ORDERS,BALDATA)
rsys = balred( ___ ,opts)
```

Description

`rsys = balred(sys,ORDERS)` computes a reduced-order approximation `rsys` of the LTI model `sys`. The desired order (number of states) for `rsys` is specified by `ORDERS`. You can try multiple orders at once by setting `ORDERS` to a vector of integers, in which case `rsys` is a vector of reduced-order models. `balred` uses implicit balancing techniques to compute the reduced- order approximation `rsys`. Use `hsvd` to plot the Hankel singular values and pick an adequate approximation order. States with relatively small Hankel singular values can be safely discarded.

When `sys` has unstable poles, it is first decomposed into its stable and unstable parts using `stabsep`, and only the stable part is approximated. Use `balredOptions` to specify additional options for the stable/unstable decomposition.

When you have System Identification Toolbox™ software installed, `sys` can only be an identified state-space model (`idss`). The reduced-order model is also an `idss` model.

`rsys = balred(sys,ORDERS,BALDATA)` uses balancing data returned by `hsvd`. Because `hsvd` does most of the work needed to compute `rsys`, this syntax is more efficient when using `hsvd` and `balred` jointly.

`rsys = balred( ___ ,opts)` computes the model reduction using the specified options for the stable/unstable decomposition and state elimination method. Use the `balredOptions` command to create the option set`opts`.

Note: The order of the approximate model is always at least the number of unstable poles and at most the minimal order of the original model (number `NNZ` of nonzero Hankel singular values using an eps-level relative threshold)

More About

- “Why Simplify Models?”

References

[1] Varga, A., "Balancing-Free Square-Root Algorithm for Computing Singular Perturbation Approximations," Proc. of 30th IEEE CDC, Brighton, UK (1991), pp. 1062-1065.

See Also

`balredOptions` | `hsvd` | `order` | `minreal` | `sminreal`

Related Examples

- “Approximate Model with Lower-Order Model”
- “Approximate Model with Unstable or Near-Unstable Pole”

balredOptions

Create option set for model order reduction

Syntax

```
opts = balredOptions
opts = balredOptions('OptionName', OptionValue)
```

Description

opts = balredOptions returns the default option set for the balred command.

opts = balredOptions('*OptionName*', *OptionValue*) accepts one or more comma-separated name/value pairs. Specify *OptionName* inside single quotes.

Input Arguments

Name-Value Pair Arguments

'StateElimMethod'

State elimination method. Specifies how to eliminate the weakly coupled states (states with smallest Hankel singular values). Specified as one of the following values:

'MatchDC'	Discards the specified states and alters the remaining states to preserve the DC gain.
'Truncate'	Discards the specified states without altering the remaining states. This method tends to product a better approximation in the frequency domain, but the DC gains are not guaranteed to match.

Default: 'MatchDC'

'AbsTol, RelTol'

Absolute and relative error tolerance for stable/unstable decomposition. Positive scalar values. For an input model G with unstable poles, balred first extracts the stable dynamics by computing the stable/unstable decomposition $G \to GS + GU$. The `AbsTol` and `RelTol` tolerances control the accuracy of this decomposition by ensuring that the frequency responses of G and $GS + GU$ differ by no more than `AbsTol` + `RelTol`*abs(G). Increasing these tolerances helps separate nearby stable and unstable modes at the expense of accuracy. See `stabsep` for more information.

Default: `AbsTol = 0; RelTol = 1e-8`

`'Offset'`

Offset for the stable/unstable boundary. Positive scalar value. In the stable/unstable decomposition, the stable term includes only poles satisfying

- `Re(s) < -Offset * max(1,|Im(s)|)` (Continuous time)
- `|z| < 1 - Offset` (Discrete time)

Increase the value of `Offset` to treat poles close to the stability boundary as unstable.

Default: `1e-8`

For additional information on the options and how to use them, see the `balred` reference page.

Examples

Reduced-Order Approximation with Offset Option

Compute a reduced-order approximation of the system given by:

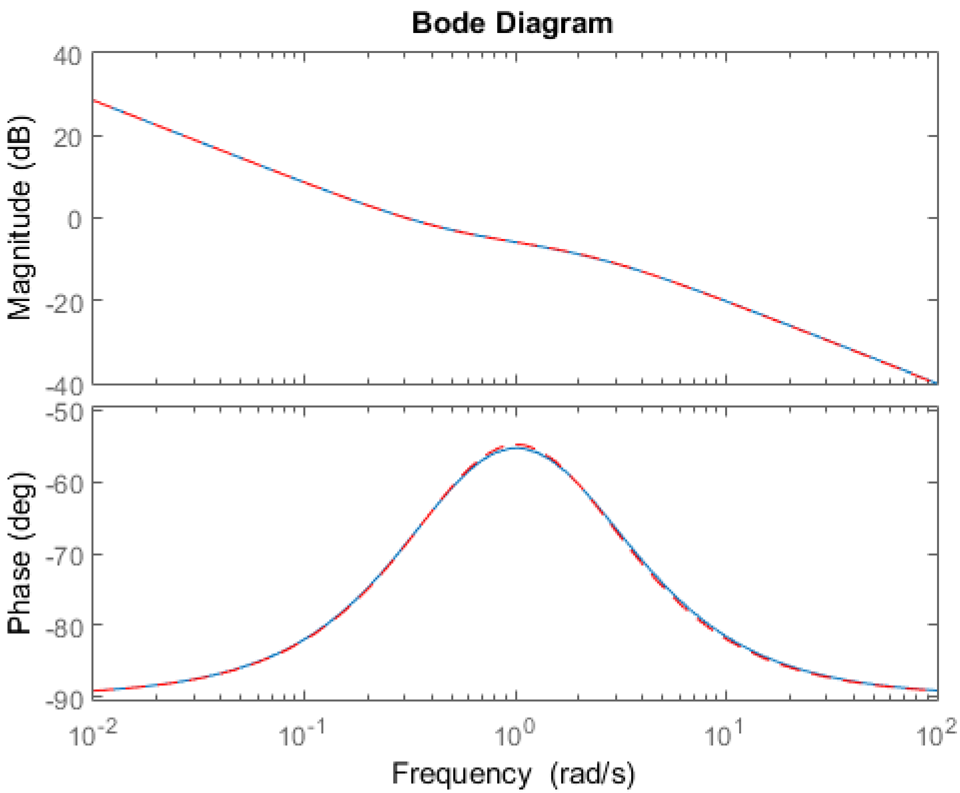
$$G(s) = \frac{(s+0.5)(s+1.1)(s+2.9)}{(s+10^{-6})(s+1)(s+2)(s+3)}.$$

Use the `Offset` option to exclude the pole at $s = 10^{-6}$ from the stable term of the stable/unstable decomposition.

```
sys = zpk([-.5 -1.1 -2.9],[-1e-6 -2 -1 -3],1);
% Create balredOptions
opt = balredOptions('Offset',.001,'StateElimMethod','Truncate');
% Compute second-order approximation
rsys = balred(sys,2,opt);
```

Compare the responses of the original and reduced-order models.

```
bodeplot(sys,rsys,'r--')
```



See Also

`balred` | `stabsep`

bandwidth

Frequency response bandwidth

Syntax

```
fb = bandwidth(sys)
fb = bandwidth(sys,dbdrop)
```

Description

`fb = bandwidth(sys)` computes the bandwidth `fb` of the SISO dynamic system model `sys`, defined as the first frequency where the gain drops below 70.79 percent (-3 dB) of its DC value. The frequency `fb` is expressed in `rad/TimeUnit`, where `TimeUnit` is the time units of the input dynamic system, specified in the TimeUnit property of sys.

For FRD models, `bandwidth` uses the first frequency point to approximate the DC gain.

`fb = bandwidth(sys,dbdrop)` specifies the critical gain drop in dB. The default value is -3 dB, or a 70.79 percent drop.

If `sys` is an S1-by...-by-Sp array of models, `bandwidth` returns an array of the same size such that

```
fb(j1,...,jp) = bandwidth(sys(:,:,j1,...,jp))
```

See Also

`issiso` | `dcgain`

bdschur

Block-diagonal Schur factorization

Syntax

```
[T,B,BLKS] = bdschur(A,CONDMAX)
[T,B] = bdschur(A,[],BLKS)
```

Description

`[T,B,BLKS] = bdschur(A,CONDMAX)` computes a transformation matrix T such that $B = T \setminus A * T$ is block diagonal and each diagonal block is a quasi upper-triangular Schur matrix.

`[T,B] = bdschur(A,[],BLKS)` pre-specifies the desired block sizes. The input matrix A should already be in Schur form when you use this syntax.

Input Arguments

- `A`: Matrix for block-diagonal Schur factorization.
- `CONDMAX`: Specifies an upper bound on the condition number of T. By default, `CONDMAX = 1/sqrt(eps)`. Use `CONDMAX` to control the tradeoff between block size and conditioning of T with respect to inversion. When `CONDMAX` is a larger value, the blocks are smaller and `T` becomes more ill-conditioned.

Output Arguments

- `T`: Transformation matrix.
- `B`: Matrix $B = T \setminus A * T$.
- `BLKS`: Vector of block sizes.

See Also

`ordschur` | `schur`

blkdiag

Block-diagonal concatenation of models

Syntax

```
sys = blkdiag(sys1,sys2,...,sysN)
```

Description

`sys = blkdiag(sys1,sys2,...,sysN)` produces the aggregate system

$$\begin{bmatrix} sys1 & 0 & .. & 0 \\ 0 & sys2 & . & : \\ : & . & . & 0 \\ 0 & .. & 0 & sysN \end{bmatrix}$$

`blkdiag` is equivalent to `append`.

Examples

The commands

```
sys1 = tf(1,[1 0]);
sys2 = ss(1,2,3,4);
sys = blkdiag(sys1,10,sys2)
```

produce the state-space model

```
a =
       x1  x2
   x1   0   0
   x2   0   1

b =
       u1  u2  u3
```

```
   x1   1   0   0
   x2   0   0   2

c =
       x1  x2
   y1   1   0
   y2   0   0
   y3   0   3

d =
       u1  u2  u3
   y1   0   0   0
   y2   0  10   0
   y3   0   0   4

Continuous-time model.
```

See Also

append | series | parallel | feedback

bode

Bode plot of frequency response, magnitude and phase of frequency response

Syntax

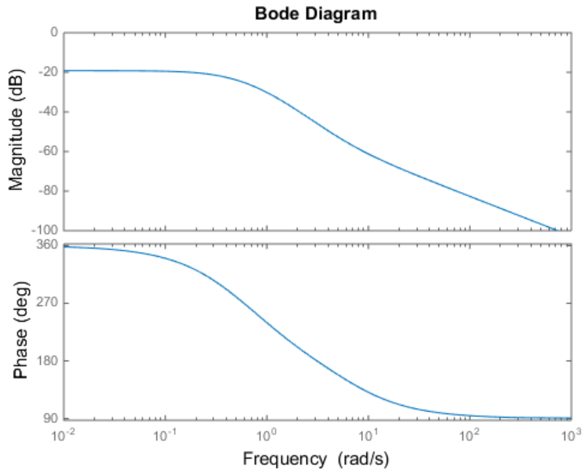
```
bode(sys)
bode(sys1,...,sysN)
bode(sys1,PlotStyle1,...,sysN,PlotStyleN)
bode(...,w)
[mag,phase] = bode(sys,w)
[mag,phase,wout] = bode(sys)
[mag,phase,wout,sdmag,sdphase] = bode(sys)
```

Description

`bode(sys)` creates a Bode plot of the frequency response of a dynamic system model sys. The plot displays the magnitude (in dB) and phase (in degrees) of the system response as a function of frequency.

When sys is a multi-input, multi-output (MIMO) model, `bode` produces an array of Bode plots, each plot showing the frequency response of one I/O pair.

`bode` automatically determines the plot frequency range based on system dynamics.



`bode(sys1,...,sysN)` plots the frequency response of multiple dynamic systems in a single figure. All systems must have the same number of inputs and outputs.

`bode(sys1,PlotStyle1,...,sysN,PlotStyleN)` plots system responses using the color, linestyle, and markers specified by the PlotStyle strings.

`bode(...,w)` plots system responses at frequencies determined by w.

- If w is a cell array `{wmin,wmax}`, `bode(sys,w)` plots the system response at frequency values in the range `{wmin,wmax}`.
- If w is a vector of frequencies, `bode(sys,w)` plots the system response at each of the frequencies specified in w.

`[mag,phase] = bode(sys,w)` returns magnitudes mag in absolute units and phase values phase in degrees. The response values in mag and phase correspond to the frequencies specified by w as follows:

- If w is a cell array `{wmin,wmax}`, `[mag,phase] = bode(sys,w)` returns the system response at frequency values in the range `{wmin,wmax}`.
- If w is a vector of frequencies, `[mag,phase] = bode(sys,w)` returns the system response at each of the frequencies specified in w.

`[mag,phase,wout] = bode(sys)` returns magnitudes, phase values, and frequency values wout corresponding to `bode(sys)`.

`[mag,phase,wout,sdmag,sdphase] = bode(sys)` additionally returns the estimated standard deviation of the magnitude and phase values when sys is an identified model and `[]` otherwise.

Input Arguments

`sys`

Dynamic system model, such as a Numeric LTI model, or an array of such models.

`PlotStyle`

Line style, marker, and color of both the line and marker, specified as a one-, two-, or three-part string enclosed in single quotes `(' ')`. The elements of the string can appear in any order. The string can specify only the line style, the marker, or the color.

For more information about configuring the PlotStyle string, see “Specify Line Style, Color, and Markers” in the MATLAB documentation.

`w`

Input frequency values, specified as a row vector or a two-element cell array.

Possible values of `w`:

- Two-element cell array `{wmin,wmax}`, where `wmin` is the minimum frequency value and `wmax` is the maximum frequency value.
- Row vector of frequency values.

  For example, use `logspace` to generate a row vector with logarithmically-spaced frequency values.

Specify frequency values in radians per `TimeUnit`, where `TimeUnit` is the time units of the input dynamic system, specified in the TimeUnit property of sys.

Output Arguments

`mag`

Bode magnitude of the system response in absolute units, returned as a 3-D array with dimensions (number of outputs) × (number of inputs) × (number of frequency points).

- For a single-input, single-output (SISO) sys, `mag(1,1,k)` gives the magnitude of the response at the `k`th frequency.
- For MIMO systems, `mag(i,j,k)` gives the magnitude of the response from the `j`th input to the `i`th output.

You can convert the magnitude from absolute units to decibels using:

```
magdb = 20*log10(mag)
```

phase

Phase of the system response in degrees, returned as a 3-D array with dimensions are (number of outputs) × (number of inputs) × (number of frequency points).

- For SISO sys, `phase(1,1,k)` gives the phase of the response at the `k`th frequency.
- For MIMO systems, `phase(i,j,k)` gives the phase of the response from the `j`th input to the `i`th output.

wout

Response frequencies, returned as a row vector of frequency points. Frequency values are in radians per `TimeUnit`, where `TimeUnit` is the value of the `TimeUnit` property of sys.

sdmag

Estimated standard deviation of the magnitude. sdmag has the same dimensions as mag.

If sys is not an identified LTI model, sdmag is `[]`.

sdphase

Estimated standard deviation of the phase. sdphase has the same dimensions as phase.

If sys is not an identified LTI model, sdphase is `[]`.

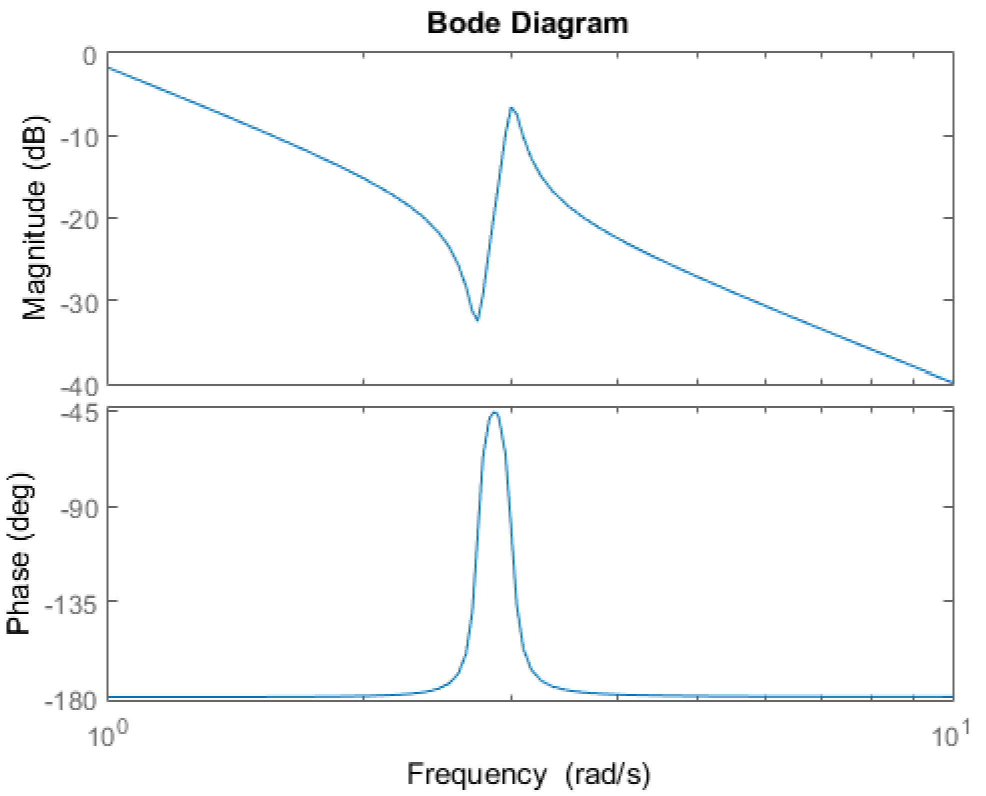
Examples

Bode Plot of Dynamic System

Create a Bode plot of the following continuous-time SISO dynamic system.

$$H(s) = \frac{s^2 + 0.1s + 7.5}{s^4 + 0.12s^3 + 9s^2}.$$

```
H = tf([1 0.1 7.5],[1 0.12 9 0 0]);
bode(H)
```

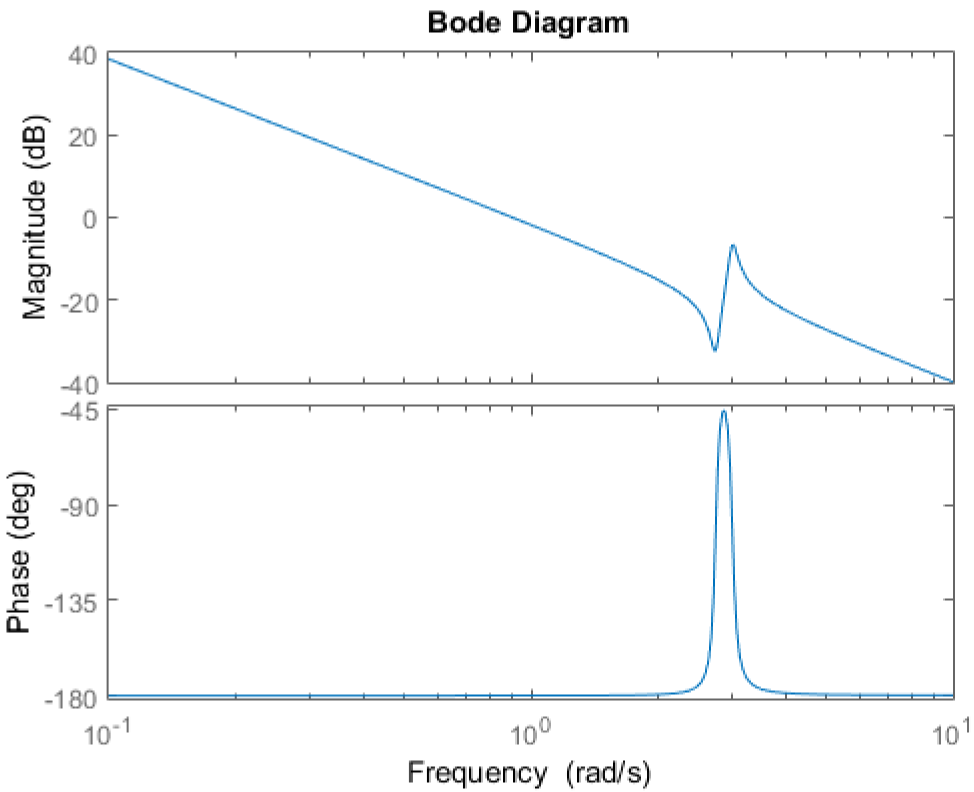


`bode` automatically selects the plot range based on the system dynamics.

Bode Plot at Specified Frequencies

Create a Bode plot over a specified frequency range. Use this approach when you want to focus on the dynamics in a particular range of frequencies.

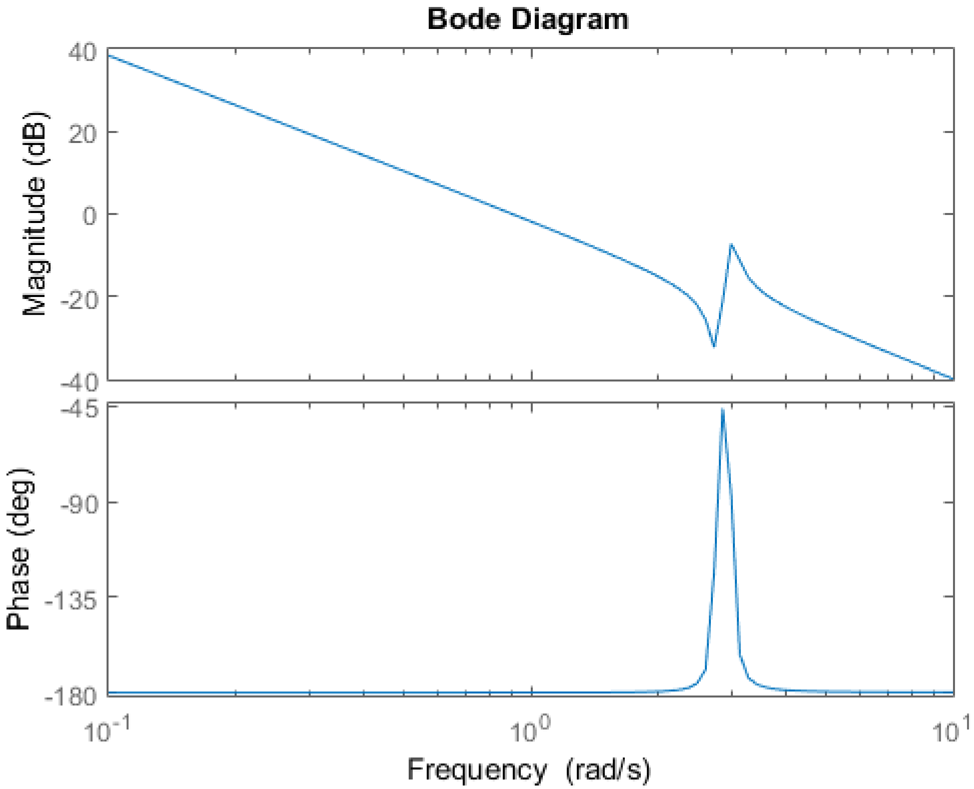
```
H = tf([1 0.1 7.5],[1 0.12 9 0 0]);
bode(H,{0.1,10})
```



The cell array `{0.1,10}` specifies the minimum and maximum frequency values in the Bode plot. When you provide frequency bounds in this way, the software selects intermediate points for frequency response data.

Alternatively, specify a vector of frequency points to use for evaluating and plotting the frequency response.

```
w = logspace(-1,1,100);
bode(H,w)
```



`logspace` defines a logarithmically spaced frequency vector in the range of 0.1-10 rad/s.

Compare Bode Plots of Several Dynamic Systems

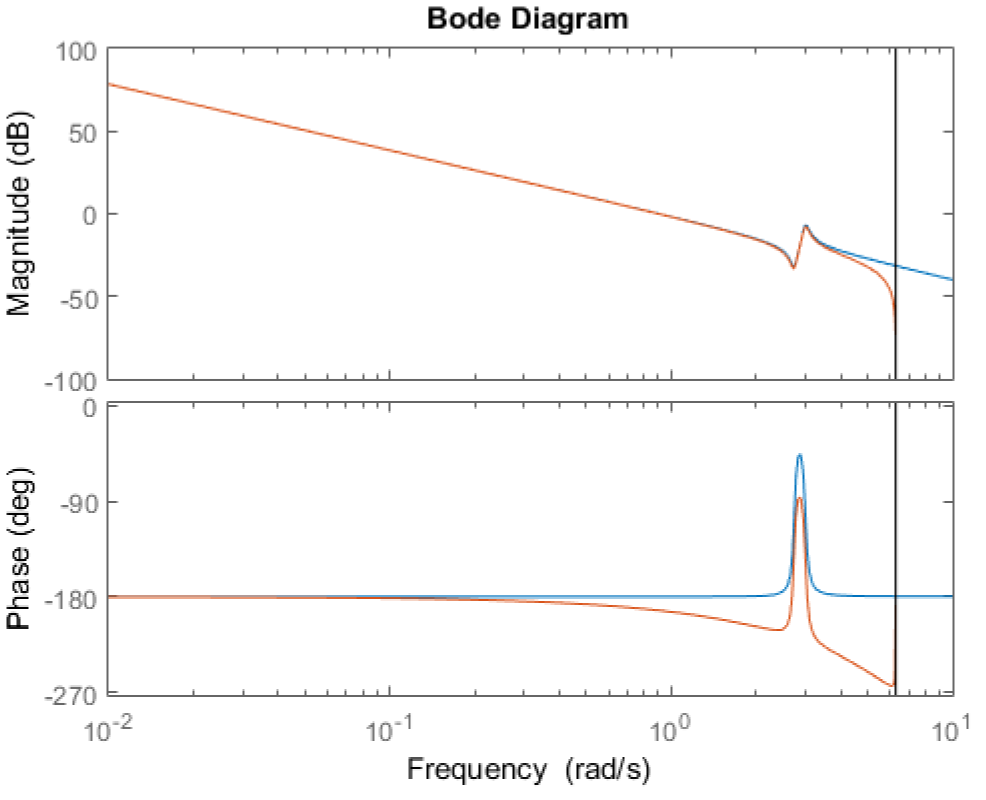
Compare the frequency response of a continuous-time system to an equivalent discretized system on the same Bode plot.

Create continuous-time and discrete-time dynamic systems.

```
H = tf([1 0.1 7.5],[1 0.12 9 0 0]);
Hd = c2d(H,0.5,'zoh');
```

Create a Bode plot that displays both systems.

```
bode(H,Hd)
```

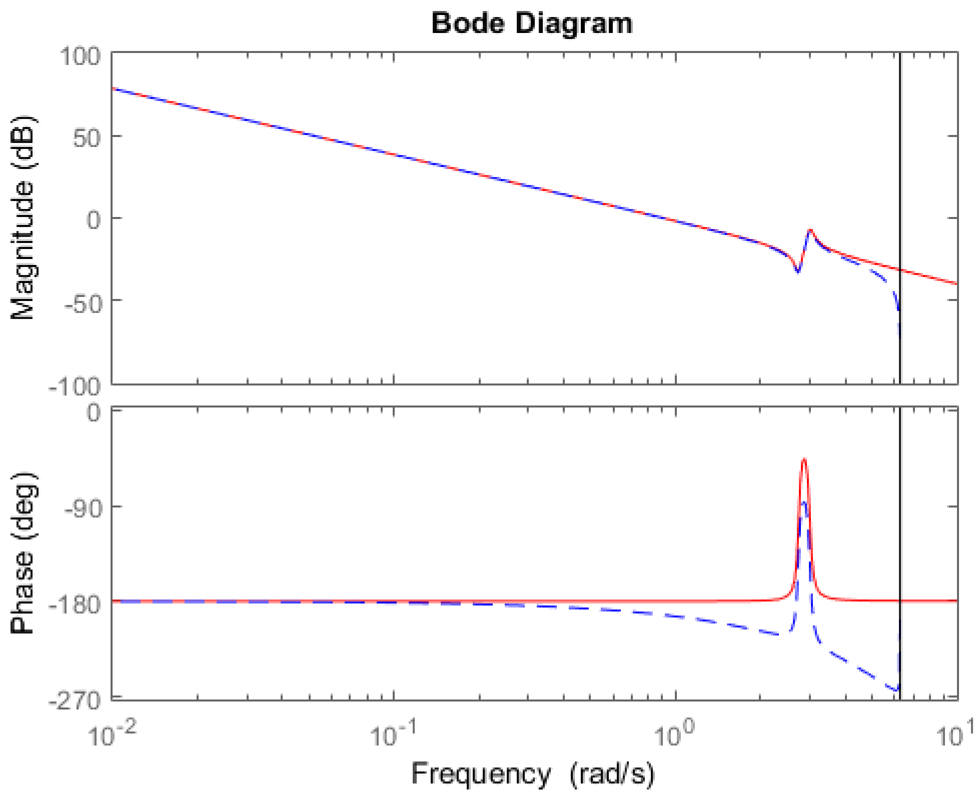


The Bode plot of a discrete-time system includes a vertical line marking the Nyquist frequency of the system.

Bode Plot with Specified Line and Marker Attributes

Specify the color, linestyle, or marker for each system in a Bode plot using the `PlotStyle` input arguments.

```
H = tf([1 0.1 7.5],[1 0.12 9 0 0]);
Hd = c2d(H,0.5,'zoh');
bode(H,'r',Hd,'b--')
```



The string `'r'` specifies a solid red line for the response of `H`. The string `'b--'` specifies a dashed blue line for the response of `Hd`.

Obtain Magnitude and Phase Data

Compute the magnitude and phase of the frequency response of a dynamic system.

```
H = tf([1 0.1 7.5],[1 0.12 9 0 0]);
[mag phase wout] = bode(H);
```

Because `H` is a SISO model, the first two dimensions of `mag` and `phase` are both 1. The third dimension is the number of frequencies in `wout`.

Bode Plot of Identified Model

Compare the frequency response of a parametric model, identified from input/output data, to a nonparametric model identified using the same data.

Identify parametric and non-parametric models based on data.

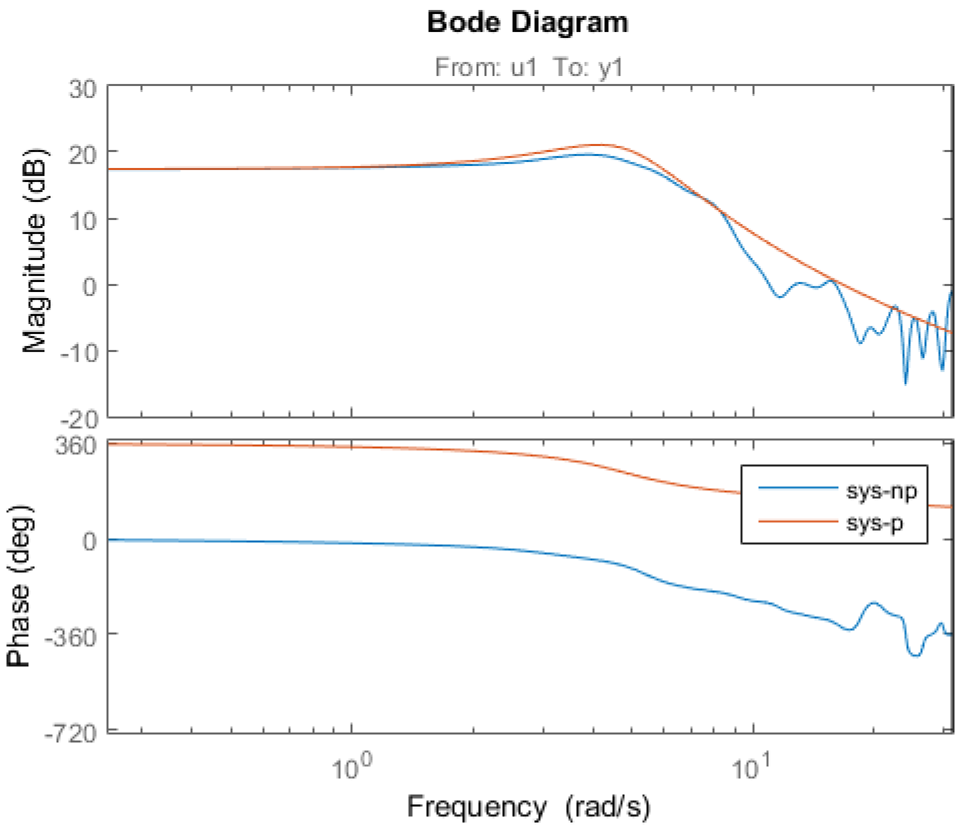
```
load iddata2 z2;
w = linspace(0,10*pi,128);
sys_np = spa(z2,[],w);
sys_p = tfest(z2,2);
```

Using the `spa` and `tfest` commands requires System Identification Toolbox™ software.

`sys_np` is a non-parametric identified model. `sys_p` is a parametric identified model.

Create a Bode plot that includes both systems.

```
bode(sys_np,sys_p,w);
legend('sys-np','sys-p')
```



Obtain Magnitude and Phase Standard Deviation Data of Identified Model

Compute the standard deviation of the magnitude and phase of an identified model. Use this data to create a 3σ plot of the response uncertainty.

Identify a transfer function model based on data. Obtain the standard deviation data for the magnitude and phase of the frequency response.

```
load iddata2 z2;
sys_p = tfest(z2,2);
w = linspace(0,10*pi,128);
```

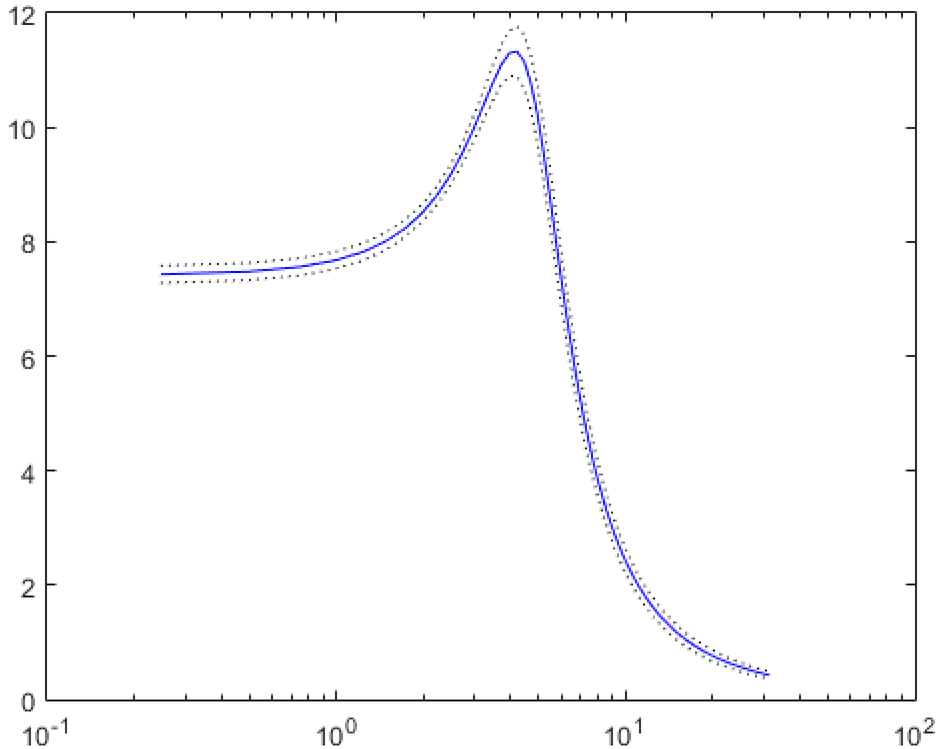
```
[mag,ph,w,sdmag,sdphase] = bode(sys_p,w);
```

Using the `tfest` command requires System Identification Toolbox™ software.

`sys_p` is an identified transfer function model. `sdmag` and `sdphase` contain the standard deviation data for the magnitude and phase of the frequency response, respectively.

Use the standard deviation data to create a 3σ plot corresponding to the confidence region.

```
mag = squeeze(mag);
sdmag = squeeze(sdmag);
semilogx(w,mag,'b',w,mag+3*sdmag,'k:',w,mag-3*sdmag,'k:');
```



Alternatives

Use `bodeplot` when you need additional plot customization options.

More About

Algorithms

`bode` computes the frequency response using these steps:

1 Computes the zero-pole-gain (`zpk`) representation of the dynamic system.

2 Evaluates the gain and phase of the frequency response based on the zero, pole, and gain data for each input/output channel of the system.

- **a** For continuous-time systems, `bode` evaluates the frequency response on the imaginary axis $s = j\omega$ and considers only positive frequencies.
- **b** For discrete-time systems, `bode` evaluates the frequency response on the unit circle. To facilitate interpretation, the command parameterizes the upper half of the unit circle as

$$z = e^{j\omega T_s}, \quad 0 \le \omega \le \omega_N = \frac{\pi}{T_s},$$

where T_s is the sample time. ω_N is the *Nyquist frequency*. The equivalent continuous-time frequency ω is then used as the x-axis variable. Because $H(e^{j\omega T_s})$ is periodic and has a period 2 ω_N, `bode` plots the response only up to the Nyquist frequency ω_N. If you do not specify a sample time, `bode` uses $T_s = 1$.

- "Dynamic System Models"

See Also

`freqresp` | `nyquist` | `bodeplot` | `nichols`

bodemag

Bode magnitude response of LTI models

Syntax

```
bodemag(sys)
bodemag(sys,{wmin,wmax})
bodemag(sys,w)
bodemag(sys1,sys2,...,sysN,w)
```

Description

`bodemag(sys)` plots the magnitude of the frequency response of the dynamic system model sys (Bode plot without the phase diagram). The frequency range and number of points are chosen automatically.

`bodemag(sys,{wmin,wmax})` draws the magnitude plot for frequencies between `wmin` and `wmax` (in `rad/TimeUnit`, where `TimeUnit` is the time units of the input dynamic system, specified in the TimeUnit property of sys).

`bodemag(sys,w)` uses the user-supplied vector W of frequencies, in `rad/TimeUnit`, at which the frequency response is to be evaluated.

`bodemag(sys1,sys2,...,sysN,w)` shows the frequency response magnitude of several models `sys1`,`sys2`,`...`,`sysN` on a single plot. The frequency vector `w` is optional. You can also specify a color, line style, and marker for each model. For example:

```
bodemag(sys1,'r',sys2,'y--',sys3,'gx')
```

See Also

`bode` | `linearSystemAnalyzer`

bodeoptions

Create list of Bode plot options

Syntax

```
P = bodeoptions
P = bodeoptions('cstprefs')
```

Description

`P = bodeoptions` returns a default set of plot options for use with the `bodeplot`. You can use these options to customize the Bode plot appearance using the command line. This syntax is useful when you want to write a script to generate plots that look the same regardless of the preference settings of the MATLAB session in which you run the script.

`P = bodeoptions('cstprefs')` initializes the plot options with the options you selected in the Control System and System Identification Toolbox Preferences Editor. For more information about the editor, see "Toolbox Preferences Editor" in the User's Guide documentation. This syntax is useful when you want to change a few plot options but otherwise use your default preferences. A script that uses this syntax may generate results that look different when run in a session with different preferences.

The following table summarizes the Bode plot options.

Option	Description
Title, XLabel, YLabel	Label text and style, specified as a structure with the following fields: • `String` — Label text, specified as a string • `FontSize` — **Default**: 8 • `FontWeight` — **Default**: `'Normal'` • `Font Angle` — **Default**: `'Normal'` • `Color` — Vector of RGB values ranging from 0 to 1. **Default**: `[0,0,0]` • `Interpreter` — **Default**: `'tex'`
TickLabel	Tick label style, specified as a structure with the following fields:

Option	Description
	• `FontSize` **Default**: 8 • `FontWeight` — **Default**: `'Normal'` • `Font Angle` — **Default**: `'Normal'` • `Color` — Vector of RGB values ranging from 0 to 1. **Default**: `[0,0,0]`
Grid	Show or hide the grid Specified as one of the following strings: `'off' | 'on'` **Default**: `'off'`
XlimMode, YlimMode	Axis limit modes. **Default**: `'auto'`
Xlim, Ylim	Axes limits, specified as an array of the form `[min,max]`
IOGrouping	Grouping of input-output pairs Specified as one of the following strings: `'none' |'inputs'|'outputs'|'all'` **Default**: `'none'`
InputLabels, OutputLabels	Input and output label styles
InputVisible, OutputVisible	Visibility of input and output channels
ConfidenceRegionNumbe	Number of standard deviations to use to plotting the response confidence region (identified models only). **Default**: `1`.

Option	Description
FreqUnits	Frequency units, specified as one of the following strings: • `'Hz'` • `'rad/second'` • `'rpm'` • `'kHz'` • `'MHz'` • `'GHz'` • `'rad/nanosecond'` • `'rad/microsecond'` • `'rad/millisecond'` • `'rad/minute'` • `'rad/hour'` • `'rad/day'` • `'rad/week'` • `'rad/month'` • `'rad/year'` • `'cycles/nanosecond'` • `'cycles/microsecond'` • `'cycles/millisecond'` • `'cycles/hour'` • `'cycles/day'` • `'cycles/week'` • `'cycles/month'` • `'cycles/year'` **Default**: `'rad/s'` You can also specify `'auto'` which uses frequency units `rad/TimeUnit` relative to system time units specified in the `TimeUnit` property. For

Option	Description
	multiple systems with different time units, the units of the first system are used.
FreqScale	Frequency scale Specified as one of the following strings: `'linear'` | `'log'` **Default**: `'log'`
MagUnits	Magnitude units Specified as one of the following strings: `'dB'` | `'abs'` **Default**: `'dB'`
MagScale	Magnitude scale Specified as one of the following strings: `'linear'` | `'log'` **Default**: `'linear'`
MagVisible	Magnitude plot visibility Specified as one of the following strings: `'on'` | `'off'` **Default**: `'on'`
MagLowerLimMode	Enables a lower magnitude limit Specified as one of the following strings: `'auto'` | `'manual'` **Default**: `'auto'`
MagLowerLim	Specifies the lower magnitude limit
PhaseUnits	Phase units Specified as one of the following strings: `'deg'` | `'rad'` **Default**: `'deg'`
PhaseVisible	Phase plot visibility Specified as one of the following strings: `'on'` | `'off'` **Default**: `'on'`
PhaseWrapping	Enables phase wrapping Specified as one of the following strings: `'on'` | `'off'` **Default**: `'off'`
PhaseMatching	Enables phase matching Specified as one of the following strings: `'on'` | `'off'` **Default**: `'off'`
PhaseMatchingFreq	Frequency for matching phase
PhaseMatchingValue	The value to which phase responses are matched closely

Examples

Create Bode Plot with Custom Settings

Create a Bode plot that suppresses the phase plot and uses frequency units Hz instead of the default radians/second. Otherwise, the plot uses the settings that are saved in the toolbox preferences.

First, create an options set based on the toolbox preferences.

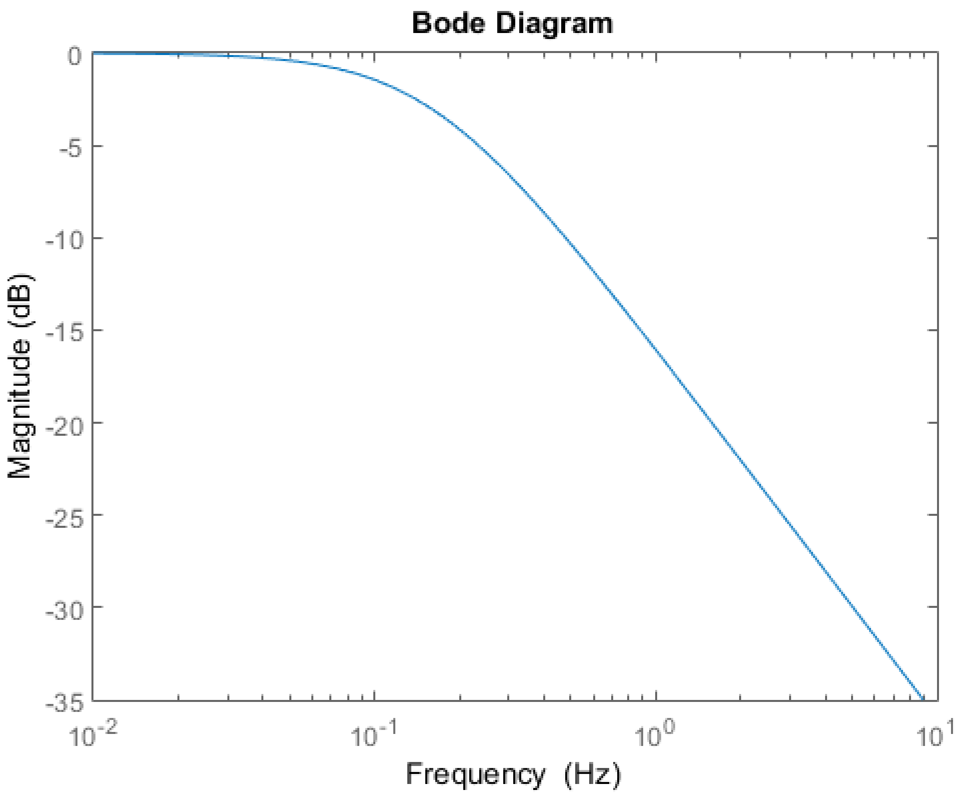
```
opts = bodeoptions('cstprefs');
```

Change properties of the options set.

```
opts.PhaseVisible = 'off';
opts.FreqUnits = 'Hz';
```

Create a plot using the options.

```
h = bodeplot(tf(1,[1,1]),opts);
```



Depending on your own toolbox preferences, the plot you obtain might look different from this plot. Only the properties that you set explicitly, in this example `PhaseVisible` and `FreqUnits`, override the toolbox preferences.

Custom Plot Settings Independent of Preferences

Create a Bode plot that uses 14-point red text for the title. This plot should look the same, regardless of the preferences of the MATLAB session in which it is generated.

First, create a default options set.

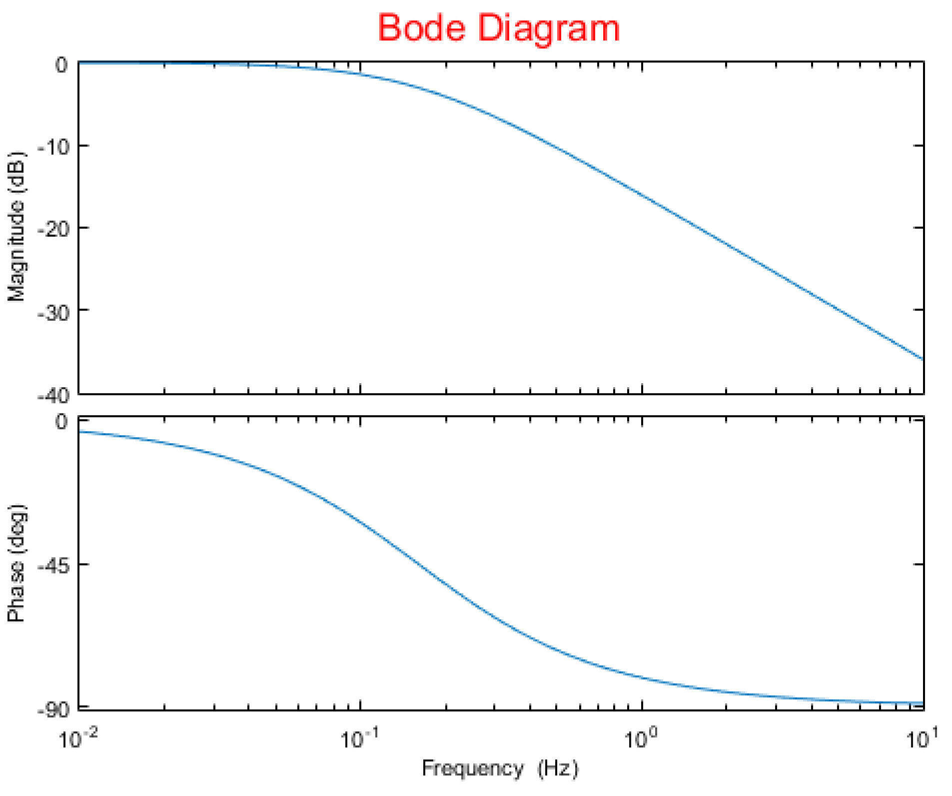
```
opts = bodeoptions;
```

Change properties of the options set.

```
opts.Title.FontSize = 14;
opts.Title.Color = [1 0 0];
opts.FreqUnits = 'Hz';
```

Create a plot using the options.

```
h = bodeplot(tf(1,[1,1]),opts);
```



Because `opts` begins with a fixed set of options, the plot result is independent of the toolbox preferences of the MATLAB session.

See Also

`bodeplot` | `getoptions` | `setoptions` | `bode`

bodeplot

Plot Bode frequency response with additional plot customization options

Syntax

```
h = bodeplot(sys)
bodeplot(sys)
bodeplot(sys1,sys2,...)
bodeplot(AX,...)
bodeplot(..., plotoptions)
bodeplot(sys,w)
```

Description

`h = bodeplot(sys)` plot the Bode magnitude and phase of the dynamic system model `sys` and returns the plot handle `h` to the plot. You can use this handle to customize the plot with the `getoptions` and `setoptions` commands.

`bodeplot(sys)` draws the Bode plot of the model `sys`. The frequency range and number of points are chosen automatically.

`bodeplot(sys1,sys2,...)` graphs the Bode response of multiple models `sys1`,`sys2`,... on a single plot. You can specify a color, line style, and marker for each model, as in

```
bodeplot(sys1,'r',sys2,'y--',sys3,'gx')
```

`bodeplot(AX,...)` plots into the axes with handle `AX`.

`bodeplot(..., plotoptions)` plots the Bode response with the options specified in `plotoptions`. Type

```
help bodeoptions
```

for a list of available plot options. See “Match Phase at Specified Frequency.” on page 1-67 for an example of phase matching using the `PhaseMatchingFreq` and `PhaseMatchingValue` options.

`bodeplot(sys,w)` draws the Bode plot for frequencies specified by `w`. When `w = {wmin,wmax}`, the Bode plot is drawn for frequencies between `wmin` and `wmax` (in `rad/TimeUnit`, where `TimeUnit` is the time units of the input dynamic system, specified in the TimeUnit property of sys.). When `w` is a user-supplied vector `w` of frequencies, in rad/TimeUnit, the Bode response is drawn for the specified frequencies.

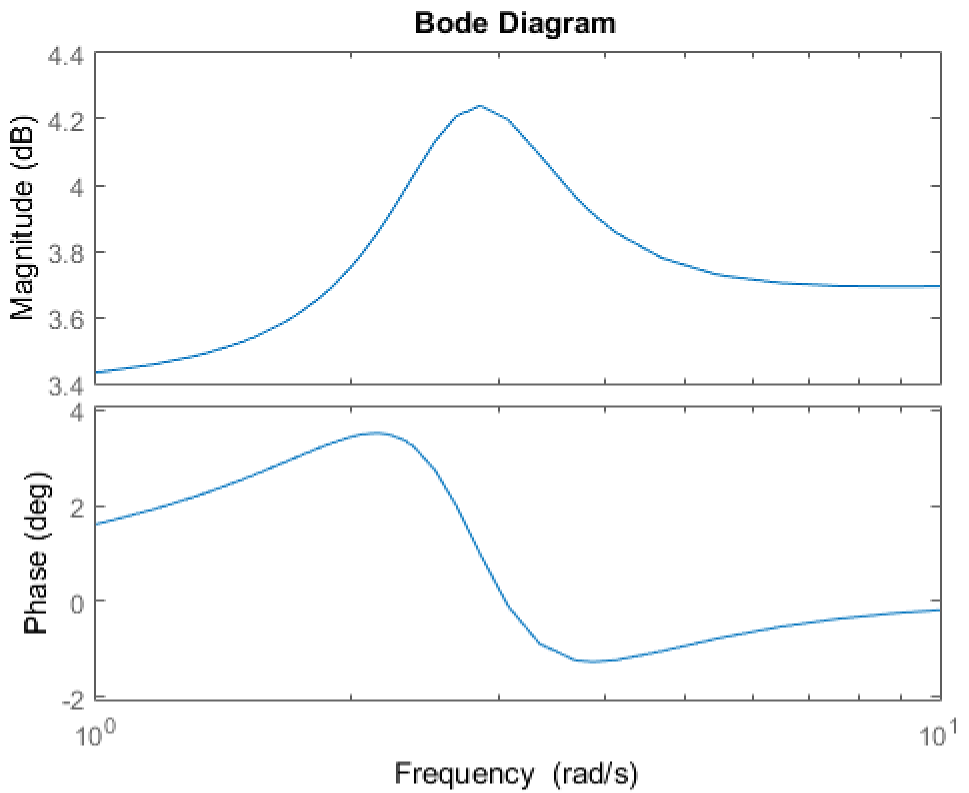
See `logspace` to generate logarithmically spaced frequency vectors.

Examples

Change Bode Plot Options with Plot Handle

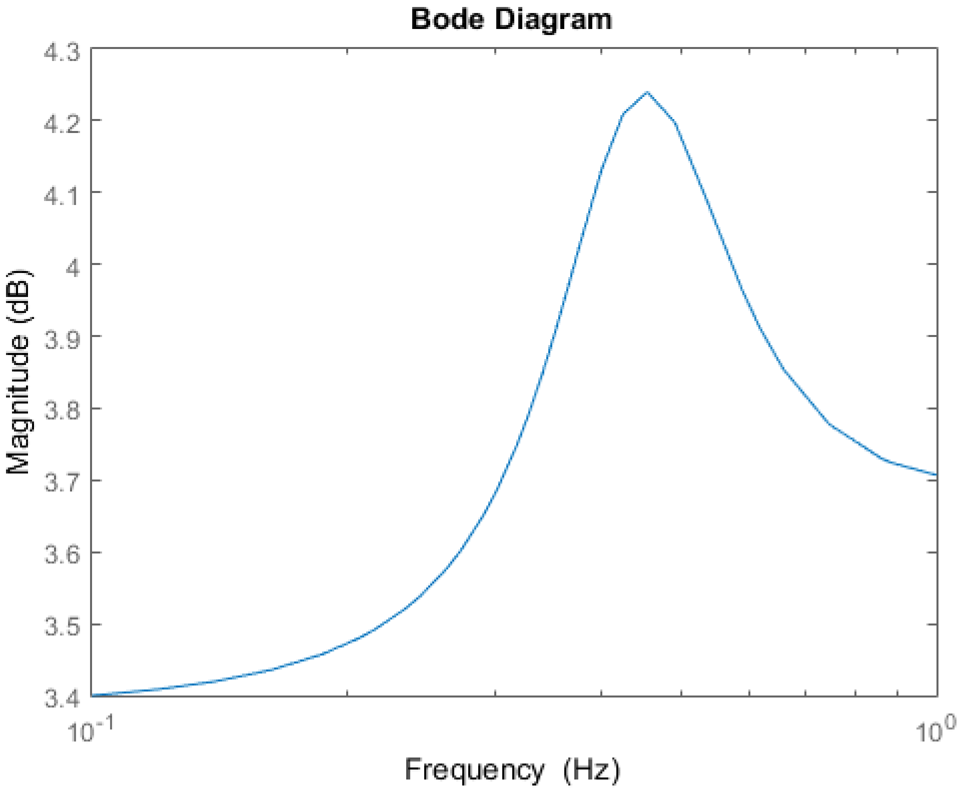
Generate a Bode plot.

```
sys = rss(5);
h = bodeplot(sys);
```



Change the units to Hz and suppress the phase plot. To do so, edit properties of the plot handle, `h`.

```
setoptions(h,'FreqUnits','Hz','PhaseVisible','off');
```

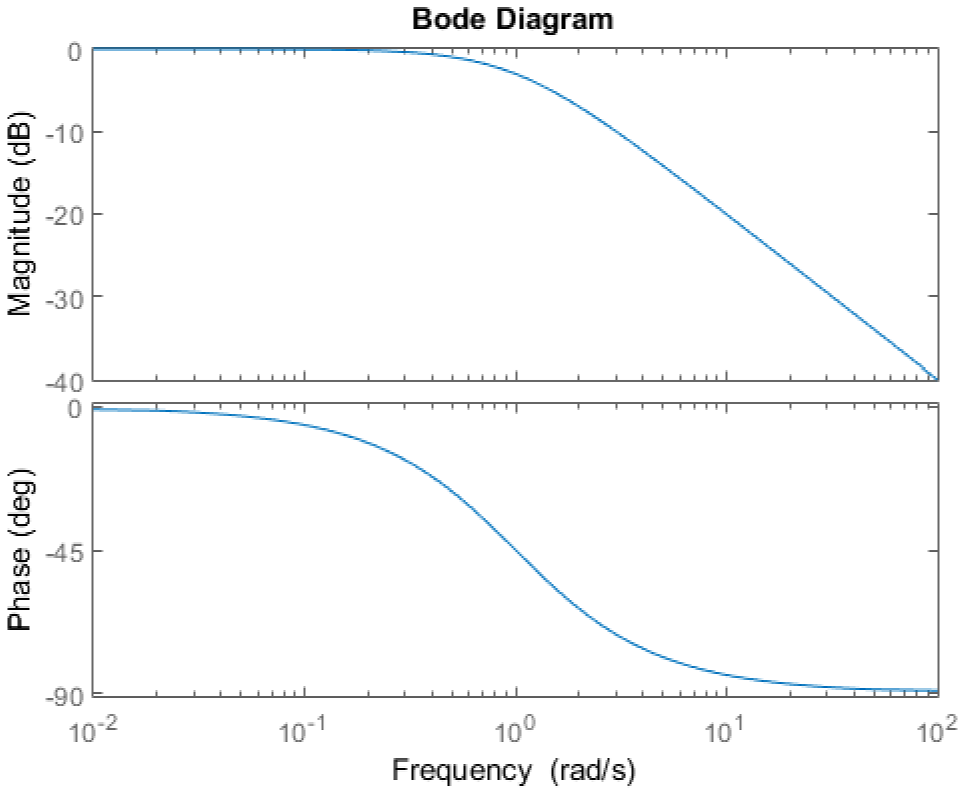


The plot automatically updates when you call `setoptions`.

Match Phase at Specified Frequency.

Create a Bode plot of a dynamic system.

```
sys = tf(1,[1 1]);
h = bodeplot(sys);
```

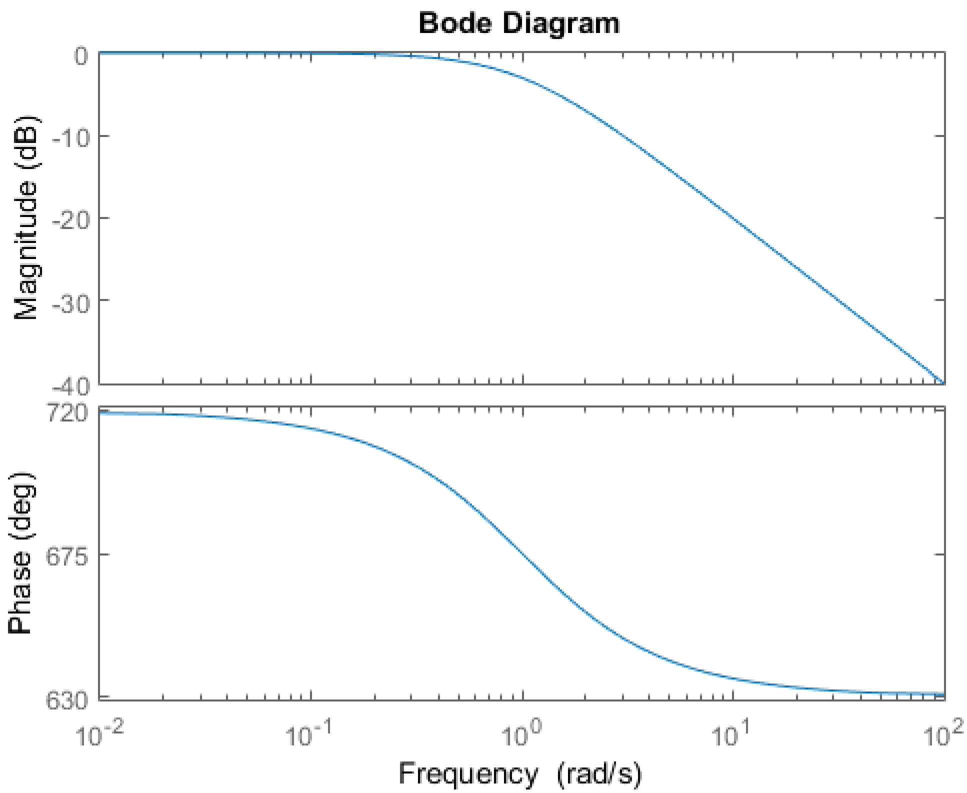


Fix the phase at 1 rad/s to 750 degrees. To do so, get the plot properties. Then alter the properties `PhaseMatchingFreq` and `PhaseMatchingValue` to match a phase to a specified frequency.

```
p = getoptions(h);
p.PhaseMatching = 'on';
p.PhaseMatchingFreq = 1;
p.PhaseMatchingValue = 750;
```

Update the plot.

```
setoptions(h,p);
```



The first bode plot has a phase of -45 degrees at a frequency of 1 rad/s. Setting the phase matching options so that at 1 rad/s the phase is near 750 degrees yields the second Bode plot. Note that, however, the phase can only be -45 + N*360, where N is an integer, and so the plot is set to the nearest allowable phase, namely 675 degrees (or 2*360 - 45 = 675).

Display Confidence Regions of Identified Models

Compare the frequency responses of identified state-space models of order 2 and 6 along with their 2 σ confidence regions.

```
load iddata1
sys1 = n4sid(z1, 2) % discrete-time IDSS model of order 2
```

```
sys2 = n4sid(z1, 6) % discrete-time IDSS model of order 6
```

Both models produce about 76% fit to data. However, sys2 shows higher uncertainty in its frequency response, especially close to Nyquist frequency as shown by the plot:

```
w = linspace(8,10*pi,256);
h = bodeplot(sys1,sys2,w);
setoptions(h, 'PhaseMatching', 'on', 'ConfidenceRegionNumberSD', 2);
```

Use the context menu by right-clicking **Characteristics** > **Confidence Region** to turn on the confidence region characteristic.

Frequency Response of Identified Parametric and Nonparametric models

Compare the frequency response of a parametric model, identified from input/output data, to a nonparametric model identified using the same data.

1. Identify parametric and non-parametric models based on data.

   ```
   load iddata2 z2;
   w = linspace(0,10*pi,128);
   sys_np = spa(z2,[],w);
   sys_p = tfest(z2,2);
   ```

   `spa` and `tfest` require System Identification Toolbox software. `sys_np` is a nonparametric identified model. `sys_p` is a parametric identified model.
2. Create a Bode plot that includes both systems.

   ```
   opt = bodeoptions;  opt.PhaseMatching = 'on';
   bodeplot(sys_np,sys_p,w, opt);
   ```

More About

Tips

You can change the properties of your plot, for example the units. For information on the ways to change properties of your plots, see “Ways to Customize Plots”.

See Also

`bodeoptions` | `getoptions` | `setoptions` | `bode`

c2d

Convert model from continuous to discrete time

Syntax

```
sysd = c2d(sys,Ts)
sysd = c2d(sys,Ts,method)
sysd = c2d(sys,Ts,opts)
[sysd,G] = c2d(sys,Ts,method)
[sysd,G] = c2d(sys,Ts,opts)
```

Description

`sysd = c2d(sys,Ts)` discretizes the continuous-time dynamic system model sys using zero-order hold on the inputs and a sample time of Ts seconds.

`sysd = c2d(sys,Ts,method)` discretizes sys using the specified discretization method method.

`sysd = c2d(sys,Ts,opts)` discretizes sys using the option set opts, specified using the `c2dOptions` command.

`[sysd,G] = c2d(sys,Ts,method)` returns a matrix, `G` that maps the continuous initial conditions x_0 and u_0 of the state-space model sys to the discrete-time initial state vector x [0]. method is optional. To specify additional discretization options, use `[sysd, G] = c2d(sys,Ts,opts)`.

Input Arguments

`sys`

Continuous-time dynamic system model (except frequency response data models). sys can represent a SISO or MIMO system, except that the `'matched'` discretization method supports SISO systems only.

sys can have input/output or internal time delays; however, the `'matched'` and `'impulse'` methods do not support state-space models with internal time delays.

The following identified linear systems cannot be discretized directly:

- `idgrey` models with `FcnType` is `'c'`. Convert to `idss` model first.
- `idproc` models. Convert to `idtf` or `idpoly` model first.

For the syntax `[sysd,G] = c2d(sys,Ts,opts)`, sys must be a state-space model.

Ts

Sample time.

method

String specifying a discretization method:

- `'zoh'` — Zero-order hold (default). Assumes the control inputs are piecewise constant over the sample time `Ts`.
- `'foh'` — Triangle approximation (modified first-order hold). Assumes the control inputs are piecewise linear over the sample time `Ts`.
- `'impulse'` — Impulse invariant discretization.
- `'tustin'` — Bilinear (Tustin) method.
- `'matched'` — Zero-pole matching method.

For more information about discretization methods, see "Continuous-Discrete Conversion Methods".

opts

Discretization options. Create opts using `c2dOptions`.

Output Arguments

sysd

Discrete-time model of the same type as the input system sys.

When sys is an identified (IDLTI) model, `sysd`:

- Includes both measured and noise components of `sys`. The innovations variance λ of the continuous-time identified model `sys`, stored in its `NoiseVariance`property, is interpreted as the intensity of the spectral density of the noise spectrum. The noise variance in `sysd` is thus λ/Ts.
- Does not include the estimated parameter covariance of `sys`. If you want to translate the covariance while discretizing the model, use `translatecov`.

G

Matrix relating continuous-time initial conditions x_0 and u_0 of the state-space model sys to the discrete-time initial state vector x [0], as follows:

$$x[0] = G \cdot \begin{bmatrix} x_0 \\ u_0 \end{bmatrix}$$

For state-space models with time delays, `c2d` pads the matrix G with zeroes to account for additional states introduced by discretizing those delays. See “Continuous-Discrete Conversion Methods” for a discussion of modeling time delays in discretized systems.

Examples

Discretize a Transfer Function

Discretize the following continuous-time transfer function:

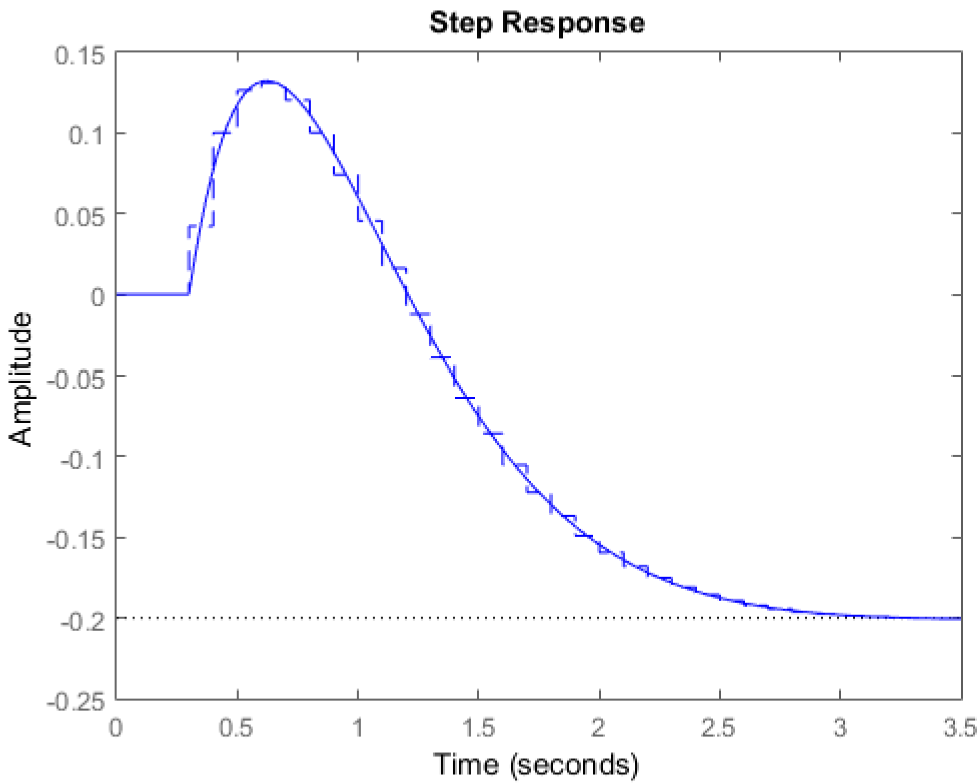
$$H(s) = e^{-0.3s} \frac{s-1}{s^2+4s+5}.$$

This system has an input delay of 0.3 s. Discretize the system using the triangle (first-order-hold) approximation with sample time `Ts` = 0.1 s.

```
H = tf([1 -1],[1 4 5],'InputDelay', 0.3);
Hd = c2d(H,0.1,'foh');
```

Compare the step responses of the continuous-time and discretized systems.

```
step(H,'-',Hd,'--')
```



Discretize Model with Fractional Delay Asborbed into Coefficients

Discretize the following delayed transfer function using zero-order hold on the input, and a 10-Hz sampling rate.

$$H(s) = e^{-0.25s} \frac{10}{s^2 + 3s + 10}.$$

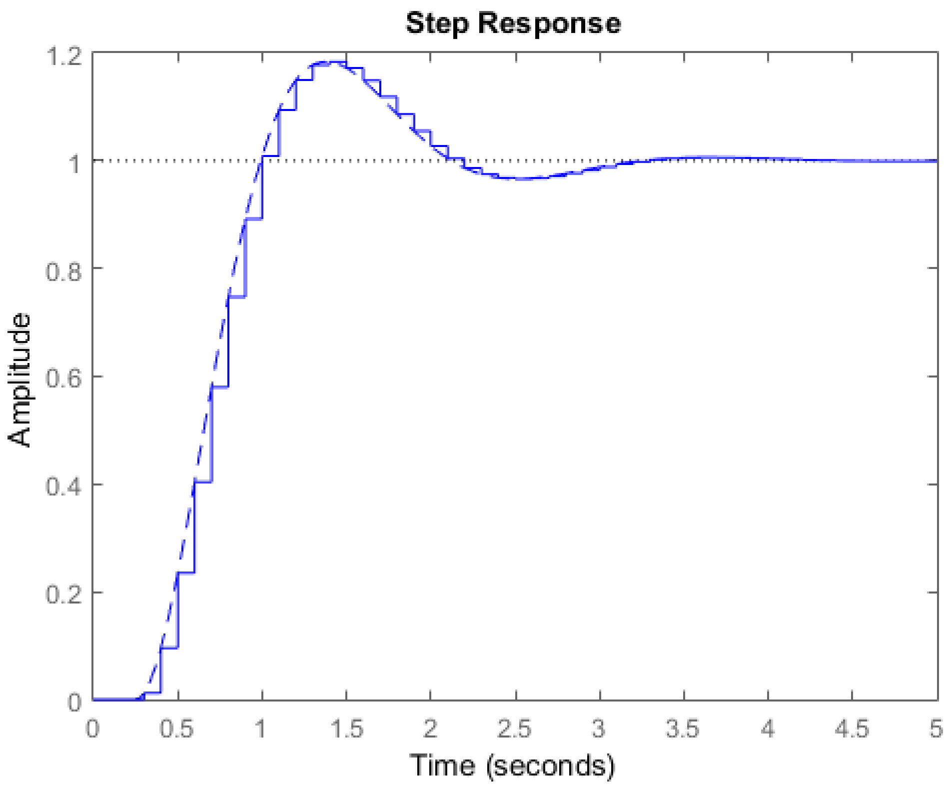
```
h = tf(10,[1 3 10],'iodelay',0.25);
hd = c2d(h, 0.1)
```

```
hd =

            0.01187 z^2 + 0.06408 z + 0.009721
  z^(-3) * ----------------------------------
                  z^2 - 1.655 z + 0.7408

Sample time: 0.1 seconds
Discrete-time transfer function.
```

In this example, the discretized model `hd` has a delay of three sampling periods. The discretization algorithm absorbs the residual half-period delay into the coefficients of `hd`.

Compare the step responses of the continuous-time and discretized models.

```
step(h,'--',hd,'-')
```



Discretize Model With Approximated Fractional Delay

Discretize a state-space model with time delay, using a Thiran filter to model fractional delays:

```
sys = ss(tf([1, 2], [1, 4, 2]));  %  create a state-space model
sys.InputDelay = 2.7              %  add input delay
```

This command creates a continuous-time state-space model with two states, as the output shows:

```
a =
       x1   x2
   x1  -4   -2
```

```
   x2   1   0

b =
       u1
   x1   2
   x2   0

c =
        x1   x2
   y1  0.5    1

d =
       u1
   y1   0

Input delays (listed by channel): 2.7

Continuous-time model.
```

Use `c2dOptions` to create a set of discretization options, and discretize the model. This example uses the Tustin discretization method.

```
opt = c2dOptions('Method', 'tustin', 'FractDelayApproxOrder', 3);
sysd1 = c2d(sys, 1, opt)     % 1s sample time
```

These commands yield the result

```
a =
             x1         x2         x3         x4         x5
   x1   -0.4286    -0.5714   -0.00265    0.06954      2.286
   x2    0.2857     0.7143  -0.001325    0.03477      1.143
   x3         0          0    -0.2432     0.1449    -0.1153
   x4         0          0       0.25          0          0
   x5         0          0          0      0.125          0

b =
             u1
   x1  0.002058
   x2  0.001029
   x3         8
   x4         0
   x5         0

c =
             x1         x2         x3         x4         x5
   y1    0.2857     0.7143  -0.001325    0.03477      1.143
```

```
d =
             u1
   y1  0.001029

Sample time: 1
Discrete-time model.
```

The discretized model now contains three additional states `x3`, `x4`, and `x5` corresponding to a third-order Thiran filter. Since the time delay divided by the sample time is 2.7, the third-order Thiran filter (`FractDelayApproxOrder` = 3) can approximate the entire time delay.

Discretized Identified Model

Discretize an identified, continuous-time transfer function and compare its performance against a directly estimated discrete-time model

Estimate a continuous-time transfer function and discretize it.

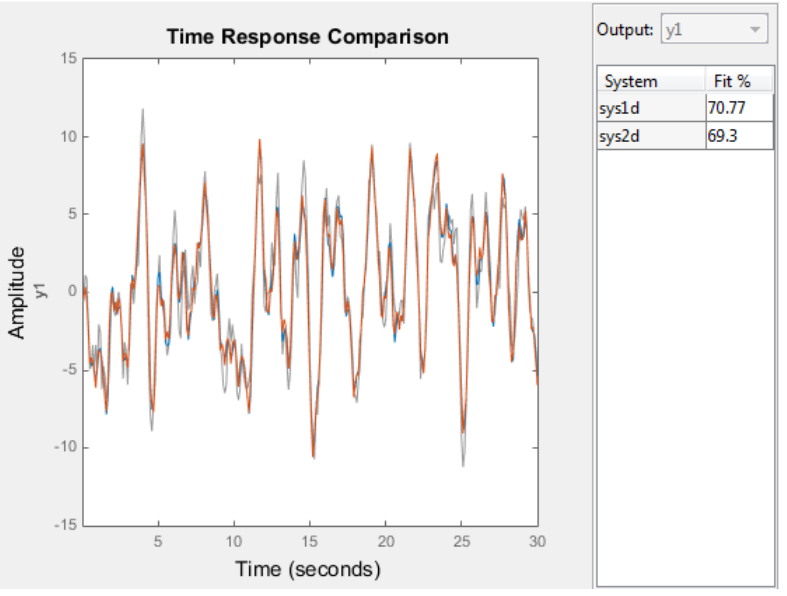
```
load iddata1
sys1c = tfest(z1,2);
sys1d = c2d(sys1c,0.1,'zoh');
```

Estimate a second order discrete-time transfer function.

```
sys2d = tfest(z1,2,'Ts',0.1);
```

Compare the two models.

```
compare(z1,sys1d,sys2d)
```



The two systems are virtually identical.

Build Predictor Model

Discretize an identified state-space model to build a one-step ahead predictor of its response.

```
load iddata2
sysc = ssest(z2,4);
sysd = c2d(sysc,0.1,'zoh');
[A,B,C,D,K] = idssdata(sysd);
Predictor = ss(A-K*C,[K B-K*D],C,[0 D],0.1);
```

The `Predictor` is a two input model which uses the measured output and input signals `([z1.y z1.u])` to compute the `1-step` predicted response of `sysc`.

More About

Tips

- Use the syntax `sysd = c2d(sys,Ts,method)` to discretize `sys` using the default options for `method`. To specify additional discretization options, use the syntax `sysd = c2d(sys,Ts,opts)`.
- To specify the `tustin` method with frequency prewarping (formerly known as the `'prewarp'` method), use the `PrewarpFrequency` option of `c2dOptions`.

Algorithms

For information about the algorithms for each `c2d` conversion method, see “Continuous-Discrete Conversion Methods”.

- “Dynamic System Models”
- “Discretize a Compensator”
- “Continuous-Discrete Conversion Methods”

See Also

`d2c` | `d2d` | `c2dOptions` | `thiran` | `translatecov`

c2dOptions

Create option set for continuous- to discrete-time conversions

Syntax

```
opts = c2dOptions
opts = c2dOptions('OptionName', OptionValue)
```

Description

opts = `c2dOptions` returns the default options for `c2d`.

opts = `c2dOptions('`*OptionName*`',` *OptionValue*`)` accepts one or more comma-separated name/value pairs that specify options for the `c2d` command. Specify *OptionName* inside single quotes.

Input Arguments

Name-Value Pair Arguments

'Method'

Discretization method, specified as one of the following values:

`'zoh'`	Zero-order hold, where `c2d` assumes the control inputs are piecewise constant over the sample time `Ts`.
`'foh'`	Triangle approximation (modified first-order hold), where `c2d` assumes the control inputs are piecewise linear over the sample time `Ts`. (See [1], p. 228.)
`'impulse'`	Impulse-invariant discretization.
`'tustin'`	Bilinear (Tustin) approximation. By default, `c2d` discretizes with no prewarp and rounds any fractional time delays to the nearest multiple of the sample time. To include prewarp, use the `PrewarpFrequency` option. To approximate fractional time delays, use the`FractDelayApproxOrder` option.

'matched'	Zero-pole matching method. (See [1], p. 224.) By default, c2d rounds any fractional time delays to the nearest multiple of the sample time. To approximate fractional time delays, use the FractDelayApproxOrder option.

Default: 'zoh'

'PrewarpFrequency'

Prewarp frequency for 'tustin' method, specified in rad/TimeUnit, where TimeUnit is the time units, specified in the TimeUnit property, of the discretized system. Takes positive scalar values. A value of 0 corresponds to the standard 'tustin' method without prewarp.

Default: 0

'FractDelayApproxOrder'

Maximum order of the Thiran filter used to approximate fractional delays in the 'tustin' and 'matched' methods. Takes integer values. A value of 0 means that c2d rounds fractional delays to the nearest integer multiple of the sample time.

Default: 0

Examples

Discretize two models using identical discretization options.

```
% generate two arbitrary continuous-time state-space models
sys1 = rss(3, 2, 2);
sys2 = rss(4, 4, 1);
```

Use c2dOptions to create a set of discretization options.

```
opt = c2dOptions('Method', 'tustin', 'PrewarpFrequency', 3.4);
```

Then, discretize both models using the option set.

```
dsys1 = c2d(sys1, 0.1, opt);  % 0.1s sample time
dsys2 = c2d(sys2, 0.2, opt);  % 0.2s sample time
```

The c2dOptions option set does not include the sample time Ts. You can use the same discretization options to discretize systems using a different sample time.

References

[1] Franklin, G.F., Powell, D.J., and Workman, M.L., *Digital Control of Dynamic Systems* (3rd Edition), Prentice Hall, 1997.

See Also

`c2d`

canon

State-space canonical realization

Syntax

```
csys = canon(sys,type)
[csys,T]= canon(sys,type)
csys = canon(sys,'modal',condt)
```

Description

`csys = canon(sys,type)` transforms the linear model sys into a canonical state-space model csys. The argument type specifies whether csys is in modal or companion form.

`[csys,T]= canon(sys,type)` also returns the state-coordinate transformation T that relates the states of the state-space model sys to the states of csys.

`csys = canon(sys,'modal',condt)` specifies an upper bound condt on the condition number of the block-diagonalizing transformation.

Input Arguments

sys

Any linear dynamic system model, except for `frd` models.

type

String specifying the type of canonical form of csys. type can take one of the two following values:

- `'modal'` — convert sys to modal form.
- `'companion'` — convert sys to companion form.

condt

Positive scalar value specifying an upper bound on the condition number of the block-diagonalizing transformation that converts sys to csys. This argument is available only when type is `'modal'`.

Increase condt to reduce the size of the eigenvalue clusters in the A matrix of csys. Setting `condt = Inf` diagonalizes A.

Default: `1e8`

Output Arguments

csys

State-space (`ss`) model. csys is a state-space realization of sys in the canonical form specified by type.

T

Matrix specifying the transformation between the state vector x of the state-space model sys and the state vector x_c of csys:

$x_c = Tx$

.

This argument is available only when sys is state-space model.

Examples

This example uses `canon` to convert a system having doubled poles and clusters of close poles to modal canonical form.

Consider the system G having the following transfer function:

$$G(s) = 100\frac{(s-1)(s+1)}{s(s+10)(s+10.0001)(s-(1+i))^2(s-(1-i))^2}.$$

To create a linear model of this system and convert it to modal canonical form, enter:

```
G = zpk([1 -1],[0 -10 -10.0001 1+1i 1-1i 1+1i 1-1i],100);
Gc = canon(G,'modal');
```

The system G has a pair of nearby poles at $s = -10$ and $s = -10.0001$. G also has two complex poles of multiplicity 2 at $s = 1 + i$ and $s = 1 - i$. As a result, the modal form, has a block of size 2 for the two poles near $s = -10$, and a block of size 4 for the complex eigenvalues. To see this, enter the following command:

```
Gc.A

ans =

         0         0         0         0         0         0         0
         0    1.0000    1.0000         0         0         0         0
         0   -1.0000    1.0000    2.0548         0         0         0
         0         0         0    1.0000    1.0000         0         0
         0         0         0   -1.0000    1.0000         0         0
         0         0         0         0         0  -10.0000    8.0573
         0         0         0         0         0         0  -10.0001
```

To separate the two poles near $s = -10$, you can increase the value of condt. For example:

```
Gc2 = canon(G,'modal',1e10);
Gc2.A

ans =

         0         0         0         0         0         0         0
         0    1.0000    1.0000         0         0         0         0
         0   -1.0000    1.0000    2.0548         0         0         0
         0         0         0    1.0000    1.0000         0         0
         0         0         0   -1.0000    1.0000         0         0
         0         0         0         0         0  -10.0000         0
         0         0         0         0         0         0  -10.0001
```

The A matrix of `Gc2` includes separate diagonal elements for the poles near $s = -10$. The cost of increasing the maximum condition number of A is that the B matrix includes some large values.

```
format shortE
Gc2.B

ans =

  3.2000e-001
 -6.5691e-003
  5.4046e-002
```

```
-1.9502e-001
 1.0637e+000
 3.2533e+005
 3.2533e+005
```

This example estimates a state-space model that is freely parameterized and convert to companion form after estimation.

```
load icEngine.mat
z = iddata(y,u,0.04);
FreeModel = n4sid(z,4,'InputDelay',2);
CanonicalModel = canon(FreeModel, 'companion')
```

Obtain the covariance of the resulting form by running a zero-iteration update to model parameters.

```
opt = ssestOptions; opt.SearchOption.MaxIter = 0;
CanonicalModel  = ssest(z, CanonicalModel, opt)
```

Compare frequency response confidence bounds of `FreeModel` to `CanonicalModel`.

```
h = bodeplot(FreeModel, CanonicalModel)
```

the bounds are identical.

More About

Modal Form

In modal form, A is a block-diagonal matrix. The block size is typically 1-by-1 for real eigenvalues and 2-by-2 for complex eigenvalues. However, if there are repeated eigenvalues or clusters of nearby eigenvalues, the block size can be larger.

For example, for a system with eigenvalues $(\lambda_1, \sigma \pm j\omega, \lambda_2)$, the modal A matrix is of the form

$$\begin{bmatrix} \lambda_1 & 0 & 0 & 0 \\ 0 & \sigma & \omega & 0 \\ 0 & -\omega & \sigma & 0 \\ 0 & 0 & 0 & \lambda_2 \end{bmatrix}$$

Companion Form

In the companion realization, the characteristic polynomial of the system appears explicitly in the rightmost column of the A matrix. For a system with characteristic polynomial

$$p(s) = s^n + \alpha_1 s^{n-1} + \ldots + \alpha_{n-1} s + \alpha_n$$

the corresponding companion A matrix is

$$A = \begin{bmatrix} 0 & 0 & .. & .. & 0 & -\alpha_n \\ 1 & 0 & 0 & .. & 0 & -\alpha_n - 1 \\ 0 & 1 & 0 & . & : & : \\ : & 0 & . & . & : & : \\ 0 & . & . & 1 & 0 & -\alpha_2 \\ 0 & .. & .. & 0 & 1 & -\alpha_1 \end{bmatrix}$$

The companion transformation requires that the system be controllable from the first input. The companion form is poorly conditioned for most state-space computations; avoid using it when possible.

Algorithms

The `canon` command uses the `bdschur` command to convert sys into modal form and to compute the transformation T. If sys is not a state-space model, the algorithm first converts it to state space using `ss`.

The reduction to companion form uses a state similarity transformation based on the controllability matrix [1].

References

[1] Kailath, T. *Linear Systems*, Prentice-Hall, 1980.

See Also

`ctrb` | `ctrbf` | `ss2ss`

care

Continuous-time algebraic Riccati equation solution

Syntax

```
[X,L,G] = care(A,B,Q)
[X,L,G] = care(A,B,Q,R,S,E)
[X,L,G,report] = care(A,B,Q,...)
[X1,X2,D,L] = care(A,B,Q,...,'factor')
```

Description

`[X,L,G] = care(A,B,Q)` computes the unique solution `X` of the continuous-time algebraic Riccati equation

$$A^T X + XA - XBB^T X + Q = 0$$

The `care` function also returns the gain matrix, $G = R^{-1} B^T XE$.

`[X,L,G] = care(A,B,Q,R,S,E)` solves the more general Riccati equation

$$A^T XE + E^T XA - (E^T XB + S)R^{-1}(B^T XE + S^T) + Q = 0$$

When omitted, `R`, `S`, and `E` are set to the default values `R=I`, `S=0`, and `E=I`. Along with the solution `X`, `care` returns the gain matrix $G = R^{-1}(B^T XE + S^T)$ and a vector `L` of closed-loop eigenvalues, where

```
L=eig(A-B*G,E)
```

`[X,L,G,report] = care(A,B,Q,...)` returns a diagnosis `report` with:

- `-1` when the associated Hamiltonian pencil has eigenvalues on or very near the imaginary axis (failure)
- `-2` when there is no finite stabilizing solution `X`

- The Frobenius norm of the relative residual if X exists and is finite.

This syntax does not issue any error message when X fails to exist.

`[X1,X2,D,L] = care(A,B,Q,...,'factor')` returns two matrices `X1`, `X2` and a diagonal scaling matrix `D` such that `X = D*(X2/X1)*D`.

The vector L contains the closed-loop eigenvalues. All outputs are empty when the associated Hamiltonian matrix has eigenvalues on the imaginary axis.

Examples

Example 1

Solve Algebraic Riccati Equation

Given

$$A = \begin{bmatrix} -3 & 2 \\ 1 & 1 \end{bmatrix} \qquad B = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \qquad C = \begin{bmatrix} 1 & -1 \end{bmatrix} \qquad R = 3$$

you can solve the Riccati equation

$$A^T X + XA - XBR^{-1}B^T X + C^T C = 0$$

by

```
a = [-3 2;1 1]
b = [0 ; 1]
c = [1 -1]
r = 3
[x,l,g] = care(a,b,c'*c,r)
```

This yields the solution

```
x

x =
    0.5895    1.8216
```

```
    1.8216    8.8188
```

You can verify that this solution is indeed stabilizing by comparing the eigenvalues of `a` and `a-b*g`.

```
[eig(a)   eig(a-b*g)]

ans =
   -3.4495   -3.5026
    1.4495   -1.4370
```

Finally, note that the variable `l` contains the closed-loop eigenvalues `eig(a-b*g)`.

```
l

l =
   -3.5026
   -1.4370
```

Example 2

Solve H-infinity (H_∞)-like Riccati Equation

To solve the H_∞-like Riccati equation

$$A^T X + XA + X(\gamma^{-2} B_1 B_1^T - B_2 B_2^T)X + C^T C = 0$$

rewrite it in the `care` format as

$$A^T X + XA - X\underbrace{[B_1, B_2]}_{B}\underbrace{\begin{bmatrix} -\gamma^2 I & 0 \\ 0 & I \end{bmatrix}^{-1}}_{R}\begin{bmatrix} B_1^T \\ B_2^T \end{bmatrix} X + C^T C = 0$$

You can now compute the stabilizing solution X by

```
B = [B1 , B2]
m1 = size(B1,2)
m2 = size(B2,2)
R = [-g^2*eye(m1) zeros(m1,m2) ; zeros(m2,m1) eye(m2)]
```

```
X = care(A,B,C'*C,R)
```

Limitations

The (A,B) pair must be stabilizable (that is, all unstable modes are controllable). In addition, the associated Hamiltonian matrix or pencil must have no eigenvalue on the imaginary axis. Sufficient conditions for this to hold are (Q,A) detectable when $S=0$ and $R>0$, or

$$\begin{bmatrix} Q & S \\ S^T & R \end{bmatrix} > 0$$

More About

Algorithms

`care` implements the algorithms described in [1]. It works with the Hamiltonian matrix when R is well-conditioned and $E=I$; otherwise it uses the extended Hamiltonian pencil and QZ algorithm.

References

[1] Arnold, W.F., III and A.J. Laub, "Generalized Eigenproblem Algorithms and Software for Algebraic Riccati Equations," *Proc. IEEE*, 72 (1984), pp. 1746-1754

See Also

`dare` | `lyap`

chgFreqUnit

Change frequency units of frequency-response data model

Syntax

```
sys_new = chgFreqUnit(sys,newfrequnits)
```

Description

`sys_new = chgFreqUnit(sys,newfrequnits)` changes units of the frequency points in sys to newfrequnits. Both `Frequency` and `FrequencyUnit` properties of sys adjust so that the frequency responses of sys and sys_new match.

Input Arguments

`sys`

Frequency-response data (`frd`, `idfrd`, or `genfrd`) model

`newfrequnits`

New units of frequency points, specified as one of the following strings:

- `'rad/TimeUnit'`
- `'cycles/TimeUnit'`
- `'rad/s'`
- `'Hz'`
- `'kHz'`
- `'MHz'`
- `'GHz'`
- `'rpm'`

rad/TimeUnit and cycles/TimeUnit express frequency units relative to the system time units specified in the TimeUnit property.

Default: 'rad/TimeUnit'

Output Arguments

sys_new

Frequency-response data model of the same type as sys with new units of frequency points. The frequency response of sys_new is same as sys.

Examples

This example shows how to change units of the frequency points in a frequency-response data model.

1 Create a frequency-response data model.

```
load AnalyzerData;
sys = frd(resp,freq);
```

The data file AnalyzerData has column vectors freq and resp. These vectors contain 256 test frequencies and corresponding complex-valued frequency response points, respectively. The default frequency units of sys is rad/TimeUnit, where TimeUnit is the system time units.

2 Change the frequency units.

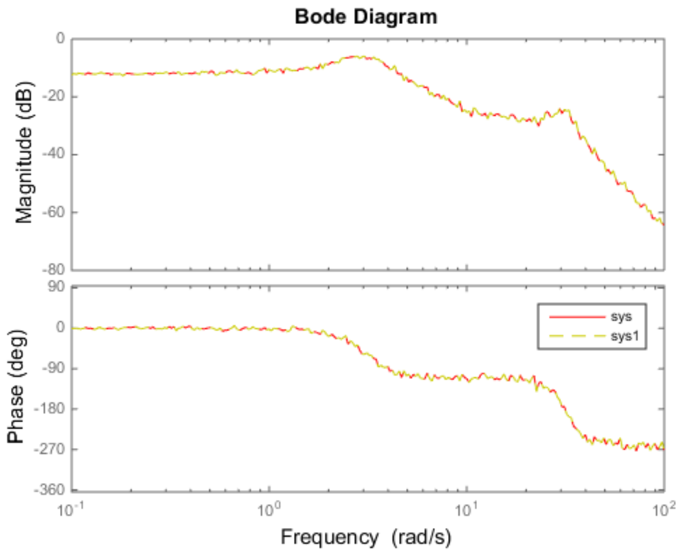
```
sys1 = chgFreqUnit(sys,'rpm');
```

The FrequencyUnit property of sys1 is rpm.

3 Compare the Bode responses of sys and sys1.

```
bodeplot(sys,'r',sys1,'y--');
legend('sys','sys1')
```

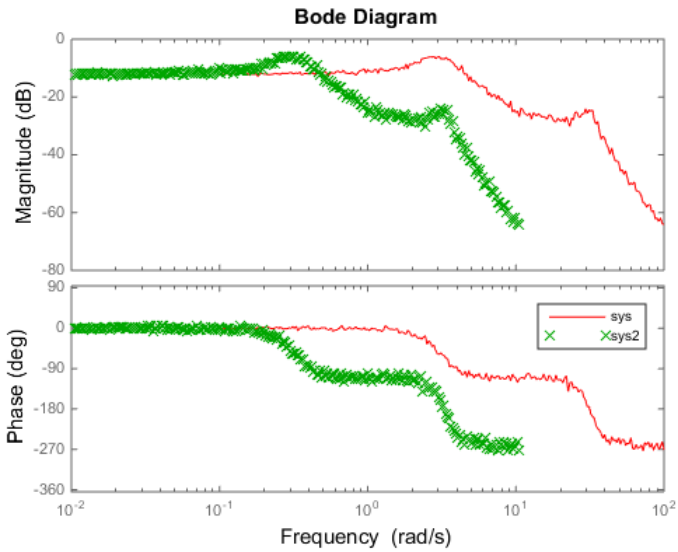
The magnitude and phase of sys and sys1 match.



4 (Optional) Change the `FrequencyUnit` property of `sys` to compare the Bode response with the original system.

```
sys2=sys;
sys2.FrequencyUnit = 'rpm';
bodeplot(sys,'r',sys2,'gx');
legend('sys','sys2');
```

Changing the `FrequencyUnit` property changes the original system. Therefore, the Bode responses of `sys` and `sys2` do not match. For example, the original corner frequency at 2 rad/s changes to 2 rpm (or 0.2 rad/s).



More About

Tips

- Use `chgFreqUnit` to change the units of frequency points without modifying system behavior.

See Also

`chgTimeUnit` | `frd`

chgTimeUnit

Change time units of dynamic system

Syntax

```
sys_new = chgTimeUnit(sys,newtimeunits)
```

Description

`sys_new = chgTimeUnit(sys,newtimeunits)` changes the time units of sys to newtimeunits. The time- and frequency-domain characteristics of sys and sys_new match.

Input Arguments

`sys`

Dynamic system model

`newtimeunits`

New time units, specified as one of the following strings:

- `'nanoseconds'`
- `'microseconds'`
- `'milliseconds'`
- `'seconds'`
- `'minutes'`
- `'hours'`
- `'days'`
- `'weeks'`

- 'months'
- 'years'

Default: 'seconds'

Output Arguments

sys_new

Dynamic system model of the same type as sys with new time units. The time response of sys_new is same as sys.

If sys is an identified linear model, both the model parameters as and their minimum and maximum bounds are scaled to the new time units.

Examples

Change Time Units of Dynamic System Model

Create a transfer function model.

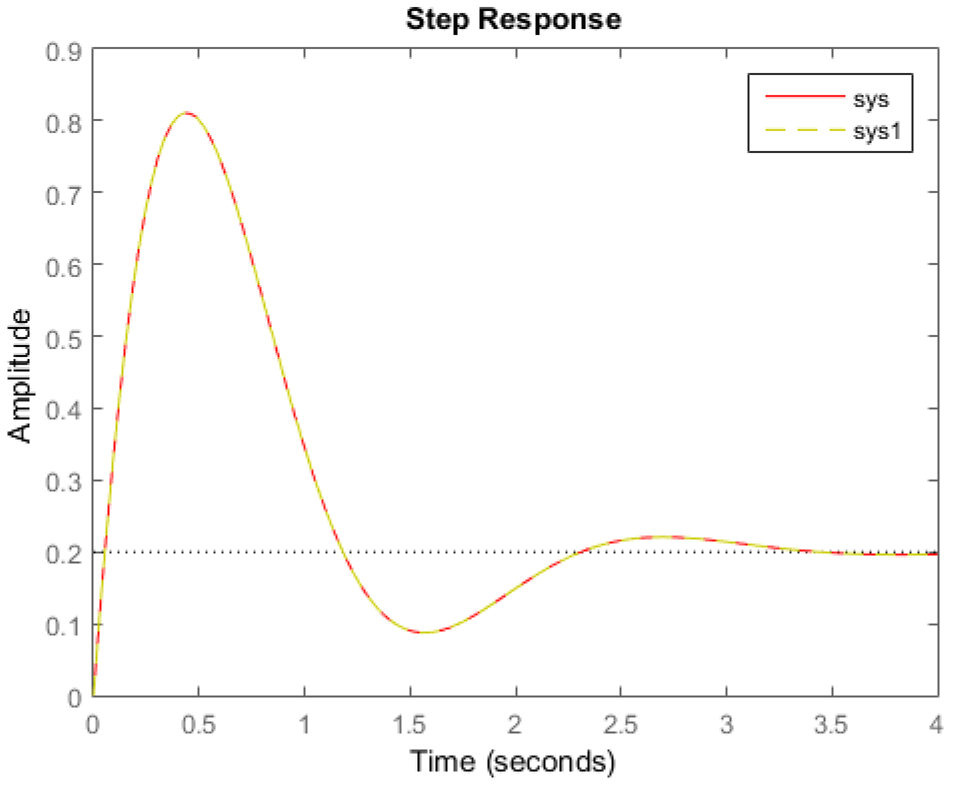
```
num = [4 2];
den = [1 3 10];
sys = tf(num,den);
```

By default, the time unit of `sys` is `'seconds'`. Create a new model with the time units changed to minutes.

```
sys1 = chgTimeUnit(sys,'minutes');
```

This command sets the `TimeUnit` property of `sys1` to `'minutes'`, without changing the dynamics. To confirm that the dynamics are unchanged, compare the step responses of `sys` and `sys1`.

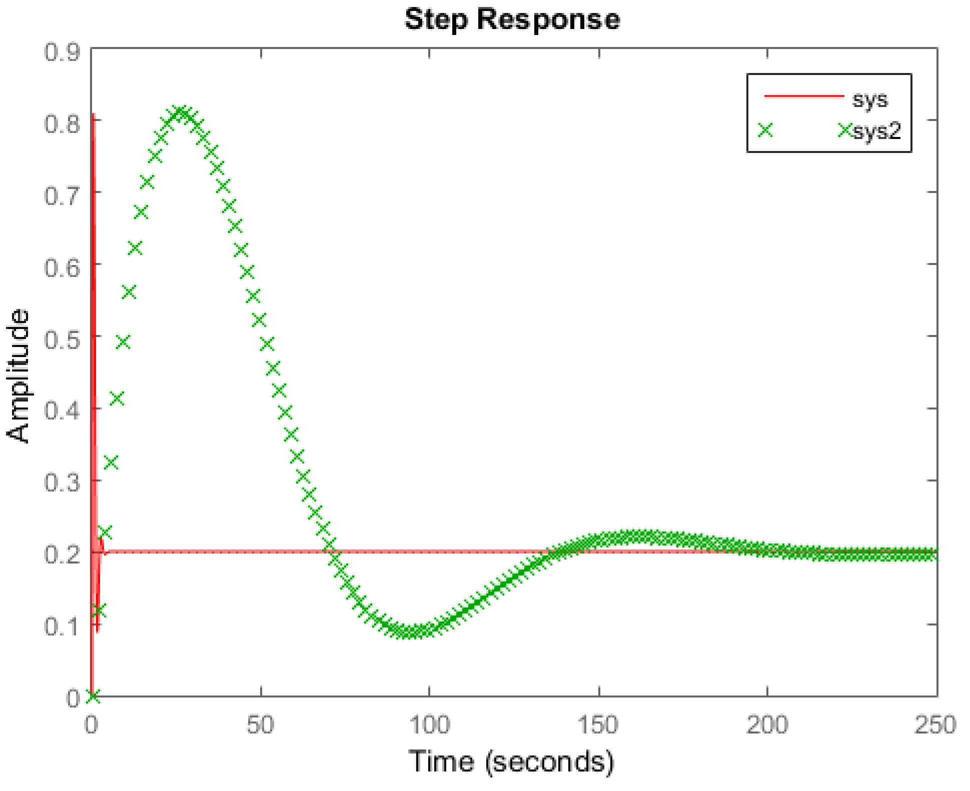
```
stepplot(sys,'r',sys1,'y--');
legend('sys','sys1');
```



The step responses are the same.

If you change the `TimeUnit` property of the system instead of using `chgTimeUnit`, the dynamics of the system do change. To see this, change the `TimeUnit` property of a copy of `sys` and compare the step response with the original system.

```
sys2 = sys;
sys2.TimeUnit = 'minutes';
stepplot(sys,'r',sys2,'gx');
legend('sys','sys2');
```



The step responses of `sys` and `sys2` do not match. For example, the original rise time of 0.04 seconds changes to 0.04 minutes.

- “Specify Model Time Units”

More About

Tips

- Use `chgTimeUnit` to change the time units without modifying system behavior.

See Also

`chgFreqUnit` | `tf` | `zpk` | `ss` | `frd` | `pid`

conj

Form model with complex conjugate coefficients

Syntax

```
sysc = conj(sys)
```

Description

`sysc = conj(sys)` constructs a complex conjugate model `sysc` by applying complex conjugation to all coefficients of the LTI model `sys`. This function accepts LTI models in transfer function (TF), zero/pole/gain (ZPK), and state space (SS) formats.

Examples

If `sys` is the transfer function

```
(2+i)/(s+i)
```

then `conj(sys)` produces the transfer function

```
(2-i)/(s-i)
```

This operation is useful for manipulating partial fraction expansions.

See Also

`append` | `ss` | `tf` | `zpk`

connect

Block diagram interconnections of dynamic systems

Syntax

```
sysc = connect(sys1,...,sysN,inputs,outputs)
sysc = connect(sys1,...,sysN,inputs,outputs,APs)
sysc = connect(blksys,connections,inputs,outputs)
sysc = connect( ___ ,opts)
```

Description

`sysc = connect(sys1,...,sysN,inputs,outputs)` connects the block diagram elements sys1,...,sysN based on signal names. The block diagram elements sys1,...,sysN are dynamic system models. These models can include summing junctions that you create using `sumblk`. The `connect` command interconnects the block diagram elements by matching the input and output signals that you specify in the `InputName` and `OutputName` properties of sys1,...,sysN. The aggregate model sysc is a dynamic system model having inputs and outputs specified by inputs and outputs respectively.

`sysc = connect(sys1,...,sysN,inputs,outputs,APs)` inserts an `AnalysisPoint` at every signal location specified in APs. Use analysis points to mark locations of interest which are internal signals in the aggregate model. For instance, a location at which you want to extract a loop transfer function or measure the stability margins is a location of interest.

`sysc = connect(blksys,connections,inputs,outputs)` uses index-based interconnection to build sysc out of an aggregate, unconnected model blksys. The matrix connections specifies how the outputs and inputs of blksys interconnect. For index-based interconnections, inputs and outputs are index vectors that specify which inputs and outputs of blksys are the external inputs and outputs of sysc. This syntax can be convenient when you do not want to assign names to all inputs and outputs of all models to connect. However, in general, it is easier to keep track of named signals.

`sysc = connect( ___ ,opts)` builds the interconnected model using additional options. You can use opts with the input arguments of any of the previous syntaxes.

Input Arguments

sys1,...,sysN

Dynamic system models that correspond to the elements of your block diagram. For example, the elements of your block diagram can include one or more `tf` or `ss` models that represent plant dynamics. Block diagram elements can also include a `pid` or `ltiblock.pid` model representing a controller. You can also include one or more summing junction that you create using `sumblk`. Provide multiple arguments sys1,...,sysN to represent all of the block diagram elements and summing junctions.

inputs

For name-based interconnection, a string or string vector that specifies the inputs of the aggregate model sysc. The strings in inputs must correspond to entries in the `InputName` or `OutputName` property of one or more of the block diagram elements sys1,...,sysN.

outputs

For name-based interconnection, a string or string vector that specifies the outputs of the aggregate model sysc. The strings in outputs must correspond to entries in the `OutputName` property of one or more of the block diagram elements sys1,...,sysN.

APs

A string or string vector that specifies locations (internal signals) of interest in the aggregate model. The resulting model contains an analysis point at each such location. (See `AnalysisPoint`). Each string in APs must correspond to an entry in the `InputName` or `OutputName` property of one or more of the block diagram elements sys1,...,sysN.

blksys

Unconnected aggregate model. To obtain blksys, use `append` to join dynamic system models of the elements of your block diagram. For example, if your block diagram contains dynamic system models `C`, `G`, and `S`, create blksys with the following command:

```
blksys = append(C,G,S)
```

connections

Matrix that specifies the connections and summing junctions of the block diagram. Each row of connections specifies one connection or summing junction in terms of the input vector `u` and output vector `y` of the unconnected aggregate model blksys. For example, the row:

```
[3 2 0 0]
```

specifies that `y(2)` connects into `u(3)`. The row

```
[7 2 -15 6]
```

indicates that `y(2)-y(15)+y(6)` feeds into `u(7)`.

If you do not specify any connection for a particular input or output, `connect` omits that input or output from the aggregate model.

`opts`

Additional options for interconnection, specified as an options set that you create with `connectOptions`.

Output Arguments

`sysc`

Interconnected system, returned as either a state-space model or frequency-response model. The type of model returned depends on the input models. For example:

- Interconnecting numeric LTI models (other than `frd` models) returns an `ss` model.
- Interconnecting a numeric LTI model with a Control Design Block returns a generalized LTI model. For instance, interconnecting a `tf` model with an `ltiblock.pid` Control Design Block returns a `genss`.
- Interconnecting any model with frequency-response data model returns a frequency response data model.

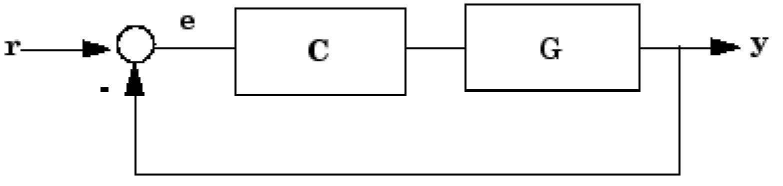
By default, `connect` automatically discards states that do not contribute to the I/O transfer function from the specified inputs to the specified outputs of the interconnected model. To retain the unconnected states, set the `Simplify` option of `connectOptions` to `false`. For example:

```
opt = connectOptions('Simplify',false);
sysc = connect(sys1,sys2,sys3,'r','y',opt);
```

Examples

SISO Feedback Loop

Create an aggregate model of the following block diagram from `r` to `y`.



Create `C` and `G`, and name the inputs and outputs.

```
C = pid(2,1);
C.u = 'e';
C.y = 'u';
G = zpk([],[-1,-1],1);
G.u = 'u';
G.y = 'y';
```

The notations `C.u` and `C.y` are shorthand expressions equivalent to `C.InputName` and `C.OutputName`, respectively. For example, entering `C.u = 'e'` is equivalent to entering `C.InputName = 'e'`. The command sets the `InputName` property of `C` to the value `'e'`.

Create the summing junction.

```
Sum = sumblk('e = r - y');
```

Combine `C`, `G`, and the summing junction to create the aggregate model from `r` to `y`.

```
T = connect(G,C,Sum,'r','y');
```

`connect` automatically joins inputs and outputs with matching names.

MIMO Feedback Loop

Create the control system of the previous example where `G` and `C` are both 2-input, 2-output models.

```
C = [pid(2,1),0;0,pid(5,6)];
```

```
C.InputName = 'e';
C.OutputName = 'u';
G = ss(-1,[1,2],[1;-1],0);
G.InputName = 'u';
G.OutputName = 'y';
```

When you specify single names for vector-valued signals, the software automatically performs vector expansion of the signal names. For example, examine the names of the inputs to C.

```
C.InputName
```

```
ans =

    'e(1)'
    'e(2)'
```

Create a 2-input, 2-output summing junction.

```
Sum = sumblk('e = r-y',2);
```

`sumblk` also performs vector expansion of the signal names.

Interconnect the models to obtain the closed-loop system.

```
T = connect(G,C,Sum,'r','y');
```

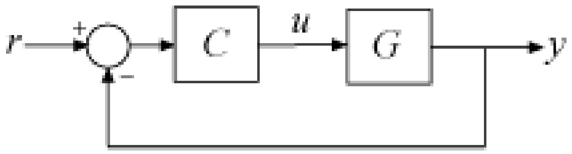
The block diagram elements `G`, `C`, and `Sum` are all 2-input, 2-output models. Therefore, `connect` performs the same vector expansion. `connect` selects all entries of the two-input signals `'r'` and `'y'` as inputs and outputs to `T`, respectively. For example, examine the input names of `T`.

```
T.InputName
```

```
ans =

    'r(1)'
    'r(2)'
```

Feedback Loop With Analysis Point Inserted by `connect`

Create a model of the following block diagram from r to y. Insert an analysis point at an internal location, u.



Create C and G, and name the inputs and outputs.

```
C = pid(2,1);
C.InputName = 'e';
C.OutputName = 'u';
G = zpk([],[-1,-1],1);
G.InputName = 'u';
G.OutputName = 'y';
```

Create the summing junction.

```
Sum = sumblk('e = r - y');
```

Combine C, G, and the summing junction to create the aggregate model, with an analysis point at u.

```
T = connect(G,C,Sum,'r','y','u')
```

```
T =

  Generalized continuous-time state-space model with 1 outputs, 1 inputs, 3 states, and
    AnalysisPoints_: Analysis point, 1 channels, 1 occurrences.

Type "ss(T)" to see the current value, "get(T)" to see all properties, and "T.Blocks" t
```

The resulting T is a genss model. The connect command creates the AnalysisPoint block, AnalysisPoints_, and inserts it into T. To see the name of the analysis point channel in AnalysisPoints_, use getPoints.

```
getPoints(T)
```

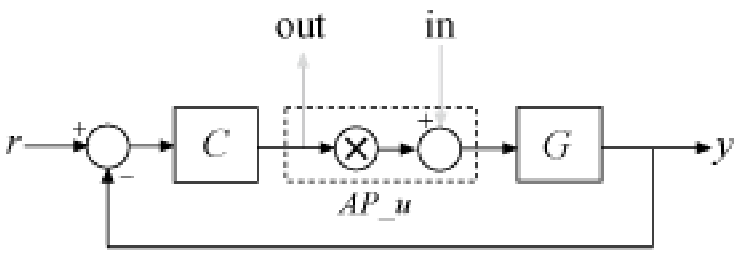
```
ans =
```

```
'u'
```

The analysis point channel is named `'u'`. You can use this analysis point to extract system responses. For example, the following commands extract the open-loop transfer at *u* and the closed-loop response at *y* to a disturbance injected at *u*.

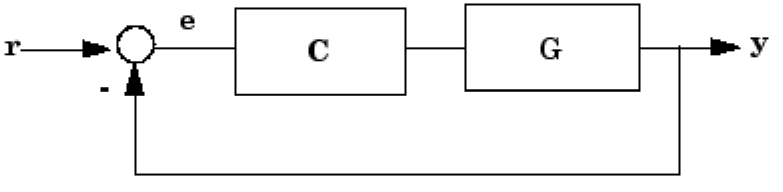
```
L = getLoopTransfer(T,'u',-1);
Tuy = getIOTransfer(T,'u','y');
```

`T` is equivalent to the following block diagram, where *AP_u* designates the `AnalysisPoint` block `AnalysisPoints_` with channel name *u*.



Index-Based Interconnection

Create an aggregate model of the following block diagram from `r` to `y` using index-based interconnection.



Create `C`, `G`, and the unconnected aggregate model `blksys`.

```
C = pid(2,1);
G = zpk([],[-1,-1],1);
blksys = append(C,G);
```

The inputs `u(1),u(2)` of `blksys` correspond to the inputs of `C` and `G`, respectively. The outputs `w(1),w(2)` of `blksys` correspond to the outputs of `C` and `G`, respectively.

Create the matrix `connections`, which specifies which outputs of `blksys` connect to which inputs of `blksys`.

```
connections = [2 1; 1 -2];
```

The first row indicates that `w(1)` connects to `u(2)`; in other words, that the output of `C` connects to the input of `G`. The second row indicates that `-w(2)` connects to `u(1)`; in other words, that the negative of the output of `G` connects to the input of `C`.

Create the connected aggregate model from `r` to `y`.

```
T = connect(blksys,connections,1,2)
```

The last two arguments specify the external inputs and outputs in terms of the indices of `blksys`. The argument `1` specifies that the external input connects to `u(1)`. The last argument, `2`, specifies that the external output connects from `w(2)`.

More About

- "Multi-Loop Control System"
- "MIMO Control System"
- "MIMO Feedback Loop"
- "Mark Analysis Points in Closed-Loop Models"

See Also

| `append` | `sumblk` | `AnalysisPoint` | `feedback` | `parallel` | `series` | `lft` | `connectOptions`

Introduced before R2006a

connectOptions

Options for the `connect` command

Syntax

```
opt = connectOptions
opt = connectOptions(Name,Value)
```

Description

`opt = connectOptions` returns the default options for `connect`.

`opt = connectOptions(Name,Value)` returns an options set with the options specified by one or more Name,Value pair arguments.

Examples

Retain Unconnected States in Model Interconnection

Use `connectOptions` to cause the `connect` command to retain unconnected states in an interconnected model.

Suppose you have dynamic system models `sys1`, `sys2`, and `sys3`. Combine these dynamic system models to build an interconnected model with input `'r'` and output `'y'`. Set the option to retain states in the model that do not contribute to the dynamics in the path from `'r'` or `'y'`.

```
opt = connectOptions('Simplify',false);
sysc = connect(sys1,sys2,sys3,'r','y',opt);
```

Input Arguments

Name-Value Pair Arguments

Specify optional comma-separated pairs of Name,Value arguments. `Name` is the argument name and `Value` is the corresponding value. `Name` must appear inside single quotes (`' '`). You can specify several name and value pair arguments in any order as `Name1,Value1,...,NameN,ValueN`.

Example: `'Simplify',false`

`'Simplify'` — Automatic elimination of unconnected states

`true` (default) | `false`

Automatic elimination of unconnected states, specified as either `true` or `false`.

- `true` — `connect` eliminates all states that do not contribute to the I/O transfer function from the specified inputs to the specified outputs of the interconnected system.
- `false` — `connect` retains unconnected states. This option can be useful, for example, when you want to compute the interconnected system response from known initial state values of the components.

Data Types: `logical`

Output Arguments

`opt` — Options for `connect`

`connectOptions` options set

Options for connect, returned as a `connectOptions` options set. Use opt as the last argument to `connect` when interconnecting models.

See Also

`connect`

controlSystemDesigner

Interactively design and tune SISO feedback loops

Syntax

```
controlSystemDesigner
controlSystemDesigner(plant)
controlSystemDesigner(plant,comp)
controlSystemDesigner(plant,comp,sensor,prefilt)
controlSystemDesigner(views)
controlSystemDesigner(views,plant,comp)
controlSystemDesigner(initdata)
controlSystemDesigner(sessiondata)
```

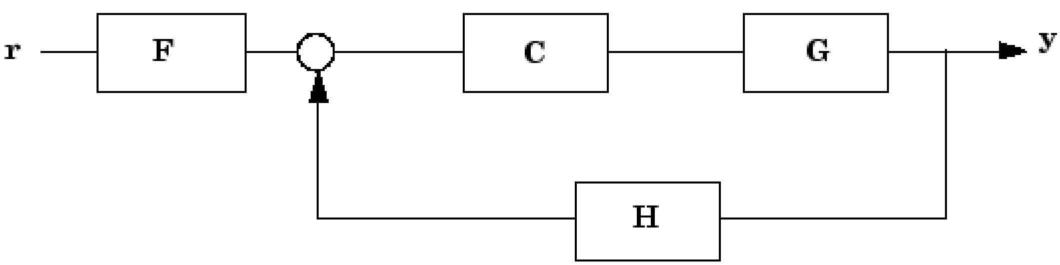
Description

`controlSystemDesigner` opens a SISO Design GUI (Control System Designer) for interactive compensator design. This GUI allows you to design a single-input/single-output (SISO) compensator using root locus, Bode diagram, Nichols and Nyquist techniques. You can also automatically design a compensator using this GUI.

By default, the SISO Design Tool:

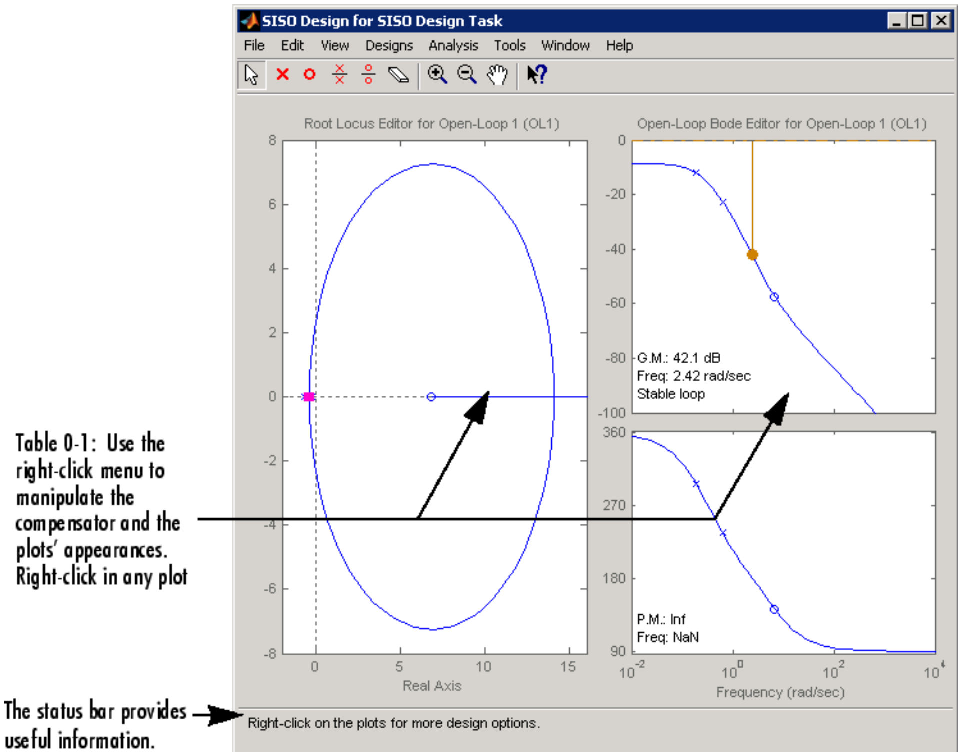
- Opens the Control and Estimation Tools Manager with a default SISO Design Task node.
- Opens the Graphical Tuning editor with root locus and open-loop Bode diagrams.
- Places the compensator, **C**, in the forward path in series with the plant, **G**.
- Assumes the prefilter, **F**, and the sensor, **H**, are unity gains. Once you specify **G** and **H**, they are *fixed* in the feedback structure.

The default control architecture is shown in this figure.



There are six control architectures available. See `sisoinit` for more information.

This picture shows the SISO Design Graphical editor.



`controlSystemDesigner(plant)` opens the SISO Design Tool, imports `plant`, and initializes the plant model **G** to `plant`. `plant` can be any SISO LTI model created with `ss`, `tf`, `zpk` or `frd`, or a row or column array of LTI models.

`controlSystemDesigner(plant,comp)` initializes the plant model **G** to `plant`, the compensator **C** to `comp`. `comp` is an LTI object.

`controlSystemDesigner(plant,comp,sensor,prefilt)` initializes the plant **G** to `plant`, compensator C to `comp`, sensor H to `sensor`, and the prefilter F to `prefilt`. `sensor` is an LTI object or a row or column array of LTI objects. If `plant` is also an array of LTI objects, the lengths of `sensor` and `plant` must match. `prefilt` is an LTI object.

`controlSystemDesigner(views)` or
`controlSystemDesigner(views,plant,comp)` specifies the initial configuration of the SISO Design Tool. `views` can be any of the following strings (or combination thereof):

- `'rlocus'` — Root Locus plot
- `'bode'` — Bode diagrams of the open-loop response
- `'nichols'` — Nichols plot
- `'filter'` — Bode diagrams of the prefilter **F** and the closed-loop response from the command into **F** to the output of the plant **G** .

For example

```
controlSystemDesigner('bode')
```

opens a SISO Design Tool with only the Bode Diagrams. If there is more than one view, the views are specified in a cell array.

`controlSystemDesigner(initdata)` initializes the SISO Design Tool with more general control system configurations. Use `sisoinit` to create the initialization data structure `initdata`.

`controlSystemDesigner(sessiondata)` opens the SISO Design Tool with a previously saved session where `sessiondata` is the MAT-file for the saved session.

Examples

Launch SISO Design Tool GUI in default configuration using LTI models:

```
% Create plant G.
G = tf(1, [1 1]);
% Create controller C.
C = tf(1,[1 2]);
```

```
% Launch the GUI.
controlSystemDesigner(G,C)
```

Launch SISO Design Tool GUI in default configuration using an array of LTI models:

```
% Specify model parameters.
m = 3;
b = 0.5;
k = 8:1:10;
T = 0.1:.05:.2;
% Create an LTI array to model variations in plant G.
for ct = 1:length(k);
    G(:,:,ct) = tf(1,[m,b,k(ct)]);
end
% Create an LTI array to model variations in sensor H.
for ct = 1:length(T);
    H(:,:,ct) = tf(1,[1/T(ct), 1]);
end
% Create a controller C.
C = tf(1,[1 2]);
% Launch the GUI.
controlSystemDesigner(G,C,H)
```

Alternatives

You can open the SISO Design GUI from the MATLAB desktop. In the **Apps** tab, in the **Control System Design and Analysis** section of the Apps gallery, click **Control System Designer**.

More About

- "SISO Design Tool"

See Also

`bode` | `linearSystemAnalyzer` | | `rlocus` | `nichols`

covar

Output and state covariance of system driven by white noise

Syntax

```
P = covar(sys,W)
[P,Q] = covar(sys,W)
```

Description

`covar` calculates the stationary covariance of the output y of an LTI model `sys` driven by Gaussian white noise inputs w. This function handles both continuous- and discrete-time cases.

`P = covar(sys,W)` returns the steady-state output response covariance

$$P = E(yy^T)$$

given the noise intensity

$$E(w(t)w(\tau)^T) = W\delta(t-\tau) \quad \text{(continuous time)}$$
$$E(w[k]w[l]^T) = W\delta_{kl} \qquad \text{(discrete time)}$$

`[P,Q] = covar(sys,W)` also returns the steady-state state covariance

$$Q = E(xx^T)$$

when `sys` is a state-space model (otherwise `Q` is set to `[]`).

When applied to an `N`-dimensional LTI array `sys`, `covar` returns multidimensional arrays P, Q such that

`P(:,:,i1,...iN)` and `Q(:,:,i1,...iN)` are the covariance matrices for the model `sys(:,:,i1,...iN)`.

Examples

Compute the output response covariance of the discrete SISO system

$$H(z) = \frac{2z+1}{z^2+0.2z+0.5}, \quad T_s = 0.1$$

due to Gaussian white noise of intensity `W = 5`. Type

```
sys = tf([2 1],[1 0.2 0.5],0.1);
p = covar(sys,5)
```

These commands produce the following result.

```
p =
    30.3167
```

You can compare this output of `covar` to simulation results.

```
randn('seed',0)
w = sqrt(5)*randn(1,1000);  % 1000 samples

% Simulate response to w with LSIM:
y = lsim(sys,w);

% Compute covariance of y values
psim = sum(y .* y)/length(w);
```

This yields

```
psim =
    32.6269
```

The two covariance values `p` and `psim` do not agree perfectly due to the finite simulation horizon.

More About

Algorithms

Transfer functions and zero-pole-gain models are first converted to state space with `ss`.

For continuous-time state-space models

$$\dot{x} = Ax + Bw$$
$$y = Cx + Dw,$$

the steady-state state covariance Q is obtained by solving the Lyapunov equation

$$AQ + QA^T + BWB^T = 0.$$

In discrete time, the state covariance Q solves the discrete Lyapunov equation

$$AQA^T - Q + BWB^T = 0.$$

In both continuous and discrete time, the output response covariance is given by $P = CQC^T + DWD^T$. For unstable systems, P and Q are infinite.

References

[1] Bryson, A.E. and Y.C. Ho, *Applied Optimal Control,* Hemisphere Publishing, 1975, pp. 458-459.

See Also

`dlyap` | `lyap`

ctrb

Controllability matrix

Syntax

```
Co = ctrb(sys)
```

Description

`ctrb` computes the controllability matrix for state-space systems. For an n-by-n matrix `A` and an n-by-m matrix `B`, `ctrb(A,B)` returns the controllability matrix

$$Co = \begin{bmatrix} B & AB & A^2B & \dots & A^{n-1}B \end{bmatrix}$$

where Co has n rows and nm columns.

`Co = ctrb(sys)` calculates the controllability matrix of the state-space LTI object `sys`. This syntax is equivalent to executing

```
Co = ctrb(sys.A,sys.B)
```

The system is controllable if `Co` has full rank n.

Examples

Check if the system with the following data

```
A =
       1     1
       4    -2

B =
       1    -1
       1    -1
```

is controllable. Type

```
Co=ctrb(A,B);

% Number of uncontrollable states
unco=length(A)-rank(Co)
```

These commands produce the following result.

```
unco =
     1
```

Limitations

Estimating the rank of the controllability matrix is ill-conditioned; that is, it is very sensitive to roundoff errors and errors in the data. An indication of this can be seen from this simple example.

$$A = \begin{bmatrix} 1 & \delta \\ 0 & 1 \end{bmatrix}, \ B = \begin{bmatrix} 1 \\ \delta \end{bmatrix}$$

This pair is controllable if $\delta \neq 0$ but if $\delta < \sqrt{eps}$, where *eps* is the relative machine precision. `ctrb(A,B)` returns

$$[B \ \ AB] = \begin{bmatrix} 1 & 1 \\ \delta & \delta \end{bmatrix}$$

which is not full rank. For cases like these, it is better to determine the controllability of a system using `ctrbf`.

See Also

`ctrbf` | `obsv`

ctrbf

Compute controllability staircase form

Syntax

```
[Abar,Bbar,Cbar,T,k] = ctrbf(A,B,C)
ctrbf(A,B,C,tol)
```

Description

If the controllability matrix of (A, B) has rank $r \le n$, where n is the size of A, then there exists a similarity transformation such that

$$\bar{A} = TAT^T, \quad \bar{B} = TB, \quad \bar{C} = CT^T$$

where T is unitary, and the transformed system has a *staircase* form, in which the uncontrollable modes, if there are any, are in the upper left corner.

$$\bar{A} = \begin{bmatrix} A_{uc} & 0 \\ A_{21} & A_c \end{bmatrix}, \quad \bar{B} = \begin{bmatrix} 0 \\ B_c \end{bmatrix}, \quad \bar{C} = [C_{nc} C_c]$$

where (A_c, B_c) is controllable, all eigenvalues of A_{uc} are uncontrollable, and $C_c(sI - A_c)^{-1}B_c = C(sI - A)^{-1}B$.

`[Abar,Bbar,Cbar,T,k] = ctrbf(A,B,C)` decomposes the state-space system represented by `A`, `B`, and `C` into the controllability staircase form, `Abar`, `Bbar`, and `Cbar`, described above. `T` is the similarity transformation matrix and `k` is a vector of length n, where n is the order of the system represented by `A`. Each entry of `k` represents the number of controllable states factored out during each step of the transformation matrix calculation. The number of nonzero elements in `k` indicates how many iterations were necessary to calculate `T`, and `sum(k)` is the number of states in A_c, the controllable portion of `Abar`.

`ctrbf(A,B,C,tol)` uses the tolerance `tol` when calculating the controllable/uncontrollable subspaces. When the tolerance is not specified, it defaults to `10*n*norm(A,1)*eps`.

Examples

Compute the controllability staircase form for

```
A =
     1     1
     4    -2

B =
     1    -1
     1    -1

C =
     1     0
     0     1
```

and locate the uncontrollable mode.

```
[Abar,Bbar,Cbar,T,k]=ctrbf(A,B,C)

Abar =
   -3.0000         0
   -3.0000    2.0000

Bbar =
    0.0000    0.0000
    1.4142   -1.4142

Cbar =
   -0.7071    0.7071
    0.7071    0.7071

T =
   -0.7071    0.7071
    0.7071    0.7071
k =
     1     0
```

The decomposed system `Abar` shows an uncontrollable mode located at -3 and a controllable mode located at 2.

More About

Algorithms

`ctrbf` implements the Staircase Algorithm of [1].

References

[1] Rosenbrock, M.M., *State-Space and Multivariable Theory*, John Wiley, 1970.

See Also

`ctrb` | `minreal`

ctrlpref

Set Control System Toolbox preferences

Syntax

```
ctrlpref
```

Description

`ctrlpref` opens a Graphical User Interface (GUI) which allows you to change the Control System Toolbox™ preferences. Preferences set in this GUI affect future plots only (existing plots are not altered).

Your preferences are stored to disk (in a system-dependent location) and will be automatically reloaded in future MATLAB sessions using the Control System Toolbox software.

See Also

`controlSystemDesigner` | `linearSystemAnalyzer`

d2c

Convert model from discrete to continuous time

Syntax

```
sysc = d2c(sysd)
sysc = d2c(sysd,method)
sysc = d2c(sysd,opts)
[sysc,G] = d2c(sysd,method,opts)
```

Description

`sysc = d2c(sysd)` produces a continuous-time model `sysc` that is equivalent to the discrete-time dynamic system model `sysd` using zero-order hold on the inputs.

`sysc = d2c(sysd,method)` uses the specified conversion method `method`.

`sysc = d2c(sysd,opts)` converts `sysd` using the option set `opts`, specified using the `d2cOptions` command.

`[sysc,G] = d2c(sysd,method,opts)` returns a matrix `G` that maps the states `xd[k]` of the state-space model `sysd` to the states `xc(t)` of `sysc`.

Input Arguments

`sysd`

Discrete-time dynamic system model

You cannot directly use an `idgrey` model with `FcnType='d'` with `d2c`. Convert the model into `idss` form first.

Default:

`method`

String specifying a discrete-to-continuous time conversion method:

- `'zoh'` — Zero-order hold on the inputs. Assumes the control inputs are piecewise constant over the sampling period.
- `'foh'` — Linear interpolation of the inputs (modified first-order hold). Assumes the control inputs are piecewise linear over the sampling period.
- `'tustin'` — Bilinear (Tustin) approximation to the derivative.
- `'matched'` — Zero-pole matching method of [1] (for SISO systems only).

Default: `'zoh'`

`opts`

Discrete-to-continuous time conversion options, created using `d2cOptions`.

Output Arguments

`sysc`

Continuous-time model of the same type as the input system sysd.

When sysd is an identified (IDLTI) model, `sysc`:

- Includes both the measured and noise components of sysd. If the noise variance is λ in `sysd`, then the continuous-time model `sysc` has an indicated level of noise spectral density equal to $Ts*\lambda$.
- Does not include the estimated parameter covariance of `sysd`. If you want to translate the covariance while converting the model, use `translatecov`.

`G`

Matrix mapping the states `xd[k]` of the state-space model `sysd` to the states `xc(t)` of `sysc`:

$$x_c(kT_s) = G\begin{bmatrix} x_d[k] \\ u[k] \end{bmatrix}.$$

Given an initial condition `x0` for `sysd` and an initial input `u0 = u[0]`, the corresponding initial condition for `sysc` (assuming `u[k] = 0` for `k < 0` is given by:

$$x_c(0) = G\begin{bmatrix} x_0 \\ u_0 \end{bmatrix}.$$

Examples

Example 1

Consider the following discrete-time transfer function:

$$H(z) = \frac{z-1}{z^2 + z + 0.3}$$

Suppose the model has sample time $T_s = 0.1$ s. You can derive a continuous-time zero-order-hold equivalent model with the following commands:

```
H = tf([1 -1], [1 1 0.3], 0.1);
Hc = d2c(H)
```

```
Hc =

   121.7 s + 3.026e-12
  ---------------------
  s^2 + 12.04 s + 776.7

Continuous-time transfer function.
```

Discretizing the resulting model `Hc` with the default zero-order hold method and sample time $T_s = 0.1$s returns the original discrete model $H(z)$:

```
c2d(Hc,0.1)
```

```
ans =

      z - 1
  -------------
  z^2 + z + 0.3

Sample time: 0.1 seconds
Discrete-time transfer function.
```

To use the Tustin approximation instead of zero-order hold, type

```
Hc = d2c(H,'tustin');
```

As with zero-order hold, the inverse discretization operation

```
c2d(Hc,0.1,'tustin');
```

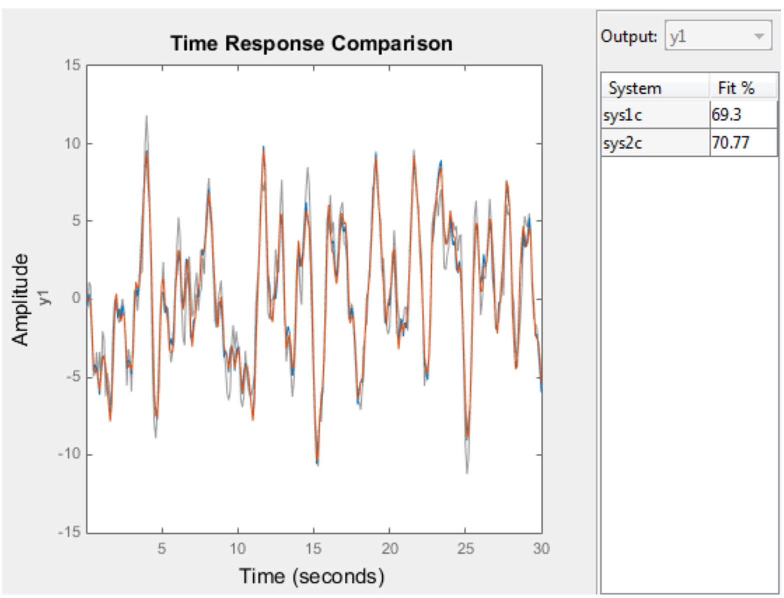
gives back the original $H(z)$.

Example 2

Convert an identified transfer function and compare its performance against a directly estimated continuous-time model.

```
load iddata1
sys1d = tfest(z1,2,'Ts',0.1);
sys1c = d2c(sys1d,'zoh');
sys2c = tfest(z1,2);

compare(z1,sys1c,sys2c)
```

The two systems are virtually identical.



Example 3

Analyze the effect of parameter uncertainty on frequency response across d2c operation on an identified model.

```
load iddata1
sysd = tfest(z1, 2, 'Ts', 0.1);
sysc = d2c(sysd, 'zoh');
```

sys1c has no covariance information. Regenerate it using a zero iteration update with the same estimation command and estimation data:

```
opt = tfestOptions;
opt.SearchOption.MaxIter = 0;
sys1c = tfest(z1, sysc, opt);

h = bodeplot(sysd, sysc);
showConfidence(h)
```

The uncertainties of sysc and sysd are comparable up to the Nyquist frequency. However, sysc exhibits large uncertainty in the frequency range for which the estimation data does not provide any information.

If you do not have access to the estimation data, use translatecov which is a Gauss-approximation formula based translation of covariance across model type conversion operations.

Limitations

The Tustin approximation is not defined for systems with poles at $z = -1$ and is ill-conditioned for systems with poles near $z = -1$.

The zero-order hold method cannot handle systems with poles at $z = 0$. In addition, the 'zoh' conversion increases the model order for systems with negative real poles, [2]. The model order increases because the matrix logarithm maps real negative poles to complex poles. Single complex poles are not physically meaningful because of their complex time response.

Instead, to ensure that all complex poles of the continuous model come in conjugate pairs, d2c replaces negative real poles $z = -a$ with a pair of complex conjugate poles near $-a$.

The conversion then yields a continuous model with higher order. For example, to convert the discrete-time transfer function

$$H(z) = \frac{z+0.2}{(z+0.5)\left(z^2+z+0.4\right)}$$

type:

```
Ts = 0.1  % sample time 0.1 s
H = zpk(-0.2,-0.5,1,Ts) * tf(1,[1 1 0.4],Ts)
Hc = d2c(H)
```

These commands produce the following result.

```
Warning: System order was increased to handle real negative poles.

Zero/pole/gain:
  -33.6556 (s-6.273) (s^2 + 28.29s + 1041)
--------------------------------------------
(s^2 + 9.163s + 637.3) (s^2 + 13.86s + 1035)
```

To convert `Hc` back to discrete time, type:

```
c2d(Hc,Ts)
```

yielding

```
Zero/pole/gain:
     (z+0.5) (z+0.2)
-------------------------
(z+0.5)^2 (z^2 + z + 0.4)

Sample time: 0.1
```

This discrete model coincides with $H(z)$ after canceling the pole/zero pair at $z = -0.5$.

More About

Tips

- Use the syntax `sysc = d2c(sysd,'method')` to convert `sysd` using the default options for`'method'`. To specify `tustin` conversion with a frequency prewarp (formerly the `'prewarp'` method), use the syntax `sysc = d2c(sysd,opts)`. See the `d2cOptions` reference page for more information.

Algorithms

`d2c` performs the `'zoh'` conversion in state space, and relies on the matrix logarithm (see `logm` in the MATLAB documentation).

See “Continuous-Discrete Conversion Methods” for more details on the conversion methods.

References

[1] Franklin, G.F., Powell,D.J., and Workman, M.L., *Digital Control of Dynamic Systems* (3rd Edition), Prentice Hall, 1997..

[2] Kollár, I., G.F. Franklin, and R. Pintelon, "On the Equivalence of z-domain and s-domain Models in System Identification," *Proceedings of the IEEE Instrumentation and Measurement Technology Conference,* Brussels, Belgium, June, 1996, Vol. 1, pp. 14-19.

See Also

`c2d` | `d2d` | `d2cOptions` | `translatecov` | `logm`

d2cOptions

Create option set for discrete- to continuous-time conversions

Syntax

```
opts = d2cOptions
opts = d2cOptions(Name,Value)
```

Description

`opts = d2cOptions` returns the default options for `d2c`.

`opts = d2cOptions(Name,Value)` creates an option set with the options specified by one or more Name,Value pair arguments.

Input Arguments

Name-Value Pair Arguments

`'method'`

Discretization method, specified as one of the following values:

`'zoh'`	Zero-order hold, where `d2c` assumes the control inputs are piecewise constant over the sample time `Ts`.
`'foh'`	Linear interpolation of the inputs (modified first-order hold). Assumes the control inputs are piecewise linear over the sampling period.
`'tustin'`	Bilinear (Tustin) approximation. By default, `d2c` converts with no prewarp. To include prewarp, use the `PrewarpFrequency` option.
`'matched'`	Zero-pole matching method. (See [1], p. 224.)

Default: `'zoh'`

'PrewarpFrequency'

Prewarp frequency for `'tustin'` method, specified in `rad/TimeUnit`, where `TimeUnit` is the time units, specified in the TimeUnit property, of the discrete-time system. Specify the prewarp frequency as a positive scalar value. A value of 0 corresponds to the `'tustin'` method without prewarp.

Default: 0

For additional information about conversion methods, see "Continuous-Discrete Conversion Methods".

Examples

Convert a discrete-time model to continuous-time using the `'tustin'` method with frequency prewarping.

Create the discrete-time transfer function

$$\frac{z+1}{z^2+z+1}$$

```
hd = tf([1 1], [1 1 1], 0.1);  % 0.1s sample time
```

To convert to continuous-time, use `d2cOptions` to create the option set.

```
opts = d2cOptions('Method', 'tustin', 'PrewarpFrequency', 20);
hc = d2c(hd, opts);
```

You can use `opts` to resample additional models using the same options.

References

[1] Franklin, G.F., Powell,D.J., and Workman, M.L., *Digital Control of Dynamic Systems* (3rd Edition), Prentice Hall, 1997.

See Also

`d2c`

d2d

Resample discrete-time model

Syntax

```
sys1 = d2d(sys, Ts)
sys1 = d2d(sys, Ts, 'method')
sys1 = d2d(sys, Ts, opts)
```

Description

`sys1 = d2d(sys, Ts)` resamples the discrete-time dynamic system model `sys` to produce an equivalent discrete-time model `sys1` with the new sample time `Ts` (in seconds), using zero-order hold on the inputs.

`sys1 = d2d(sys, Ts, 'method')` uses the specified resampling method `'method'`:

- `'zoh'` — Zero-order hold on the inputs
- `'tustin'` — Bilinear (Tustin) approximation

`sys1 = d2d(sys, Ts, opts)` resamples `sys` using the option set with `d2dOptions`.

Examples

Example 1

Consider the zero-pole-gain model

$$H(z) = \frac{z - 0.7}{z - 0.5}$$

with sample time 0.1 s. You can resample this model at 0.05 s by typing

```
H = zpk(0.7,0.5,1,0.1)
```

```
H2 = d2d(H,0.05)
Zero/pole/gain:
(z-0.8243)
----------
(z-0.7071)

Sample time: 0.05
```

The inverse resampling operation, performed by typing `d2d(H2,0.1)`, yields back the initial model $H(z)$.

```
Zero/pole/gain:
(z-0.7)
-------
(z-0.5)

Sample time: 0.1
```

Example 2

Suppose you estimates a discrete-time model of a sample time commensurate with the estimation data (`Ts = 0.1 seconds`). However, your deployment application demands a faster sampling frequency (`Ts = 0.01 seconds`).

```
load iddata1
sys = oe(z1, [2 2 1]);
sysFast = d2d(sys, 0.01, 'zoh')

bode(sys, sysFast)
```

More About

Tips

- Use the syntax `sys1 = d2d(sys, Ts, 'method')` to resample `sys` using the default options for`'method'`. To specify `tustin` resampling with a frequency prewarp (formerly the `'prewarp'` method), use the syntax `sys1 = d2d(sys, Ts, opts)`. See the `d2dOptions` reference page.
- When `sys` is an identified (IDLTI) model, `sys1` does not include the estimated parameter covariance of `sys`. If you want to translate the covariance while converting the model, use `translatecov`.

See Also

`c2d` | `d2c` | `d2dOptions` | `upsample` | `translatecov`

d2dOptions

Create option set for discrete-time resampling

Syntax

```
opts = d2dOptions
opts = d2dOptions('OptionName', OptionValue)
```

Description

opts = `d2dOptions` returns the default options for `d2d`.

opts = `d2dOptions('`*OptionName*`',` *OptionValue*`)` accepts one or more comma-separated name/value pairs that specify options for the `d2d` command. Specify *OptionName* inside single quotes.

This table summarizes the options that the `d2d` command supports.

Input Arguments

Name-Value Pair Arguments

`'Method'`

Discretization method, specified as one of the following values:

`'zoh'`	Zero-order hold, where `d2d` assumes the control inputs are piecewise constant over the sample time `Ts`.
`'tustin'`	Bilinear (Tustin) approximation. By default, `d2d` resamples with no prewarp. To include prewarp, use the `PrewarpFrequency` option.

Default: `'zoh'`

'PrewarpFrequency'

Prewarp frequency for `'tustin'` method, specified in `rad/TimeUnit`, where `TimeUnit` is the time units, specified in the TimeUnit property, of the resampled system. Takes positive scalar values. The prewarp frequency must be smaller than the Nyquist frequency before and after resampling. A value of 0 corresponds to the standard `'tustin'` method without prewarp.

Default: 0

Examples

Resample a discrete-time model using the `'tustin'` method with frequency prewarping.

Create the discrete-time transfer function

$$\frac{z+1}{z^2+z+1}$$

```
h1 = tf([1 1], [1 1 1], 0.1);  % 0.1s sample time
```

To resample to a different sample time, use `d2dOptions` to create the option set.

```
opts = d2dOptions('Method', 'tustin', 'PrewarpFrequency', 20);
h2 = d2d(h1, 0.05, opts);
```

You can use `opts` to resample additional models using the same options.

See Also

`d2d`

damp

Natural frequency and damping ratio

Syntax

```
damp(sys)
[Wn,zeta] = damp(sys)
[Wn,zeta,P] = damp(sys)
```

Description

`damp(sys)` displays a table of the damping ratio (also called *damping factor*), natural frequency, and time constant of the poles of the linear model sys. For a discrete-time model, the table also includes the magnitude of each pole. Frequencies are expressed in units of the reciprocal of the `TimeUnit` property of sys. Time constants are expressed in the same units as the `TimeUnit` property of sys.

`[Wn,zeta] = damp(sys)` returns the natural frequencies, Wn, and damping ratios,zeta, of the poles of sys.

`[Wn,zeta,P] = damp(sys)` returns the poles of sys.

Input Arguments

`sys`

Any linear dynamic system model.

Output Arguments

`Wn`

Vector containing the natural frequencies of each pole of sys, in order of increasing frequency. Frequencies are expressed in units of the reciprocal of the `TimeUnit` property of sys.

If sys is a discrete-time model with specified sample time, Wn contains the natural frequencies of the equivalent continuous-time poles (see "Algorithms" on page 1-142). If sys has an unspecified sample time (`Ts = -1`), then the software uses `Ts = 1` and calculates Wn accordingly.

zeta

Vector containing the damping ratios of each pole of sys, in the same order as Wn.

If sys is a discrete-time model with specified sample time, zeta contains the damping ratios of the equivalent continuous-time poles (see "Algorithms" on page 1-142). If sys has an unspecified sample time (`Ts = -1`), then the software uses `Ts = 1` and calculates zeta accordingly.

P

Vector containing the poles of sys, in order of increasing natural frequency. P is the same as the output of `pole(sys)`, except for the order.

Examples

Natural Frequency, Damping Ratio, and Poles of Continuous-Time System

Calculate the natural frequency, damping ratio, time constant, and poles of the continuous-time transfer function:

$$H(s) = \frac{2s^2 + 5s + 1}{s^2 + 2s + 3}.$$

```
H = tf([2 5 1],[1 2 3]);
```

Display the natural frequencies, damping ratios, time constants, and poles of H.

```
damp(H)
```

```
         Pole              Damping       Frequency       Time Constant
                                       (rad/seconds)       (seconds)

 -1.00e+00 + 1.41e+00i     5.77e-01       1.73e+00          1.00e+00
 -1.00e+00 - 1.41e+00i     5.77e-01       1.73e+00          1.00e+00
```

Obtain vectors containing the natural frequencies and damping ratios of the poles.

```
[Wn,zeta] = damp(H);
```

Calculate the associated time constants.

```
tau = 1./(zeta.*Wn);
```

Natural Frequency, Damping Ratio, and Poles of Discrete-Time System

Calculate the natural frequency, damping ratio, time constant, and poles of a discrete-time transfer function.

```
H = tf([5 3 1],[1 6 4 4],0.01);
```

Display information about the poles of *H*.

```
damp(H)
```

```
          Pole              Magnitude     Damping       Frequency       Time Constant
                                                      (rad/seconds)      (seconds)

 -3.02e-01 + 8.06e-01i      8.61e-01     7.74e-02       1.93e+02          6.68e-02
 -3.02e-01 - 8.06e-01i      8.61e-01     7.74e-02       1.93e+02          6.68e-02
 -5.40e+00                  5.40e+00    -4.73e-01       3.57e+02         -5.93e-03
```

The `Magnitude` column displays the discrete-time pole magnitudes. The `Damping`, `Frequency`, and `Time Constant` columns display values calculated using the equivalent continuous-time poles.

Obtain vectors containing the natural frequencies and damping ratios of the poles.

```
[Wn,zeta] = damp(H);
```

Calculate the associated time constants.

```
tau = 1./(zeta.*Wn);
```

More About

Algorithms

The natural frequency, time constant, and damping ratio of the system poles are defined in the following table:

	Continuous Time	Discrete Time with Sample Time Ts
Pole Location	s	z
Equivalent Continuous-Time Pole	Not applicable	$s = \frac{ln(z)}{T_s}$
Natural Frequency	$\omega_n = \lvert s \rvert$	$\omega_n = \lvert s \rvert = \left\lvert \frac{ln(z)}{T_s} \right\rvert$
Damping Ratio	$\zeta = -cos(\angle s)$	$\zeta = -cos(\angle s) = -cos(\angle ln(z))$
Time Constant	$\tau = \frac{1}{\omega_n \zeta}$	$\tau = \frac{1}{\omega_n \zeta}$

See Also

`eig` | `esort` | `dsort` | `pole` | `pzmap` | `zero`

dare

Solve discrete-time algebraic Riccati equations (DAREs)

Syntax

```
[X,L,G] = dare(A,B,Q,R)
[X,L,G] = dare(A,B,Q,R,S,E)
[X,L,G,report] = dare(A,B,Q,...)
[X1,X2,L,report] = dare(A,B,Q,...,'factor')
```

Description

`[X,L,G] = dare(A,B,Q,R)` computes the unique stabilizing solution `X` of the discrete-time algebraic Riccati equation

$$A^T XA - X - A^T XB(B^T XB + R)^{-1} B^T XA + Q = 0$$

The `dare` function also returns the gain matrix, $G = (B^T XB + R)^{-1} B^T XA$, and the vector `L` of closed loop eigenvalues, where

```
L=eig(A-B*G,E)
```

`[X,L,G] = dare(A,B,Q,R,S,E)` solves the more general discrete-time algebraic Riccati equation,

$$A^T XA - E^T XE - (A^T XB + S)(B^T XB + R)^{-1}(B^T XA + S^T) + Q = 0$$

or, equivalently, if `R` is nonsingular,

$$E^T XE = F^T XF - F^T XB(B^T XB + R)^{-1} B^T XF + Q - SR^{-1} S^T$$

where $F = A - BR^{-1}S^T$. When omitted, `R`, `S`, and `E` are set to the default values `R=I`, `S=0`, and `E=I`.

The `dare` function returns the corresponding gain matrix

$$G = (B^T XB + R)^{-1}(B^T XA + S^T)$$

and a vector `L` of closed-loop eigenvalues, where

```
L= eig(A-B*G,E)
```

`[X,L,G,report] = dare(A,B,Q,...)` returns a diagnosis `report` with value:

- `-1` when the associated symplectic pencil has eigenvalues on or very near the unit circle
- `-2` when there is no finite stabilizing solution `X`
- The Frobenius norm if `X` exists and is finite

`[X1,X2,L,report] = dare(A,B,Q,...,'factor')` returns two matrices, `X1` and `X2`, and a diagonal scaling matrix D such that `X = D*(X2/X1)*D`. The vector L contains the closed-loop eigenvalues. All outputs are empty when the associated Symplectic matrix has eigenvalues on the unit circle.

Limitations

The (A, B) pair must be stabilizable (that is, all eigenvalues of A outside the unit disk must be controllable). In addition, the associated symplectic pencil must have no eigenvalue on the unit circle. Sufficient conditions for this to hold are (Q, A) detectable when $S = 0$ and $R > 0$, or

$$\begin{bmatrix} Q & S \\ S^T & R \end{bmatrix} > 0$$

More About

Algorithms

`dare` implements the algorithms described in [1]. It uses the QZ algorithm to deflate the extended symplectic pencil and compute its stable invariant subspace.

References

[1] Arnold, W.F., III and A.J. Laub, "Generalized Eigenproblem Algorithms and Software for Algebraic Riccati Equations," *Proc. IEEE*, 72 (1984), pp. 1746-1754.

See Also

`care` | `dlyap` | `gdare`

db2mag

Convert decibels (dB) to magnitude

Syntax

```
y = db2mag(ydb)
```

Description

`y = db2mag(ydb)` returns the corresponding magnitude y for a given decibel (dB) value ydb. The relationship between magnitude and decibels is $ydb = 20 * \log_{10}(y)$.

See Also

`mag2db`

dcgain

Low-frequency (DC) gain of LTI system

Syntax

```
k = dcgain(sys)
```

Description

`k = dcgain(sys)` computes the DC gain `k` of the LTI model `sys`.

Continuous Time

The continuous-time DC gain is the transfer function value at the frequency $s = 0$. For state-space models with matrices (A, B, C, D), this value is
$K = D - CA^{-1}B$

Discrete Time

The discrete-time DC gain is the transfer function value at $z = 1$. For state-space models with matrices (A, B, C, D), this value is
$K = D + C\,(I - A)^{-1}B$

Examples

Example 1

To compute the DC gain of the MIMO transfer function

$$H(s) = \begin{bmatrix} 1 & \dfrac{s-1}{s^2+s+3} \\ \dfrac{1}{s+1} & \dfrac{s+2}{s-3} \end{bmatrix}$$

type

```
H = [1 tf([1 -1],[1 1 3]) ; tf(1,[1 1]) tf([1 2],[1 -3])];
dcgain(H)
```

to get the result:

```
ans =
    1.0000   -0.3333
    1.0000   -0.6667
```

Example 2

To compute the DC gain of an identified process model, type;

```
load iddata1
sys = idproc('p1d');
syse = procest(z1, sys)

dcgain(syse)
```

The DC gain is stored same as `syse.Kp`.

More About

Tips

The DC gain is infinite for systems with integrators.

See Also

`norm` | `evalfr`

delay2z

Replace delays of discrete-time TF, SS, or ZPK models by poles at z=0, or replace delays of FRD models by phase shift

Note: `delay2z` has been removed. Use `absorbDelay` instead.

delayss

Create state-space models with delayed inputs, outputs, and states

Syntax

```
sys=delayss(A,B,C,D,delayterms)
sys=delayss(A,B,C,D,ts,delayterms)
```

Description

`sys=delayss(A,B,C,D,delayterms)` constructs a continuous-time state-space model of the form:

$$\frac{dx}{dt} = Ax(t) + Bu(t) + \sum_{j=1}^{N} (A_j x(t - t_j) + B_j u(t - t_j))$$

$$y(t) = Cx(t) + Du(t) + \sum_{j=1}^{N} (C_j x(t - t_j) + D_j u(t - t_j))$$

where t_j, j=1,..,N are time delays expressed in seconds. `delayterms` is a struct array with fields `delay`, `a`, `b`, `c`, `d` where the fields of `delayterms(j)` contain the values of `tj`, `Aj`, `Bj`, `Cj`, and `Dj`, respectively. The resulting model `sys` is a state-space (`SS`) model with internal delays.

`sys=delayss(A,B,C,D,ts,delayterms)` constructs the discrete-time counterpart:

$$x[k+1] = Ax[k] + Bu[k] + \sum_{j=1}^{N} \{A_j x[k - n_j] + B_j u[k - n_j]\}$$

$$y[k] = Cx[k] + Du[k] + \sum_{j=1}^{N} \{C_j x[k - n_j] + D_j u[k - n_j]\}$$

where Nj, j=1,..,N are time delays expressed as integer multiples of the sample time `ts`.

Examples

To create the model:

$$\frac{dx}{dt} = x(t) - x(t-1.2) + 2u(t-0.5)$$
$$y(t) = x(t-0.5) + u(t)$$

type

```
DelayT(1) = struct('delay',0.5,'a',0,'b',2,'c',1,'d',0);
DelayT(2) = struct('delay',1.2,'a',-1,'b',0,'c',0,'d',0);
sys = delayss(1,0,0,1,DelayT)

a =
       x1
   x1   0

b =
       u1
   x1   2

c =
       x1
   y1   1

d =
       u1
   y1   1

(values computed with all internal delays set to zero)

Internal delays: 0.5  0.5  1.2

Continuous-time model.
```

See Also

getdelaymodel | ss

dlqr

Linear-quadratic (LQ) state-feedback regulator for discrete-time state-space system

Syntax

```
[K,S,e] = dlqr(A,B,Q,R,N)
```

Description

`[K,S,e] = dlqr(A,B,Q,R,N)` calculates the optimal gain matrix `K` such that the state-feedback law

$$u[n] = -Kx[n]$$

minimizes the quadratic cost function

$$J(u) = \sum_{n=1}^{\infty} (x[n]^T Qx[n] + u[n]^T Ru[n] + 2x[n]^T Nu[n])$$

for the discrete-time state-space mode

$$x[n+1] = Ax[n] + Bu[n]$$

The default value `N=0` is assumed when `N` is omitted.

In addition to the state-feedback gain `K`, `dlqr` returns the infinite horizon solution S of the associated discrete-time Riccati equation

$$A^T SA - S - (A^T SB + N)(B^T SB + R)^{-1}(B^T SA + N^T) + Q = 0$$

and the closed-loop eigenvalues `e = eig(A-B*K)`. Note that K is derived from S by

$$K = (B^T SB + R)^{-1}(B^T SA + N^T)$$

Limitations

The problem data must satisfy:

- The pair (A, B) is stabilizable.
- $R > 0$ and $Q - NR^{-1}N^{T} \geq 0$
- $(Q - NR^{-1}N^{T}, A - BR^{-1}N^{T})$ has no unobservable mode on the unit circle.

See Also

`dare` | `lqgreg` | `lqr` | `lqrd` | `lqry`

dlyap

Solve discrete-time Lyapunov equations

Syntax

```
X = dlyap(A,Q)
X = dlyap(A,B,C)
X = dlyap(A,Q,[],E)
```

Description

`X = dlyap(A,Q)` solves the discrete-time Lyapunov equation $AXA^T - X + Q = 0$,

where A and Q are n-by-n matrices.

The solution X is symmetric when Q is symmetric, and positive definite when Q is positive definite and A has all its eigenvalues inside the unit disk.

`X = dlyap(A,B,C)` solves the Sylvester equation $AXB - X + C = 0$,

where A, B, and C must have compatible dimensions but need not be square.

`X = dlyap(A,Q,[],E)` solves the generalized discrete-time Lyapunov equation $AXA^T - EXE^T + Q = 0$,

where Q is a symmetric matrix. The empty square brackets, `[]`, are mandatory. If you place any values inside them, the function will error out.

Diagnostics

The discrete-time Lyapunov equation has a (unique) solution if the eigenvalues $a_1, a_2, \ldots, a_N$ of A satisfy $a_i a_j \neq 1$ for all (i, j).

If this condition is violated, `dlyap` produces the error message

```
Solution does not exist or is not unique.
```

More About

Algorithms

`dlyap` uses SLICOT routines SB03MD and SG03AD for Lyapunov equations and SB04QD (SLICOT) for Sylvester equations.

References

[1] Barraud, A.Y., “A numerical algorithm to solve A XA - X = Q,” *IEEE Trans. Auto. Contr.*, AC-22, pp. 883-885, 1977.

[2] Bartels, R.H. and G.W. Stewart, "Solution of the Matrix Equation AX + XB = C," *Comm. of the ACM*, Vol. 15, No. 9, 1972.

[3] Hammarling, S.J., “Numerical solution of the stable, non-negative definite Lyapunov equation,” *IMA J. Num. Anal.*, Vol. 2, pp. 303-325, 1982.

[4] Higham, N.J., ”FORTRAN codes for estimating the one-norm of a real or complex matrix, with applications to condition estimation,” *A.C.M. Trans. Math. Soft.*, Vol. 14, No. 4, pp. 381-396, 1988.

[5] Penzl, T., ”Numerical solution of generalized Lyapunov equations,” *Advances in Comp. Math.*, Vol. 8, pp. 33-48, 1998.

[6] Golub, G.H., Nash, S. and Van Loan, C.F. “A Hessenberg-Schur method for the problem AX + XB = C,” *IEEE Trans. Auto. Contr.*, AC-24, pp. 909-913, 1979.

[7] Sima, V. C, “Algorithms for Linear-quadratic Optimization,” Marcel Dekker, Inc., New York, 1996.

See Also

`covar` | `lyap`

dlyapchol

Square-root solver for discrete-time Lyapunov equations

Syntax

```
R = dlyapchol(A,B)
X = dlyapchol(A,B,E)
```

Description

`R = dlyapchol(A,B)` computes a Cholesky factorization `X = R'*R` of the solution `X` to the Lyapunov matrix equation:

```
A*X*A'- X + B*B' = 0
```

All eigenvalues of `A` matrix must lie in the open unit disk for `R` to exist.

`X = dlyapchol(A,B,E)` computes a Cholesky factorization `X = R'*R` of `X` solving the Sylvester equation

```
A*X*A' - E*X*E' + B*B' = 0
```

All generalized eigenvalues of (A,E) must lie in the open unit disk for `R` to exist.

More About

Algorithms

`dlyapchol` uses SLICOT routines SB03OD and SG03BD.

References

[1] Bartels, R.H. and G.W. Stewart, "Solution of the Matrix Equation AX + XB = C," *Comm. of the ACM*, Vol. 15, No. 9, 1972.

[2] Hammarling, S.J., “Numerical solution of the stable, non-negative definite Lyapunov equation,” *IMA J. Num. Anal.*, Vol. 2, pp. 303-325, 1982.

[3] Penzl, T., ”Numerical solution of generalized Lyapunov equations,” *Advances in Comp. Math.*, Vol. 8, pp. 33-48, 1998.

See Also

`dlyap` | `lyapchol`

drss

Generate random discrete test model

Syntax

```
sys = drss(n)
drss(n,p)
drss(n,p,m)
drss(n,p,m,s1,...sn)
```

Description

`sys = drss(n)` generates an *n*-th order model with one input and one output, and returns the model in the state-space object `sys`. The poles of `sys` are random and stable with the possible exception of poles at `z = 1` (integrators).

`drss(n,p)` generates an *n*-th order model with one input and `p` outputs.

`drss(n,p,m)` generates an *n*-th order model with `p` outputs and `m` inputs.

`drss(n,p,m,s1,...sn)` generates a *s1*-by-*sn* array of *n*-th order models with `m` inputs and `p` outputs.

In all cases, the discrete-time state-space model or array returned by `drss` has an unspecified sample time. To generate transfer function or zero-pole-gain systems, convert `sys` using `tf` or `zpk`.

Examples

Generate a discrete LTI system with three states, four outputs, and two inputs.

```
sys = drss(3,4,2)

a =
              x1        x2        x3
   x1     0.4766    0.1102   -0.7222
```

```
   x2   0.1102   0.9115   0.1628
   x3  -0.7222   0.1628   -0.202

b =
            u1       u2
   x1  -0.4326   0.2877
   x2       -0       -0
   x3        0    1.191

c =
             x1        x2        x3
   y1     1.189   -0.1867        -0
   y2  -0.03763    0.7258    0.1139
   y3    0.3273   -0.5883     1.067
   y4    0.1746     2.183         0

d =
             u1        u2
   y1  -0.09565         0
   y2   -0.8323     1.624
   y3    0.2944   -0.6918
   y4        -0     0.858

Sample time: unspecified
Discrete-time model.
```

See Also

`rss` | `tf` | `zpk`

dsort

Sort discrete-time poles by magnitude

Syntax

```
dsort
[s,ndx] = dsort(p)
```

Description

`dsort` sorts the discrete-time poles contained in the vector `p` in descending order by magnitude. Unstable poles appear first.

When called with one lefthand argument, `dsort` returns the sorted poles in `s`.

`[s,ndx] = dsort(p)` also returns the vector `ndx` containing the indices used in the sort.

Examples

Sort the following discrete poles.

```
p =
  -0.2410 + 0.5573i
  -0.2410 - 0.5573i
   0.1503
  -0.0972
  -0.2590

s = dsort(p)

s =
  -0.2410 + 0.5573i
  -0.2410 - 0.5573i
  -0.2590
   0.1503
  -0.0972
```

Limitations

The poles in the vector `p` must appear in complex conjugate pairs.

See Also

`eig` | `esort` | `sort` | `pole` | `pzmap` | `zero`

dss

Create descriptor state-space models

Syntax

```
sys = dss(A,B,C,D,E)
sys = dss(A,B,C,D,E,Ts)
sys = dss(A,B,C,D,E,ltisys)
```

Description

`sys = dss(A,B,C,D,E)` creates the continuous-time descriptor state-space model

$$\begin{aligned} E\frac{dx}{dt} &= Ax + Bu \\ y &= Cx + Du \end{aligned}$$

The output `sys` is an SS model storing the model data (see "State-Space Models"). Note that `ss` produces the same type of object. If the matrix $\boldsymbol{D} = \mathbf{0}$, you can simply set `d` to the scalar `0` (zero).

`sys = dss(A,B,C,D,E,Ts)` creates the discrete-time descriptor model

$$\begin{aligned} Ex[n+1] &= Ax[n] + Bu[n] \\ y[n] &= Cx[n] + Du[n] \end{aligned}$$

with sample time `Ts` (in seconds).

`sys = dss(A,B,C,D,E,ltisys)` creates a descriptor model with properties inherited from the LTI model `ltisys` (including the sample time).

Any of the previous syntaxes can be followed by property name/property value pairs

```
'Property',Value
```

Each pair specifies a particular LTI property of the model, for example, the input names or some notes on the model history. See `set` and the example below for details.

Examples

The command

```
sys = dss(1,2,3,4,5,'inputdelay',0.1,'inputname','voltage',...
                                         'notes','Just an example');
```

creates the model

$$\begin{aligned} 5\dot{x} &= x + 2u \\ y &= 3x + 4u \end{aligned}$$

with a 0.1 second input delay. The input is labeled `'voltage'`, and a note is attached to tell you that this is just an example.

See Also

`dssdata` | `get` | `set` | `ss`

dssdata

Extract descriptor state-space data

Syntax

```
[A,B,C,D,E] = dssdata(sys)
[A,B,C,D,E,Ts] = dssdata(sys)
```

Description

`[A,B,C,D,E] = dssdata(sys)` returns the values of the A, B, C, D, and E matrices for the descriptor state-space model `sys` (see `dss`). `dssdata` equals `ssdata` for regular state-space models (i.e., when E=I).

If `sys` has internal delays, `A`, `B`, `C`, `D` are obtained by first setting all internal delays to zero (creating a zero-order Padé approximation). For some systems, setting delays to zero creates singular algebraic loops, which result in either improper or ill-defined, zero-delay approximations. For these systems, `dssdata` cannot display the matrices and returns an error. This error does not imply a problem with the model `sys` itself.

`[A,B,C,D,E,Ts] = dssdata(sys)` also returns the sample time `Ts`.

You can access other properties of `sys` using `get` or direct structure-like referencing (e.g., `sys.Ts`).

For arrays of SS models with variable order, use the syntax

```
[A,B,C,D,E] = dssdata(sys,'cell')
```

to extract the state-space matrices of each model as separate cells in the cell arrays A, B, C, D, and E.

See Also

`dss` | `get` | `getdelaymodel` | `ssdata`

esort

Sort continuous-time poles by real part

Syntax

```
s = esort(p)
[s,ndx] = esort(p)
```

Description

`esort` sorts the continuous-time poles contained in the vector `p` by real part. Unstable eigenvalues appear first and the remaining poles are ordered by decreasing real parts.

When called with one left-hand argument, `s = esort(p)` returns the sorted eigenvalues in `s`.

`[s,ndx] = esort(p)` returns the additional argument `ndx`, a vector containing the indices used in the sort.

Examples

Sort the following continuous eigenvalues.

```
p
p =
  -0.2410+ 0.5573i
  -0.2410- 0.5573i
   0.1503
  -0.0972
  -0.2590

esort(p)

ans =
   0.1503
  -0.0972
  -0.2410+ 0.5573i
```

```
-0.2410- 0.5573i
-0.2590
```

Limitations

The eigenvalues in the vector `p` must appear in complex conjugate pairs.

See Also

`dsort` | `sort` | `eig` | `pole` | `pzmap` | `zero`

estim

Form state estimator given estimator gain

Syntax

```
est = estim(sys,L)
est = estim(sys,L,sensors,known)
```

Description

`est = estim(sys,L)` produces a state/output estimator `est` given the plant state-space model `sys` and the estimator gain `L`. All inputs w of `sys` are assumed stochastic (process and/or measurement noise), and all outputs y are measured. The estimator `est` is returned in state-space form (SS object).

For a continuous-time plant `sys` with equations

$$\dot{x} = Ax + Bw$$
$$y = Cx + Dw$$

`estim` uses the following equations to generate a plant output estimate $\hat{y}$ and a state estimate $\hat{x}$, which are estimates of $y(t)$=C and $x(t)$, respectively:

$$\dot{\hat{x}} = A\hat{x} + L(y - C\hat{x})$$
$$\begin{bmatrix} \hat{y} \\ \hat{x} \end{bmatrix} = \begin{bmatrix} C \\ I \end{bmatrix} \hat{x}$$

For a discrete-time plant `sys` with the following equations:

$$x[n+1] = Ax[n] + Bw[n]$$
$$y[n] = Cx[n] + Dw[n]$$

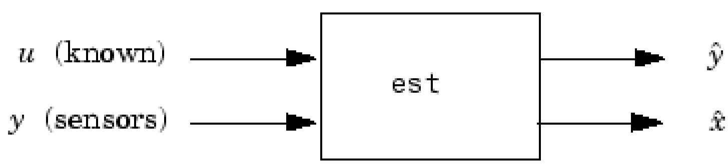
`estim` uses estimator equations similar to those for continuous-time to generate a plant output estimate $y[n|n-1]$ and a state estimate $x[n|n-1]$, which are estimates of $y[n]$ and $x[n]$, respectively. These estimates are based on past measurements up to $y[n\text{-}1]$.

`est = estim(sys,L,sensors,known)` handles more general plants `sys` with both known (deterministic) inputs u and stochastic inputs w, and both measured outputs y and nonmeasured outputs z.

$$\dot{x} = Ax + B_1 w + B_2 u$$
$$\begin{bmatrix} z \\ y \end{bmatrix} = \begin{bmatrix} C_1 \\ C_2 \end{bmatrix} x + \begin{bmatrix} D_{11} \\ D_{21} \end{bmatrix} w + \begin{bmatrix} D_{12} \\ D_{22} \end{bmatrix} u$$

The index vectors `sensors` and `known` specify which outputs of `sys` are measured (y), and which inputs of `sys` are known (u). The resulting estimator `est`, found using the following equations, uses both u and y to produce the output and state estimates.

$$\dot{\hat{x}} = A\hat{x} + B_2 u + L(y - C_2\hat{x} - D_{22}u)$$
$$\begin{bmatrix} \hat{y} \\ \hat{x} \end{bmatrix} = \begin{bmatrix} C_2 \\ I \end{bmatrix} \hat{x} + \begin{bmatrix} D_{22} \\ 0 \end{bmatrix} u$$



Examples

Consider a state-space model `sys` with seven outputs and four inputs. Suppose you designed a Kalman gain matrix L using outputs 4, 7, and 1 of the plant as sensor measurements and inputs 1, 4, and 3 of the plant as known (deterministic) inputs. You can then form the Kalman estimator by

```
sensors = [4,7,1];
known = [1,4,3];
est = estim(sys,L,sensors,known)
```

See the function `kalman` for direct Kalman estimator design.

More About

Tips

You can use the functions `place` (pole placement) or `kalman` (Kalman filtering) to design an adequate estimator gain L. Note that the estimator poles (eigenvalues of A-LC) should be faster than the plant dynamics (eigenvalues of A) to ensure accurate estimation.

See Also

`kalman` | `ss` | `ssest` | `predict` | `place` | `reg` | `kalmd` | `lqgreg`

evalfr

Evaluate frequency response at given frequency

Syntax

```
frsp = evalfr(sys,f)
```

Description

`frsp = evalfr(sys,f)` evaluates the transfer function of the TF, SS, or ZPK model `sys` at the complex number `f`. For state-space models with data (A, B, C, D), the result is $H(f) = D + C\,(fI - A)^{-1}B$

`evalfr` is a simplified version of `freqresp` meant for quick evaluation of the response at a single point. Use `freqresp` to compute the frequency response over a set of frequencies.

Examples

Example 1

To evaluate the discrete-time transfer function

$$H(z) = \frac{z-1}{z^2 + z + 1}$$

at $z = 1 + j$, type

```
H = tf([1 -1],[1 1 1],-1);
z = 1+j;
evalfr(H,z)
```

to get the result:

```
ans =
```

```
  2.3077e-01 +  1.5385e-01i
```

Example 2

To evaluate the frequency response of a continuous-time IDTF model at frequency `w = 0.1 rad/s`, type:

```
sys = idtf(1,[1 2 1]);
w = 0.1;
s = 1j*w;
evalfr(sys, s)
```

The result is same as `freqresp(sys, w)`.

Limitations

The response is not finite when `f` is a pole of `sys`.

See Also

`freqresp` | `bode` | `sigma`

lti/exp

Create pure continuous-time delays

Syntax

```
d = exp(tau,s)
```

Description

`d = exp(tau,s)` creates pure continuous-time delays. The transfer function of a pure delay `tau` is:

```
d(s) = exp(-tau*s)
```

You can specify this transfer function using `exp`.

```
s = zpk('s')
d = exp(-tau*s)
```

More generally, given a 2D array `M`,

```
s = zpk('s')
D = exp(-M*s)
```

creates an array `D` of pure delays where
$D(i,j) = \exp(-M(i,j)s)$.

All entries of `M` should be non negative for causality.

See Also

`zpk` | `tf`

fcat

Concatenate FRD models along frequency dimension

Syntax

`sys = fcat(sys1,sys2,...)`

Description

`sys = fcat(sys1,sys2,...)` takes two or more `frd` models and merges their frequency responses into a single `frd` model `sys`. The resulting frequency vector is sorted by increasing frequency. The frequency vectors of `sys1, sys2,...` should not intersect. If the frequency vectors do intersect, use `fdel` to remove intersecting data from one or more of the models.

See Also

`fselect` | `interp` | `fdel` | `frd`

fdel

Delete specified data from frequency response data (FRD) models

Syntax

`sysout = fdel(sys, freq)`

Description

`sysout = fdel(sys, freq)` removes from the `frd` model `sys` the data nearest to the frequency values specified in the vector `freq`.

Input Arguments

`sys`

`frd` model.

`freq`

Vector of frequency values.

Output Arguments

`sysout`

`frd` model containing the data remaining in `sys` after removing the frequency points closest to the entries of `freq`.

Examples

Remove selected data from a `frd` model. In this example, first obtain an `frd` model:

```
sys = frd(tf([1],[1 1]), logspace(0,1,10))

  Frequency(rad/s)        Response
  ----------------        --------
        1.0000        0.5000 - 0.5000i
        1.2915        0.3748 - 0.4841i
        1.6681        0.2644 - 0.4410i
        2.1544        0.1773 - 0.3819i
        2.7826        0.1144 - 0.3183i
        3.5938        0.0719 - 0.2583i
        4.6416        0.0444 - 0.2059i
        5.9948        0.0271 - 0.1623i
        7.7426        0.0164 - 0.1270i
       10.0000        0.0099 - 0.0990i

Continuous-time frequency response.
```

The following commands remove the data nearest 2, 3.5, and 6 rad/s from `sys`.

```
freq = [2, 3.5, 6];
sysout = fdel(sys, freq)

  Frequency(rad/s)        Response
  ----------------        --------
        1.0000        0.5000 - 0.5000i
        1.2915        0.3748 - 0.4841i
        1.6681        0.2644 - 0.4410i
        2.7826        0.1144 - 0.3183i
        4.6416        0.0444 - 0.2059i
        7.7426        0.0164 - 0.1270i
       10.0000        0.0099 - 0.0990i

Continuous-time frequency response.
```

You do not have to specify the exact frequency of the data to remove. `fdel` removes the data nearest to the specified frequencies.

More About

Tips

- Use `fdel` to remove unwanted data (for example, outlier points) at specified frequencies.

- Use `fdel` to remove data at intersecting frequencies from `frd` models before merging them with `fcat`. `fcat` produces an error when you attempt to merge `frd` models that have intersecting frequency data.
- To remove data from an `frd` model within a range of frequencies, use `fselect`.

See Also

`fcat` | `fselect` | `frd`

feedback

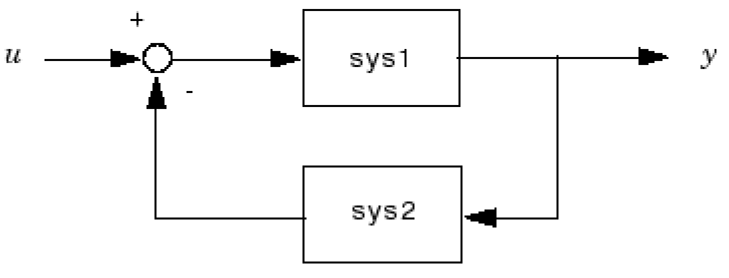
Feedback connection of two models

Syntax

```
sys = feedback(sys1,sys2)
```

Description

`sys = feedback(sys1,sys2)` returns a model object `sys` for the negative feedback interconnection of model objects `sys1` and `sys2`.



The closed-loop model `sys` has *u* as input vector and *y* as output vector. The models `sys1` and `sys2` must be both continuous or both discrete with identical sample times. Precedence rules are used to determine the resulting model type (see “Rules That Determine Model Type”).

To apply positive feedback, use the syntax

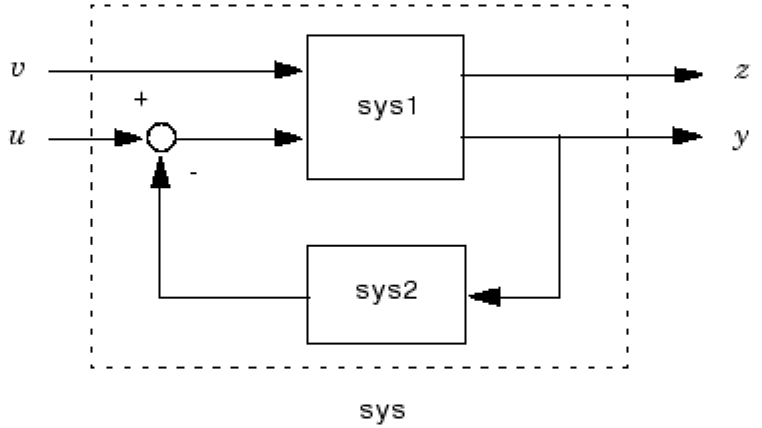
```
sys = feedback(sys1,sys2,+1)
```

By default, `feedback(sys1,sys2)` assumes negative feedback and is equivalent to `feedback(sys1,sys2,-1)`.

Finally,

```
sys = feedback(sys1,sys2,feedin,feedout)
```

computes a closed-loop model sys for the more general feedback loop.



The vector feedin contains indices into the input vector of sys1 and specifies which inputs *u* are involved in the feedback loop. Similarly, feedout specifies which outputs *y* of sys1 are used for feedback. The resulting model sys has the same inputs and outputs as sys1 (with their order preserved). As before, negative feedback is applied by default and you must use

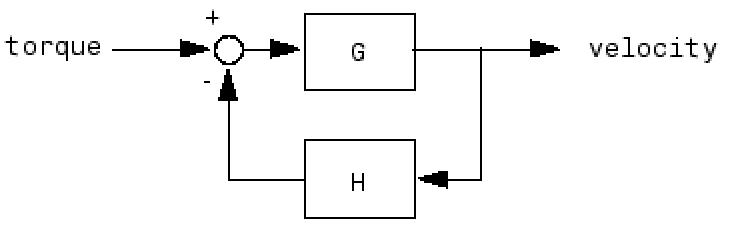
```
sys = feedback(sys1,sys2,feedin,feedout,+1)
```

to apply positive feedback.

For more complicated feedback structures, use append and connect.

Examples

Example 1



To connect the plant

$$G(s) = \frac{2s^2 + 5s + 1}{s^2 + 2s + 3}$$

with the controller

$$H(s) = \frac{5(s+2)}{s+10}$$

using negative feedback, type

```
G = tf([2 5 1],[1 2 3],'inputname','torque',...
                        'outputname','velocity');
H = zpk(-2,-10,5)
Cloop = feedback(G,H)
```

These commands produce the following result.

```
Zero/pole/gain from input "torque" to output "velocity":
0.18182 (s+10) (s+2.281) (s+0.2192)
-----------------------------------
 (s+3.419) (s^2 + 1.763s + 1.064)
```

The result is a zero-pole-gain model as expected from the precedence rules. Note that `Cloop` inherited the input and output names from `G`.

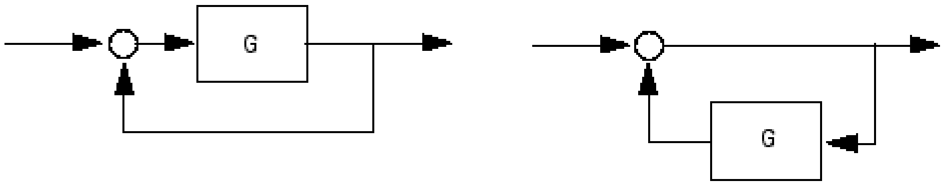
Example 2

Consider a state-space plant `P` with five inputs and four outputs and a state-space feedback controller `K` with three inputs and two outputs. To connect outputs 1, 3, and 4 of the plant to the controller inputs, and the controller outputs to inputs 4 and 2 of the plant, use

```
feedin = [4 2];
feedout = [1 3 4];
Cloop = feedback(P,K,feedin,feedout)
```

Example 3

You can form the following negative-feedback loops



by

```
Cloop = feedback(G,1)       % left diagram
Cloop = feedback(1,G)      % right diagram
```

Limitations

The feedback connection should be free of algebraic loop. If D_1 and D_2 are the feedthrough matrices of `sys1` and `sys2`, this condition is equivalent to:

- $I + D_1D_2$ nonsingular when using negative feedback
- $I - D_1D_2$ nonsingular when using positive feedback.

See Also

`series` | `parallel` | `connect`

filt

Specify discrete transfer functions in DSP format

Syntax

```
sys = filt(num,den)
sys = filt(num,den,Ts)
sys = filt(M)
```

Description

In digital signal processing (DSP), it is customary to write transfer functions as rational expressions in z^{-1} and to order the numerator and denominator terms in *ascending* powers of z^{-1}. For example:

$$H\left(z^{-1}\right) = \frac{2 + z^{-1}}{1 + 0.4z^{-1} + 2z^{-2}}$$

The function `filt` is provided to facilitate the specification of transfer functions in DSP format.

`sys = filt(num,den)` creates a discrete-time transfer function `sys` with numerator(s) `num` and denominator(s) `den`. The sample time is left unspecified (`sys.Ts = -1`) and the output `sys` is a TF object.

`sys = filt(num,den,Ts)` further specifies the sample time `Ts` (in seconds).

`sys = filt(M)` specifies a static filter with gain matrix `M`.

Any of the previous syntaxes can be followed by property name/property value pairs of the form

```
'Property',Value
```

Each pair specifies a particular property of the model, for example, the input names or the transfer function variable. For information about the available properties and their values, see the `tf` reference page.

Arguments

For SISO transfer functions, `num` and `den` are row vectors containing the numerator and denominator coefficients ordered in ascending powers of z^{-1}. For example, `den = [1 0.4 2]` represents the polynomial $1 + 0.4z^{-1} + 2z^{-2}$.

MIMO transfer functions are regarded as arrays of SISO transfer functions (one per I/O channel), each of which is characterized by its numerator and denominator. The input arguments `num` and `den` are then cell arrays of row vectors such that:

- `num` and `den` have as many rows as outputs and as many columns as inputs.
- Their (i, j) entries `num{i,j}` and `den{i,j}` specify the numerator and denominator of the transfer function from input `j` to output `i`.

If all SISO entries have the same denominator, you can also set `den` to the row vector representation of this common denominator.

Examples

Create a two-input digital filter with input names `'channel1'` and `'channel2'`:

```
num = {1 , [1 0.3]};
den = {[1 1 2] ,[5 2]};
H = filt(num,den,'inputname',{'channel1' 'channel2'})
```

This syntax returns:

```
Transfer function from input "channel1" to output:
        1
-----------------
1 + z^-1 + 2 z^-2

Transfer function from input "channel2" to output:
1 + 0.3 z^-1
------------
```

```
 5 + 2 z^-1

Sample time: unspecified
```

More About

Tips

`filt` behaves as `tf` with the `Variable` property set to `'z^-1'`. See `tf` entry below for details.

See Also

`tf` | `zpk` | `ss`

fnorm

Pointwise peak gain of FRD model

Syntax

```
fnrm = fnorm(sys)
fnrm = fnorm(sys,ntype)
```

Description

`fnrm = fnorm(sys)` computes the pointwise 2-norm of the frequency response contained in the FRD model `sys`, that is, the peak gain at each frequency point. The output `fnrm` is an FRD object containing the peak gain across frequencies.

`fnrm = fnorm(sys,ntype)` computes the frequency response gains using the matrix norm specified by `ntype`. See `norm` for valid matrix norms and corresponding NTYPE values.

See Also

`norm` | `abs`

frd

Create frequency-response data model, convert to frequency-response data model

Syntax

```
sys = frd(response,frequency)
sys = frd(response,frequency,Ts)
sys = frd
sysfrd = frd(sys,frequency)
sysfrd = frd(sys,frequency,units)
```

Description

`sys = frd(response,frequency)` creates a frequency-response data (`frd`) model object `sys` from the frequency response data stored in the multidimensional array `response`. The vector `frequency` represents the underlying frequencies for the frequency response data. See Data Format for the Argument Response in FRD Models for a list of response data formats.

`sys = frd(response,frequency,Ts)` creates a discrete-time `frd` model object `sys` with scalar sample time `Ts`. Set `Ts` = -1 to create a discrete-time `frd` model object without specifying the sample time.

`sys = frd` creates an empty `frd` model object.

The input argument list for any of these syntaxes can be followed by property name/property value pairs of the form

```
'PropertyName',PropertyValue
```

You can use these extra arguments to set the various properties the model. For more information about available properties of `frd` models, see "Properties" on page 1-187.

To force an FRD model `sys` to inherit all of its generic LTI properties from any existing LTI model `refsys`, use the syntax

```
sys = frd(response,frequency,ltisys)
```

`sysfrd = frd(sys,frequency)` converts a dynamic system model `sys` to frequency response data form. The frequency response is computed at the frequencies provided by the vector `frequency`, in `rad/TimeUnit`, where `TimeUnit` is the time units of the input dynamic system, specified in the TimeUnit property of sys.

`sysfrd = frd(sys,frequency,units)` converts a dynamic system model to an `frd` model and interprets frequencies in the `frequency` vector to have the units specified by the string `units`. For a list of values for the string `units`, see the `FrequencyUnit` property in “Properties” on page 1-187.

Arguments

When you specify a SISO or MIMO FRD model, or an array of FRD models, the input argument `frequency` is always a vector of length `Nf`, where `Nf` is the number of frequency data points in the FRD. The specification of the input argument `response` is summarized in the following table.

Data Format for the Argument Response in FRD Models

Model Form	Response Data Format
SISO model	Vector of length `Nf` for which `response(i)` is the frequency response at the frequency `frequency(i)`
MIMO model with `Ny` outputs and `Nu` inputs	`Ny`-by-`Nu`-by-`Nf` multidimensional array for which `response(i,j,k)` specifies the frequency response from input `j` to output `i` at frequency `frequency(k)`
`S1`-by-`...`-by-`Sn` array of models with `Ny` outputs and `Nu` inputs	Multidimensional array of size `[Ny Nu S1 ... Sn]` for which `response(i,j,k,:)` specifies the array of frequency response data from input `j` to output `i` at frequency `frequency(k)`

Properties

`frd` objects have the following properties:

`Frequency`

Frequency points of the frequency response data. Specify `Frequency` values in the units specified by the `FrequencyUnit` property.

FrequencyUnit

Frequency units of the model.

`FrequencyUnit` is a string that specifies the units of the frequency vector in the `Frequency` property. Set `FrequencyUnit` to one of the following values:

- `'rad/TimeUnit'`
- `'cycles/TimeUnit'`
- `'rad/s'`
- `'Hz'`
- `'kHz'`
- `'MHz'`
- `'GHz'`
- `'rpm'`

The units `'rad/TimeUnit'` and `'cycles/TimeUnit'` are relative to the time units specified in the `TimeUnit` property.

Changing this property changes the overall system behavior. Use `chgFreqUnit` to convert between frequency units without modifying system behavior.

Default: `'rad/TimeUnit'`

ResponseData

Frequency response data.

The `'ResponseData'` property stores the frequency response data as a 3-D array of complex numbers. For SISO systems, `'ResponseData'` is a vector of frequency response values at the frequency points specified in the `'Frequency'` property. For MIMO systems with `Nu` inputs and `Ny` outputs, `'ResponseData'` is an array of size `[Ny Nu Nw]`, where `Nw` is the number of frequency points.

ioDelay

Transport delays. `ioDelay` is a numeric array specifying a separate transport delay for each input/output pair.

For continuous-time systems, specify transport delays in the time unit stored in the `TimeUnit` property. For discrete-time systems, specify transport delays in integer multiples of the sample time, `Ts`.

For a MIMO system with `Ny` outputs and `Nu` inputs, set `ioDelay` to a `Ny`-by-`Nu` array. Each entry of this array is a numerical value that represents the transport delay for the corresponding input/output pair. You can also set `ioDelay` to a scalar value to apply the same delay to all input/output pairs.

Default: `0` for all input/output pairs

`InputDelay`

Input delay for each input channel, specified as a scalar value or numeric vector. For continuous-time systems, specify input delays in the time unit stored in the `TimeUnit` property. For discrete-time systems, specify input delays in integer multiples of the sample time `Ts`. For example, `InputDelay = 3` means a delay of three sample times.

For a system with `Nu` inputs, set `InputDelay` to an `Nu`-by-1 vector. Each entry of this vector is a numerical value that represents the input delay for the corresponding input channel.

You can also set `InputDelay` to a scalar value to apply the same delay to all channels.

Default: 0

`OutputDelay`

Output delays. `OutputDelay` is a numeric vector specifying a time delay for each output channel. For continuous-time systems, specify output delays in the time unit stored in the `TimeUnit` property. For discrete-time systems, specify output delays in integer multiples of the sample time `Ts`. For example, `OutputDelay = 3` means a delay of three sampling periods.

For a system with `Ny` outputs, set `OutputDelay` to an `Ny`-by-1 vector, where each entry is a numerical value representing the output delay for the corresponding output channel. You can also set `OutputDelay` to a scalar value to apply the same delay to all channels.

Default: 0 for all output channels

`Ts`

Sample time. For continuous-time models, `Ts = 0`. For discrete-time models, `Ts` is a positive scalar representing the sampling period. This value is expressed in the unit specified by the `TimeUnit` property of the model. To denote a discrete-time model with unspecified sample time, set `Ts = -1`.

Changing this property does not discretize or resample the model. Use `c2d` and `d2c` to convert between continuous- and discrete-time representations. Use `d2d` to change the sample time of a discrete-time system.

Default: `0` (continuous time)

`TimeUnit`

String representing the unit of the time variable. This property specifies the units for the time variable, the sample time `Ts`, and any time delays in the model. Use any of the following values:

- `'nanoseconds'`
- `'microseconds'`
- `'milliseconds'`
- `'seconds'`
- `'minutes'`
- `'hours'`
- `'days'`
- `'weeks'`
- `'months'`
- `'years'`

Changing this property has no effect on other properties, and therefore changes the overall system behavior. Use `chgTimeUnit` to convert between time units without modifying system behavior.

Default: `'seconds'`

`InputName`

Input channel names. Set `InputName` to a string for single-input model. For a multi-input model, set `InputName` to a cell array of strings.

Alternatively, use automatic vector expansion to assign input names for multi-input models. For example, if `sys` is a two-input model, enter:

```
sys.InputName = 'controls';
```

The input names automatically expand to `{'controls(1)';'controls(2)'}`.

You can use the shorthand notation `u` to refer to the `InputName` property. For example, `sys.u` is equivalent to `sys.InputName`.

Input channel names have several uses, including:

- Identifying channels on model display and plots
- Extracting subsystems of MIMO systems
- Specifying connection points when interconnecting models

Default: Empty string `''` for all input channels

InputUnit

Input channel units. Use `InputUnit` to keep track of input signal units. For a single-input model, set `InputUnit` to a string. For a multi-input model, set `InputUnit` to a cell array of strings. `InputUnit` has no effect on system behavior.

Default: Empty string `''` for all input channels

InputGroup

Input channel groups. The `InputGroup` property lets you assign the input channels of MIMO systems into groups and refer to each group by name. Specify input groups as a structure. In this structure, field names are the group names, and field values are the input channels belonging to each group. For example:

```
sys.InputGroup.controls = [1 2];
sys.InputGroup.noise = [3 5];
```

creates input groups named `controls` and `noise` that include input channels 1, 2 and 3, 5, respectively. You can then extract the subsystem from the `controls` inputs to all outputs using:

```
sys(:,'controls')
```

Default: Struct with no fields

OutputName

Output channel names. Set `OutputName` to a string for single-output model. For a multi-output model, set `OutputName` to a cell array of strings.

Alternatively, use automatic vector expansion to assign output names for multi-output models. For example, if `sys` is a two-output model, enter:

```
sys.OutputName = 'measurements';
```

The output names automatically expand to
`{'measurements(1)';'measurements(2)'}`.

You can use the shorthand notation `y` to refer to the `OutputName` property. For example, `sys.y` is equivalent to `sys.OutputName`.

Output channel names have several uses, including:

- Identifying channels on model display and plots
- Extracting subsystems of MIMO systems
- Specifying connection points when interconnecting models

Default: Empty string `''` for all output channels

OutputUnit

Output channel units. Use `OutputUnit` to keep track of output signal units. For a single-output model, set `OutputUnit` to a string. For a multi-output model, set `OutputUnit` to a cell array of strings. `OutputUnit` has no effect on system behavior.

Default: Empty string `''` for all output channels

OutputGroup

Output channel groups. The `OutputGroup` property lets you assign the output channels of MIMO systems into groups and refer to each group by name. Specify output groups as a structure. In this structure, field names are the group names, and field values are the output channels belonging to each group. For example:

```
sys.OutputGroup.temperature = [1];
sys.InputGroup.measurement = [3 5];
```

creates output groups named `temperature` and `measurement` that include output channels 1, and 3, 5, respectively. You can then extract the subsystem from all inputs to the `measurement` outputs using:

```
sys('measurement',:)
```

Default: Struct with no fields

Name

System name. Set `Name` to a string to label the system.

Default: `''`

Notes

Any text that you want to associate with the system. Set `Notes` to a string or a cell array of strings.

Default: `{}`

UserData

Any type of data you wish to associate with system. Set `UserData` to any MATLAB data type.

Default: `[]`

SamplingGrid

Sampling grid for model arrays, specified as a data structure.

For model arrays that are derived by sampling one or more independent variables, this property tracks the variable values associated with each model in the array. This information appears when you display or plot the model array. Use this information to trace results back to the independent variables.

Set the field names of the data structure to the names of the sampling variables. Set the field values to the sampled variable values associated with each model in the array. All sampling variables should be numeric and scalar valued, and all arrays of sampled values should match the dimensions of the model array.

For example, suppose you create a 11-by-1 array of linear models, `sysarr`, by taking snapshots of a linear time-varying system at times `t = 0:10`. The following code stores the time samples with the linear models.

```
sysarr.SamplingGrid = struct('time',0:10)
```

Similarly, suppose you create a 6-by-9 model array, `M`, by independently sampling two variables, `zeta` and `w`. The following code attaches the `(zeta,w)` values to `M`.

```
[zeta,w] = ndgrid(<6 values of zeta>,<9 values of w>)
M.SamplingGrid = struct('zeta',zeta,'w',w)
```

When you display `M`, each entry in the array includes the corresponding `zeta` and `w` values.

```
M
```

```
M(:,:,1,1) [zeta=0.3, w=5] =

        25
  --------------
  s^2 + 3 s + 25


M(:,:,2,1) [zeta=0.35, w=5] =

         25
  ----------------
  s^2 + 3.5 s + 25

...
```

For model arrays generated by linearizing a Simulink® model at multiple parameter values or operating points, the software populates `SamplingGrid` automatically with the variable values that correspond to each entry in the array. For example, the Simulink Control Design™ commands `linearize` and `slLinearizer` populate `SamplingGrid` in this way.

Default: `[]`

Examples

Create Frequency-Response Model

Create a SISO FRD model from a frequency vector and response data:

```
% generate a frequency vector and response data
freq = logspace(1,2);
resp = .05*(freq).*exp(i*2*freq);
% Create a FRD model
sys = frd(resp,freq);
```

More About

- “What Are Model Objects?”
- “Frequency Response Data (FRD) Models”

See Also

`chgTimeUnit` | `chgFreqUnit` | `frdata` | `set` | `ss` | `tf` | `zpk` | `idfrd`

frdata

Access data for frequency response data (FRD) object

Syntax

```
[response,freq] = frdata(sys)
[response,freq,covresp] = frdata(sys)
[response,freq,Ts,covresp] = frdata(sys,'v')
[response,freq,Ts] = frdata(sys)
```

Description

`[response,freq] = frdata(sys)` returns the response data and frequency samples of the FRD model `sys`. For an FRD model with `Ny` outputs and `Nu` inputs at `Nf` frequencies:

- `response` is an `Ny`-by-`Nu`-by-`Nf` multidimensional array where the `(i,j)` entry specifies the response from input `j` to output `i`.
- `freq` is a column vector of length `Nf` that contains the frequency samples of the FRD model.

See the `frd` reference page for more information on the data format for FRD response data.

`[response,freq,covresp] = frdata(sys)` also returns the covariance `covresp` of the response data `resp` for `idfrd` model `sys`. (Using `idfrd` models requires System Identification Toolbox software.) The covariance `covresp` is a 5D-array where `covH(i,j,k,:,:)` contains the 2-by-2 covariance matrix of the response `resp(i,j,k)`. The `(1,1)` element is the variance of the real part, the `(2,2)` element the variance of the imaginary part and the `(1,2)` and `(2,1)` elements the covariance between the real and imaginary parts.

For SISO FRD models, the syntax

```
[response,freq] = frdata(sys,'v')
```

forces `frdata` to return the response data as a column vector rather than a 3-dimensional array (see example below). Similarly `[response,freq,Ts,covresp] = frdata(sys,'v')` for an IDFRD model sys returns covresp as a 3-dimensional rather than a 5-dimensional array.

`[response,freq,Ts] = frdata(sys)` also returns the sample time `Ts`.

Other properties of `sys` can be accessed with `get` or by direct structure-like referencing (e.g., `sys.Frequency`).

Arguments

The input argument `sys` to `frdata` must be an FRD model.

Examples

Extract Data from Frequency Response Data Model

Create a frequency response data model and extract the frequency response data.

Create a frequency response data by computing the response of a transfer function on a grid of frequencies.

```
H = tf([-1.2,-2.4,-1.5],[1,20,9.1]);
w = logspace(-2,3,101);
sys = frd(H,w);
```

`sys` is a SISO frequency response data (`frd`) model containing the frequency response at 101 frequencies.

Extract the frequency response data from `sys`.

```
[response,freq] = frdata(sys);
```

`response` is a 1-by-1-by-101 array. `response(1,1,k)` is the complex frequency response at the frequency `freq(k)`.

See Also

`frd` | `get` | `set` | `freqresp`

freqresp

Frequency response over grid

Syntax

```
[H,wout] = freqresp(sys)
H = freqresp(sys,w)
H = freqresp(sys,w,units)
[H,wout,covH] = freqresp(idsys,...)
```

Description

`[H,wout] = freqresp(sys)` returns the frequency response of the dynamic system model sys at frequencies wout. The `freqresp` command automatically determines the frequencies based on the dynamics of sys.

`H = freqresp(sys,w)` returns the frequency response on the real frequency grid specified by the vector `w`.

`H = freqresp(sys,w,units)` explicitly specifies the frequency units of w with the string units.

`[H,wout,covH] = freqresp(idsys,...)` also returns the covariance covH of the frequency response of the identified model idsys.

Input Arguments

`sys`

Any dynamic system model or model array.

`w`

Vector of real frequencies at which to evaluate the frequency response. Specify frequencies in units of `rad/TimeUnit`, where `TimeUnit` is the time units specified in the TimeUnit property of sys.

units

String specifying the units of the frequencies in the input frequency vector w. Units can take the following values:

- 'rad/TimeUnit' — radians per the time unit specified in the TimeUnit property of sys
- 'cycles/TimeUnit' — cycles per the time unit specified in the TimeUnit property of sys
- 'rad/s'
- 'Hz'
- 'kHz'
- 'MHz'
- 'GHz'
- 'rpm'

Default: 'rad/TimeUnit'

idsys

Any identified model.

Output Arguments

H

Array containing the frequency response values.

If sys is an individual dynamic system model having Ny outputs and Nu inputs, H is a 3D array with dimensions Ny-by-Nu-by-Nw, where Nw is the number of frequency points. Thus, H(:,:,k) is the response at the frequency w(k) or wout(k).

If sys is a model array of size [Ny Nu S1 ... Sn], H is an array with dimensions Ny-by-Nu-by-Nw-by-S1-by-...-by-Sn] array.

If sys is a frequency response data model (such as frd, genfrd, or idfrd), freqresp(sys,w) evaluates to NaN for values of w falling outside the frequency interval defined by `sys.frequency`. The `freqresp` command can interpolate between frequencies in `sys.frequency`. However, `freqresp` cannot extrapolate beyond the frequency interval defined by `sys.frequency`.

wout

Vector of frequencies corresponding to the frequency response values in `H`. If you omit w from the inputs to `freqresp`, the command automatically determines the frequencies of wout based on the system dynamics. If you specify w, then wout = w

covH

Covariance of the response H. The covariance is a 5D array where `covH(i,j,k,:,:)` contains the 2-by-2 covariance matrix of the response from the `i`th input to the `j`th output at frequency `w(k)`. The (1,1) element of this 2-by-2 matrix is the variance of the real part of the response. The (2,2) element is the variance of the imaginary part. The (1,2) and (2,1) elements are the covariance between the real and imaginary parts of the response.

Examples

Frequency Response

Compute the frequency response of the 2-input, 2-output system

$$sys = \begin{bmatrix} 0 & \dfrac{1}{s+1} \\ \dfrac{s-1}{s+2} & 1 \end{bmatrix}$$

```
sys11 = 0;
sys22 = 1;
sys12 = tf(1,[1 1]);
sys21 = tf([1 -1],[1 2]);
sys = [sys11,sys12;sys21,sys22];

[H,wout] = freqresp(sys);
```

H is a 2-by-2-by-45 array. Each entry `H(:,:,k)` in H is a 2-by-2 matrix giving the complex frequency response of all input-output pairs of `sys` at the corresponding frequency `wout(k)`. The 45 frequencies in `wout` are automatically selected based on the dynamics of `sys`.

Response on Specified Frequency Grid

Compute the frequency response of the 2-input, 2-output system

$$sys = \begin{bmatrix} 0 & \dfrac{1}{s+1} \\ \dfrac{s-1}{s+2} & 1 \end{bmatrix}$$

on a logarithmically-spaced grid of 200 frequency points between 10 and 100 radians per second.

```
sys11 = 0;
sys22 = 1;
sys12 = tf(1,[1 1]);
sys21 = tf([1 -1],[1 2]);
sys = [sys11,sys12;sys21,sys22];

w = logspace(1,2,200);

H = freqresp(sys,w);
```

H is a 2-by-2-by-200 array. Each entry `H(:,:,k)` in H is a 2-by-2 matrix giving the complex frequency response of all input-output pairs of `sys` at the corresponding frequency `w(k)`.

Frequency Response and Associated Covariance

Compute the frequency response and associated covariance for an identified model at its peak response frequency.

```
load iddata1 z1
model = procest(z1, 'P2UZ');
w = 4.26;
```

```
[H,~,covH] = freqresp(model, w)
```

Alternatives

Use `evalfr` to evaluate the frequency response at individual frequencies or small numbers of frequencies. `freqresp` is optimized for medium-to-large vectors of frequencies.

More About

Frequency Response

In continuous time, the *frequency response* at a frequency ω is the transfer function value at $s = j\omega$. For state-space models, this value is given by

$$H(j\omega) = D + C(j\omega I - A)^{-1}B$$

In discrete time, the frequency response is the transfer function evaluated at points on the unit circle that correspond to the real frequencies. `freqresp` maps the real frequencies `w(1)`,..., `w(N)` to points on the unit circle using the transformation $z = e^{j\omega T_s}$. T_s is the sample time. The function returns the values of the transfer function at the resulting z values. For models with unspecified sample time, `freqresp` uses $T_s = 1$.

Algorithms

For transfer functions or zero-pole-gain models, `freqresp` evaluates the numerator(s) and denominator(s) at the specified frequency points. For continuous-time state-space models (A, B, C, D), the frequency response is

$$D + C(j\omega - A)^{-1}B, \quad \omega = \omega_1, \ldots, \omega_N$$

For efficiency, A is reduced to upper Hessenberg form and the linear equation $(j\omega - A)X = B$ is solved at each frequency point, taking advantage of the Hessenberg structure. The reduction to Hessenberg form provides a good compromise between efficiency and reliability. See [1] for more details on this technique.

References

[1] Laub, A.J., "Efficient Multivariable Frequency Response Computations," *IEEE Transactions on Automatic Control*, AC-26 (1981), pp. 407-408.

See Also

`bode` | `nyquist` | `interp` | `evalfr` | `nichols` | `sigma` | `linearSystemAnalyzer` | `spectrum`

freqsep

Slow-fast decomposition

Syntax

```
[Gs,Gf] = freqsep(G,fcut)
[Gs,Gf] = freqsep(G,fcut,options)
```

Description

`[Gs,Gf] = freqsep(G,fcut)` decomposes a linear dynamic system into slow and fast components around the specified cutoff frequency. The decomposition is such that G = Gs + Gf.

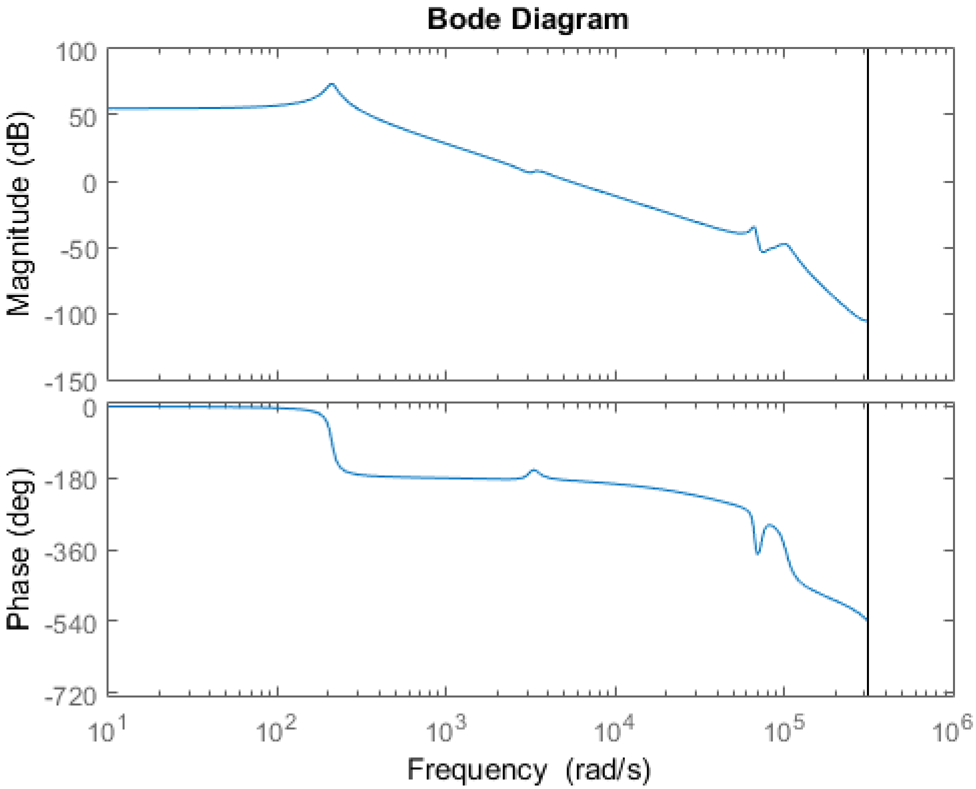
`[Gs,Gf] = freqsep(G,fcut,options)` specifies additional options for the decomposition.

Examples

Decompose Model into Fast and Slow Dynamics

Load a dynamic system model.

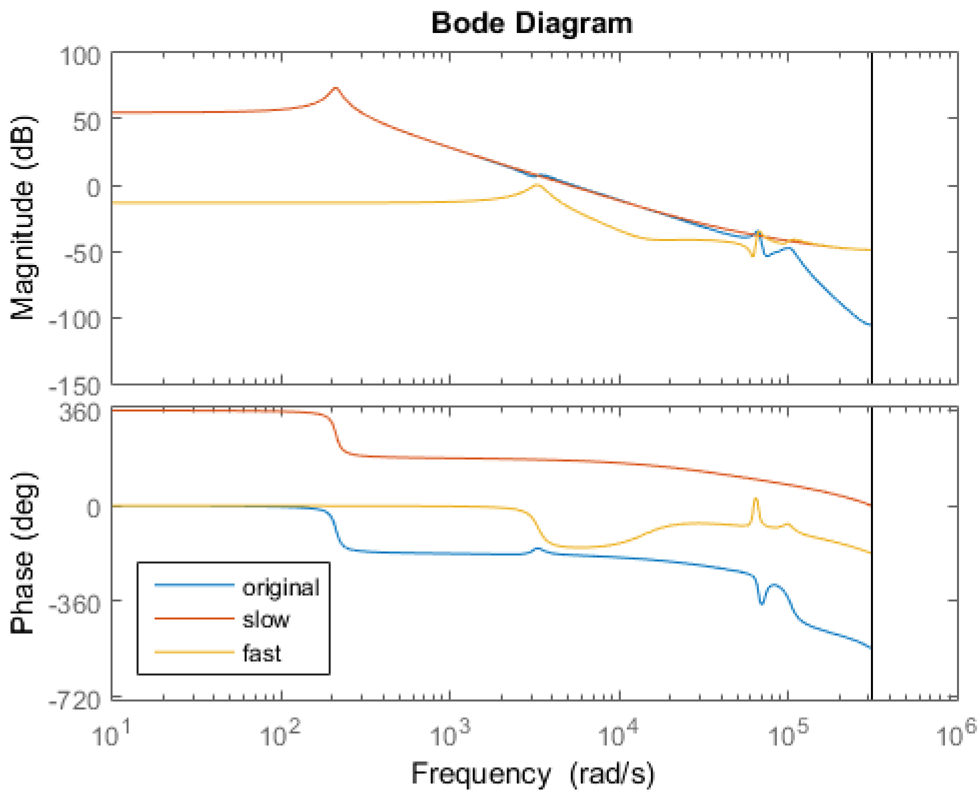
```
load numdemo Pd
bode(Pd)
```



`Pd` has four complex poles and one real pole. The Bode plot shows a resonance around 210 rad/s and a higher-frequency resonance below 10,000 rad/s.

Decompose this model around 1000 rad/s to separate these two resonances.

```
[Gs,Gf] = freqsep(Pd,10^3);
bode(Pd,Gs,Gf)
legend('original','slow','fast','Location','Southwest')
```



The Bode plot shows that the slow component, `Gs`, contains only the lower-frequency resonance. This component also matches the DC gain of the original model. The fast component, `Gf`, contains the higher-frequency resonances and matches the response of the original model at high frequencies. The sum of the two components `Gs+Gf` yields the original model.

Separate Nearby Modes by Adjusting Tolerance

Decompose a model into slow and fast components between poles that are closely spaced.

The following system includes a real pole and a complex pair of poles that are all close to s = -2.

```
G = zpk(-.5,[-1.9999 -2+1e-4i -2-1e-4i],10);
```

Try to decompose the model about 2 rad/s, so that the slow component cotains the real pole and the fast component contains the complex pair.

```
[Gs,Gf] = freqsep(G,2);
```

```
Warning: One or more fast modes could not be separated from the slow modes. To
force separation, increase the absolute or relative tolerances ("AbsTol" and
"RelTol" options). Type "help freqsepOptions" for more information.
```

These poles are too close together for `freqsep` to separate. Increase the relative tolerance to allow the separation.

```
options = freqsepOptions('RelTol',1e-4);
[Gs,Gf] = freqsep(G,2,options);
```

Now `freqsep` successfully separates the dynamics about 2 rad/s.

```
slowpole = pole(Gs)
fastpole = pole(Gf)
```

```
slowpole =

   -1.9999


fastpole =

  -2.0000 + 0.0001i
  -2.0000 - 0.0001i
```

Input Arguments

`G` — Dynamic system to decompose

numeric LTI model

Dynamic system to decompose, specified as a numeric LTI model, such as a `ss` or `tf` model.

`fcut` — Cutoff frequency

positive scalar

Cutoff frequency for fast-slow decomposition, specified as a positive scalar. The output Gs contains all poles with natural frequency less than fcut. The output Gf contains all poles with natural frequency greater than or equal to fcut.

`options` — Options for decomposition

`freqsepOptions` options set

Options for the decomposition, specified as an options set you create with `freqsepOptions`. Available options include absolute and relative tolerance for accuracy of the decomposed systems.

Output Arguments

`Gs` — Slow dynamics

numeric LTI model

Slow dynamics of the decomposed system, returned as a numeric LTI model of the same type as G. Gs contains all poles of G with natural frequency less than fcut, and is such that G = Gs + Gf.

`Gf` — Fast dynamics

numeric LTI model

Fast dynamics of the decomposed system, returned as a numeric LTI model of the same type as G. Gf contains all poles of G with natural frequency greater than or equal to fcut, and is such that G = Gs + Gf.

See Also

`freqsepOptions`

freqsepOptions

Options for slow-fast decomposition

Syntax

```
opt = freqsepOptions
opt = freqsepOptions(Name,Value)
```

Description

`opt = freqsepOptions` returns the default options for `freqsep`.

`opt = freqsepOptions(Name,Value)` returns an options set with the options specified by one or more Name,Value pair arguments.

Examples

Separate Nearby Modes by Adjusting Tolerance

Decompose a model into slow and fast components between poles that are closely spaced.

The following system includes a real pole and a complex pair of poles that are all close to s = -2.

```
G = zpk(-.5,[-1.9999 -2+1e-4i -2-1e-4i],10);
```

Try to decompose the model about 2 rad/s, so that the slow component cotains the real pole and the fast component contains the complex pair.

```
[Gs,Gf] = freqsep(G,2);
```

```
Warning: One or more fast modes could not be separated from the slow modes. To
force separation, increase the absolute or relative tolerances ("AbsTol" and
"RelTol" options). Type "help freqsepOptions" for more information.
```

These poles are too close together for `freqsep` to separate. Increase the relative tolerance to allow the separation.

```
options = freqsepOptions('RelTol',1e-4);
[Gs,Gf] = freqsep(G,2,options);
```

Now `freqsep` successfully separates the dynamics about 2 rad/s.

```
slowpole = pole(Gs)
fastpole = pole(Gf)
```

```
slowpole =

   -1.9999


fastpole =

  -2.0000 + 0.0001i
  -2.0000 - 0.0001i
```

Input Arguments

Name-Value Pair Arguments

Specify optional comma-separated pairs of Name,Value arguments. `Name` is the argument name and `Value` is the corresponding value. `Name` must appear inside single quotes (`' '`). You can specify several name and value pair arguments in any order as `Name1,Value1,...,NameN,ValueN`.

Example: `'AbsTol',1e-4`

`'AbsTol'` — Absolute tolerance for decomposition

0 (default) | nonnegative scalar

Absolute tolerance for slow-fast decomposition, specified as a nonnegative scalar value. `freqresp` ensures that the frequency responses of the original system, `G`, and the sum of the decomposed systems `Gs+Gf`, differ by no more than `AbsTol + RelTol*abs(G)`. Increase `AbsTol` to help separate nearby modes, at the expense of the accuracy of the decomposition.

`'RelTol'` — Relative tolerance for decomposition

`1e-8` (default) | nonnegative scalar

Relative tolerance for slow-fast decomposition, specified as a nonnegative scalar value. `freqresp` ensures that the frequency responses of the original system, `G`, and the sum of the decomposed systems `Gs+Gf`, differ by no more than `AbsTol + RelTol*abs(G)`. Increase `RelTol` to help separate nearby modes, at the expense of the accuracy of the decomposition.

Output Arguments

`opt` — Options for `freqsep`

`freqsepOptions` options set

Options for `freqsep`, returned as a `freqsepOptions` options set. Use opt as the last argument to `freqsep` when computing slow-fast decomposition.

See Also

`freqsep`

fselect

Select frequency points or range in FRD model

Syntax

```
subsys = fselect(sys,fmin,fmax)
subsys = fselect(sys,index)
```

Description

`subsys = fselect(sys,fmin,fmax)` takes an FRD model sys and selects the portion of the frequency response between the frequencies `fmin` and `fmax`. The selected range `[fmin,fmax]` should be expressed in the FRD model units. For an IDFRD model (requires System Identification Toolbox software), the `SpectrumData`, `CovarianceData` and `NoiseCovariance` values, if non-empty, are also selected in the chosen range.

`subsys = fselect(sys,index)` selects the frequency points specified by the vector of indices index. The resulting frequency grid is

```
sys.Frequency(index)
```

See Also

`fcat` | `fdel` | `interp` | `frd`

gcare

Generalized solver for continuous-time algebraic Riccati equation

Syntax

```
[X,L,report] = gcare(H,J,ns)
[X1,X2,D,L] = gcare(H,...,'factor')
```

Description

`[X,L,report] = gcare(H,J,ns)` computes the unique stabilizing solution X of the continuous-time algebraic Riccati equation associated with a Hamiltonian pencil of the form

$$H - tJ = \begin{bmatrix} A & F & S1 \\ G & -A' & -S2 \\ S2' & S1' & R \end{bmatrix} - \begin{bmatrix} E & 0 & 0 \\ 0 & E' & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

The optional input `ns` is the row size of the A matrix. Default values for `J` and `ns` correspond to $E = I$ and $R = [\,]$.

Optionally, `gcare` returns the vector `L` of closed-loop eigenvalues and a diagnosis `report` with value:

- -1 if the Hamiltonian pencil has jw-axis eigenvalues
- -2 if there is no finite stabilizing solution `X`
- 0 if a finite stabilizing solution `X` exists

This syntax does not issue any error message when `X` fails to exist.

`[X1,X2,D,L] = gcare(H,...,'factor')` returns two matrices `X1`, `X2` and a diagonal scaling matrix `D` such that `X = D*(X2/X1)*D`. The vector `L` contains the closed-loop eigenvalues. All outputs are empty when the associated Hamiltonian matrix has eigenvalues on the imaginary axis.

See Also

`care` | `gdare`

gdare

Generalized solver for discrete-time algebraic Riccati equation

Syntax

```
[X,L,report] = gdare(H,J,ns)
[X1,X2,D,L] = gdare(H,J,NS,'factor')
```

Description

`[X,L,report] = gdare(H,J,ns)` computes the unique stabilizing solution `X` of the discrete-time algebraic Riccati equation associated with a Symplectic pencil of the form

$$H - tJ = \begin{bmatrix} A & F & B \\ -Q & E' & -S \\ S' & 0 & R \end{bmatrix} - \begin{bmatrix} E & 0 & 0 \\ 0 & A' & 0 \\ 0 & B' & 0 \end{bmatrix}$$

The third input `ns` is the row size of the A matrix.

Optionally, `gdare` returns the vector `L` of closed-loop eigenvalues and a diagnosis `report` with value:

- -1 if the Symplectic pencil has eigenvalues on the unit circle
- -2 if there is no finite stabilizing solution `X`
- 0 if a finite stabilizing solution `X` exists

This syntax does not issue any error message when `X` fails to exist.

`[X1,X2,D,L] = gdare(H,J,NS,'factor')` returns two matrices `X1`, `X2` and a diagonal scaling matrix `D` such that `X = D*(X2/X1)*D`. The vector `L` contains the closed-loop eigenvalues. All outputs are empty when the Symplectic pencil has eigenvalues on the unit circle.

See Also

`dare` | `gcare`

genfrd

Generalized frequency response data (FRD) model

Description

Generalized FRD (`genfrd`) models arise when you combine numeric FRD models with models containing tunable components (Control Design Blocks). `genfrd` models keep track of how the tunable blocks interact with the tunable components. For more information about Control Design Blocks, see "Generalized Models".

Construction

To construct a `genfrd` model, use `series`, `parallel`, `lft`, or `connect`, or the arithmetic operators `+`, `-`, `*`, `/`, `\`, and `^`, to combine a numeric FRD model with control design blocks.

You can also convert any numeric LTI model or control design block `sys` to `genfrd` form.

`frdsys = genfrd(sys,freqs,frequnits)` converts any static model or dynamic system sys to a generalized FRD model. If sys is not an `frd` model object, `genfrd` computes the frequency response of each frequency point in the vector freqs. The frequencies freqs are in the units specified by the optional argument frequnits. If frequnits is omitted, the units of freqs are `'rad/TimeUnit'`.

`frdsys = genfrd(sys,freqs,frequnits,timeunits)` further specifies the time units for converting sys to `genfrd` form.

For more information about time and frequency units of `genfrd` models, see "Properties" on page 1-218.

Input Arguments

`sys`

A static model or dynamic system model object.

freqs

Vector of frequency points. Express frequencies in the unit specified in frequnits.

frequnits

String specifying the frequency units of the `genfrd` model. Set frequnits to one of the following values:

- `'rad/TimeUnit'`
- `'cycles/TimeUnit'`
- `'rad/s'`
- `'Hz'`
- `'kHz'`
- `'MHz'`
- `'GHz'`
- `'rpm'`

Default: `'rad/TimeUnit'`

timeunits

String specifying the time units of the `genfrd` model. Set timeunits to one of the following values:

- `'nanoseconds'`
- `'microseconds'`
- `'milliseconds'`
- `'seconds'`
- `'minutes'`
- `'hours'`
- `'days'`
- `'weeks'`
- `'months'`
- `'years'`

Default: `'seconds'`

Properties

`Blocks`

Structure containing the control design blocks included in the generalized LTI model or generalized matrix. The field names of `Blocks` are the `Name` property of each control design block.

You can change some attributes of these control design blocks using dot notation. For example, if the generalized LTI model or generalized matrix `M` contains a `realp` tunable parameter `a`, you can change the current value of `a` using:

```
M.Blocks.a.Value = -1;
```

`Frequency`

Frequency points of the frequency response data. Specify `Frequency` values in the units specified by the `FrequencyUnit` property.

`FrequencyUnit`

Frequency units of the model.

`FrequencyUnit` is a string that specifies the units of the frequency vector in the `Frequency` property. Set `FrequencyUnit` to one of the following values:

- `'rad/TimeUnit'`
- `'cycles/TimeUnit'`
- `'rad/s'`
- `'Hz'`
- `'kHz'`
- `'MHz'`
- `'GHz'`
- `'rpm'`

The units `'rad/TimeUnit'` and `'cycles/TimeUnit'` are relative to the time units specified in the `TimeUnit` property.

Changing this property changes the overall system behavior. Use `chgFreqUnit` to convert between frequency units without modifying system behavior.

Default: `'rad/TimeUnit'`

`InputDelay`

Input delay for each input channel, specified as a scalar value or numeric vector. For continuous-time systems, specify input delays in the time unit stored in the `TimeUnit` property. For discrete-time systems, specify input delays in integer multiples of the sample time `Ts`. For example, `InputDelay = 3` means a delay of three sample times.

For a system with `Nu` inputs, set `InputDelay` to an `Nu`-by-1 vector. Each entry of this vector is a numerical value that represents the input delay for the corresponding input channel.

You can also set `InputDelay` to a scalar value to apply the same delay to all channels.

Default: 0

`OutputDelay`

Output delays. `OutputDelay` is a numeric vector specifying a time delay for each output channel. For continuous-time systems, specify output delays in the time unit stored in the `TimeUnit` property. For discrete-time systems, specify output delays in integer multiples of the sample time `Ts`. For example, `OutputDelay = 3` means a delay of three sampling periods.

For a system with `Ny` outputs, set `OutputDelay` to an `Ny`-by-1 vector, where each entry is a numerical value representing the output delay for the corresponding output channel. You can also set `OutputDelay` to a scalar value to apply the same delay to all channels.

Default: 0 for all output channels

`Ts`

Sample time. For continuous-time models, `Ts = 0`. For discrete-time models, `Ts` is a positive scalar representing the sampling period. This value is expressed in the unit specified by the `TimeUnit` property of the model. To denote a discrete-time model with unspecified sample time, set `Ts = -1`.

Changing this property does not discretize or resample the model. Use `c2d` and `d2c` to convert between continuous- and discrete-time representations. Use `d2d` to change the sample time of a discrete-time system.

Default: `0` (continuous time)

`TimeUnit`

String representing the unit of the time variable. This property specifies the units for the time variable, the sample time `Ts`, and any time delays in the model. Use any of the following values:

- `'nanoseconds'`
- `'microseconds'`
- `'milliseconds'`
- `'seconds'`
- `'minutes'`
- `'hours'`
- `'days'`
- `'weeks'`
- `'months'`
- `'years'`

Changing this property has no effect on other properties, and therefore changes the overall system behavior. Use `chgTimeUnit` to convert between time units without modifying system behavior.

Default: `'seconds'`

`InputName`

Input channel names. Set `InputName` to a string for single-input model. For a multi-input model, set `InputName` to a cell array of strings.

Alternatively, use automatic vector expansion to assign input names for multi-input models. For example, if `sys` is a two-input model, enter:

```
sys.InputName = 'controls';
```

The input names automatically expand to `{'controls(1)';'controls(2)'}`.

You can use the shorthand notation `u` to refer to the `InputName` property. For example, `sys.u` is equivalent to `sys.InputName`.

Input channel names have several uses, including:

- Identifying channels on model display and plots
- Extracting subsystems of MIMO systems
- Specifying connection points when interconnecting models

Default: Empty string `''` for all input channels

`InputUnit`

Input channel units. Use `InputUnit` to keep track of input signal units. For a single-input model, set `InputUnit` to a string. For a multi-input model, set `InputUnit` to a cell array of strings. `InputUnit` has no effect on system behavior.

Default: Empty string `''` for all input channels

`InputGroup`

Input channel groups. The `InputGroup` property lets you assign the input channels of MIMO systems into groups and refer to each group by name. Specify input groups as a structure. In this structure, field names are the group names, and field values are the input channels belonging to each group. For example:

```
sys.InputGroup.controls = [1 2];
sys.InputGroup.noise = [3 5];
```

creates input groups named `controls` and `noise` that include input channels 1, 2 and 3, 5, respectively. You can then extract the subsystem from the `controls` inputs to all outputs using:

```
sys(:,'controls')
```

Default: Struct with no fields

`OutputName`

Output channel names. Set `OutputName` to a string for single-output model. For a multi-output model, set `OutputName` to a cell array of strings.

Alternatively, use automatic vector expansion to assign output names for multi-output models. For example, if `sys` is a two-output model, enter:

```
sys.OutputName = 'measurements';
```

The output names automatically expand to `{'measurements(1)';'measurements(2)'}`.

You can use the shorthand notation `y` to refer to the `OutputName` property. For example, `sys.y` is equivalent to `sys.OutputName`.

Output channel names have several uses, including:

- Identifying channels on model display and plots
- Extracting subsystems of MIMO systems
- Specifying connection points when interconnecting models

Default: Empty string `''` for all output channels

`OutputUnit`

Output channel units. Use `OutputUnit` to keep track of output signal units. For a single-output model, set `OutputUnit` to a string. For a multi-output model, set `OutputUnit` to a cell array of strings. `OutputUnit` has no effect on system behavior.

Default: Empty string `''` for all output channels

`OutputGroup`

Output channel groups. The `OutputGroup` property lets you assign the output channels of MIMO systems into groups and refer to each group by name. Specify output groups as a structure. In this structure, field names are the group names, and field values are the output channels belonging to each group. For example:

```
sys.OutputGroup.temperature = [1];
sys.InputGroup.measurement = [3 5];
```

creates output groups named `temperature` and `measurement` that include output channels 1, and 3, 5, respectively. You can then extract the subsystem from all inputs to the `measurement` outputs using:

```
sys('measurement',:)
```

Default: Struct with no fields

`Name`

System name. Set `Name` to a string to label the system.

Default: `''`

`Notes`

Any text that you want to associate with the system. Set `Notes` to a string or a cell array of strings.

Default: `{}`

`UserData`

Any type of data you wish to associate with system. Set `UserData` to any MATLAB data type.

Default: `[]`

`SamplingGrid`

Sampling grid for model arrays, specified as a data structure.

For model arrays that are derived by sampling one or more independent variables, this property tracks the variable values associated with each model in the array. This information appears when you display or plot the model array. Use this information to trace results back to the independent variables.

Set the field names of the data structure to the names of the sampling variables. Set the field values to the sampled variable values associated with each model in the array. All sampling variables should be numeric and scalar valued, and all arrays of sampled values should match the dimensions of the model array.

For example, suppose you create a 11-by-1 array of linear models, `sysarr`, by taking snapshots of a linear time-varying system at times `t = 0:10`. The following code stores the time samples with the linear models.

```
 sysarr.SamplingGrid = struct('time',0:10)
```

Similarly, suppose you create a 6-by-9 model array, `M`, by independently sampling two variables, `zeta` and `w`. The following code attaches the `(zeta,w)` values to `M`.

```
[zeta,w] = ndgrid(<6 values of zeta>,<9 values of w>)
M.SamplingGrid = struct('zeta',zeta,'w',w)
```

When you display `M`, each entry in the array includes the corresponding `zeta` and `w` values.

```
M

M(:,:,1,1) [zeta=0.3, w=5] =

        25
  --------------
  s^2 + 3 s + 25


M(:,:,2,1) [zeta=0.35, w=5] =

         25
  ----------------
  s^2 + 3.5 s + 25

...
```

For model arrays generated by linearizing a Simulink model at multiple parameter values or operating points, the software populates `SamplingGrid` automatically with the variable values that correspond to each entry in the array. For example, the Simulink Control Design commands `linearize` and `slLinearizer` populate `SamplingGrid` in this way.

Default: `[]`

More About

Tips

- You can manipulate `genfrd` models as ordinary `frd` models. Frequency-domain analysis commands such as `bode` evaluate the model by replacing each tunable parameter with its current value.
- "Models with Tunable Coefficients"
- "Generalized Models"

See Also

`frd` | `genss` | `getValue` | `chgFreqUnit`

genmat

Generalized matrix with tunable parameters

Description

Generalized matrices (`genmat`) are matrices that depend on tunable parameters (see `realp`). You can use generalized matrices for parameter studies. You can also use generalized matrices for building generalized LTI models (see `genss`) that represent control systems having a mixture of fixed and tunable components.

Construction

Generalized matrices arise when you combine numeric values with static blocks such as `realp`objects. You create such combinations using any of the arithmetic operators `+`, `-`, `*`, `/`, `\`, and `^`. For example, if `a` and `b` are tunable parameters, the expression `M = a + b` is represented as a generalized matrix.

A generalized matrix can represent a tunable gain surface for constructing gain-scheduled controllers. Use the Robust Control Toolbox command `gainsurf` to create such a tunable gain surface.

The internal data structure of the `genmat` object `M` keeps track of how `M` depends on the parameters `a` and `b`. The `Blocks` property of `M` lists the parameters `a` and `b`.

`M = genmat(A)` converts the numeric array or tunable parameter A into a `genmat` object.

Input Arguments

A

Static control design block, such as a `realp` object.

If A is a numeric array, `M` is a generalized matrix of the same dimensions as A, with no tunable parameters.

If A is a static control design block, `M` is a generalized matrix whose `Blocks` property lists A as the only block.

Properties

`Blocks`

Structure containing the control design blocks included in the generalized LTI model or generalized matrix. The field names of `Blocks` are the `Name` property of each control design block.

You can change some attributes of these control design blocks using dot notation. For example, if the generalized LTI model or generalized matrix `M` contains a `realp` tunable parameter `a`, you can change the current value of `a` using:

```
M.Blocks.a.Value = -1;
```

`SamplingGrid`

Sampling grid for model arrays, specified as a data structure.

For model arrays that are derived by sampling one or more independent variables, this property tracks the variable values associated with each model in the array. This information appears when you display or plot the model array. Use this information to trace results back to the independent variables.

Set the field names of the data structure to the names of the sampling variables. Set the field values to the sampled variable values associated with each model in the array. All sampling variables should be numeric and scalar valued, and all arrays of sampled values should match the dimensions of the model array.

For example, suppose you create a 11-by-1 array of linear models, `sysarr`, by taking snapshots of a linear time-varying system at times `t = 0:10`. The following code stores the time samples with the linear models.

```
 sysarr.SamplingGrid = struct('time',0:10)
```

Similarly, suppose you create a 6-by-9 model array, `M`, by independently sampling two variables, `zeta` and `w`. The following code attaches the `(zeta,w)` values to `M`.

```
[zeta,w] = ndgrid(<6 values of zeta>,<9 values of w>)
```

```
M.SamplingGrid = struct('zeta',zeta,'w',w)
```

When you display `M`, each entry in the array includes the corresponding `zeta` and `w` values.

```
M
```

```
M(:,:,1,1) [zeta=0.3, w=5] =

        25
  --------------
  s^2 + 3 s + 25


M(:,:,2,1) [zeta=0.35, w=5] =

         25
  ----------------
  s^2 + 3.5 s + 25

...
```

For model arrays generated by linearizing a Simulink model at multiple parameter values or operating points, the software populates `SamplingGrid` automatically with the variable values that correspond to each entry in the array. For example, the Simulink Control Design commands `linearize` and `slLinearizer` populate `SamplingGrid` in this way.

Default: `[]`

Examples

Generalized Matrix With Two Tunable Parameters

This example shows how to use algebraic combinations of tunable parameters to create the generalized matrix:

$$M = \begin{bmatrix} 1 & a+b \\ 0 & ab \end{bmatrix},$$

where a and b are tunable parameters with initial values –1 and 3, respectively.

1 Create the tunable parameters using `realp`.

```
a = realp('a',-1);
b = realp('b',3);
```

2 Define the generalized matrix using algebraic expressions of `a` and `b`.

```
M = [1 a+b;0 a*b]
```

`M` is a generalized matrix whose `Blocks` property contains `a` and `b`. The initial value of `M` is `M = [1 2;0 -3]`, from the initial values of `a` and `b`.

3 (Optional) Change the initial value of the parameter `a`.

```
M.Blocks.a.Value = -3;
```

4 (Optional) Use `double` to display the new value of `M`.

```
double(M)
```

The new value of `M` is `M = [1 0;0 -9]`.

More About

- "Models with Tunable Coefficients"
- "Dynamic System Models"

See Also

`realp` | `genss` | `getValue` | `gainsurf`

gensig

Generate test input signals for `lsim`

Syntax

```
[u,t] = gensig(type,tau)
[u,t] = gensig(type,tau,Tf,Ts)
```

Description

`[u,t] = gensig(type,tau)` generates a scalar signal `u` of class `type` and with period `tau` (in seconds). The following types of signals are available.

`'sin'`	Sine wave.
`'square'`	Square wave.
`'pulse'`	Periodic pulse.

`gensig` returns a vector `t` of time samples and the vector `u` of signal values at these samples. All generated signals have unit amplitude.

`[u,t] = gensig(type,tau,Tf,Ts)` also specifies the time duration `Tf` of the signal and the spacing `Ts` between the time samples `t`.

You can feed the outputs `u` and `t` directly to `lsim` and simulate the response of a single-input linear system to the specified signal. Since `t` is uniquely determined by `Tf` and `Ts`, you can also generate inputs for multi-input systems by repeated calls to `gensig`.

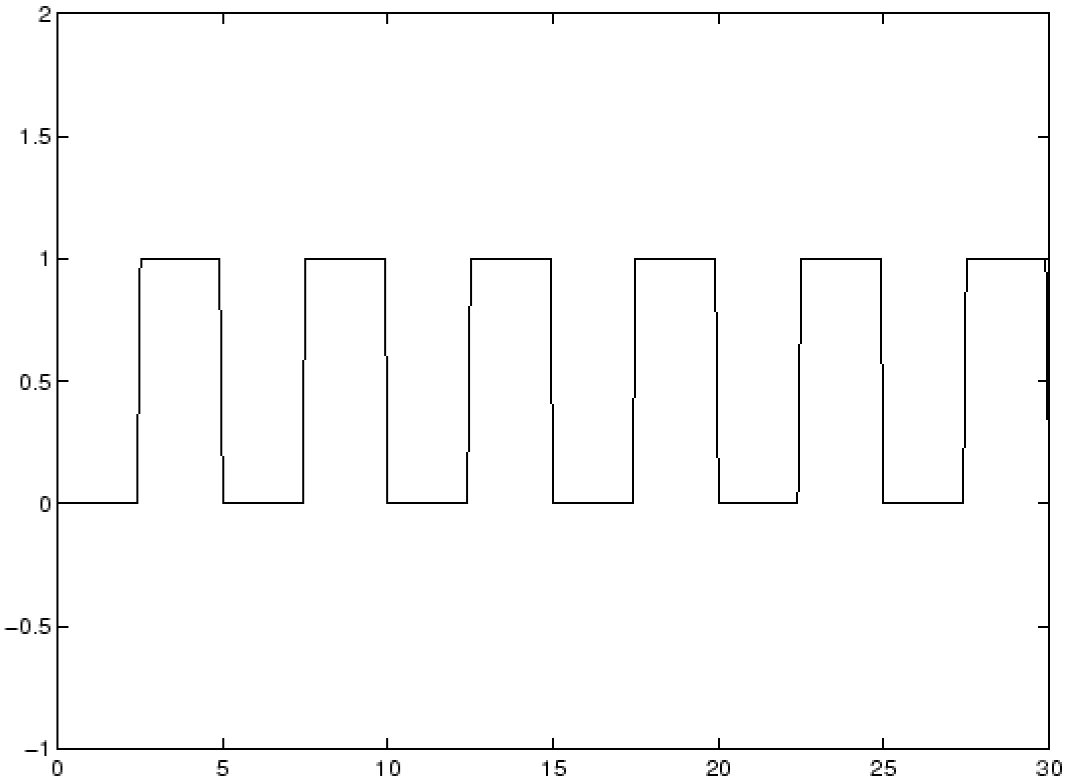
Examples

Generate a square wave with period 5 seconds, duration 30 seconds, and sampling every 0.1 second.

```
[u,t] = gensig('square',5,30,0.1)
```

Plot the resulting signal.

```
plot(t,u)
axis([0 30 -1 2])
```



See Also

`lsim`

genss

Generalized state-space model

Description

Generalized state-space (`genss`) models are state-space models that include tunable parameters or components. `genss` models arise when you combine numeric LTI models with models containing tunable components (control design blocks). For more information about numeric LTI models and control design blocks, see “Models with Tunable Coefficients”.

You can use generalized state-space models to represent control systems having a mixture of fixed and tunable components. Use generalized state-space models for control design tasks such as parameter studies and parameter tuning with `hinfstruct` (requires Robust Control Toolbox).

Construction

To construct a `genss` model:

- Use `series`, `parallel`, `lft`, or `connect`, or the arithmetic operators `+`, `-`, `*`, `/`, `\`, and `^`, to combine numeric LTI models with control design blocks.
- Use `tf` or `ss` with one or more input arguments that is a generalized matrix (`genmat`) instead of a numeric array
- Convert any numeric LTI model, control design block, or `slTuner` interface (requires Simulink Control Design), for example, `sys`, to `genss` form using:

  ```
  gensys = genss(sys)
  ```

  When `sys` is an `slTuner` interface, `gensys` contains all the tunable blocks and analysis points specified in this interface. To compute a tunable model of a particular I/O transfer function, call `getIOTransfer(gensys,in,out)`. Here, `in` and `out` are the analysis points of interest. (Use `getPoints(sys)` to get the full list of analysis points.) Similarly, to compute a tunable model of a particular open-loop transfer function, use `getLoopTransfer(gensys,loc)`. Here, `loc` is the analysis point of interest.

Properties

Blocks

Structure containing the control design blocks included in the generalized LTI model or generalized matrix. The field names of `Blocks` are the `Name` property of each control design block.

You can change some attributes of these control design blocks using dot notation. For example, if the generalized LTI model or generalized matrix `M` contains a `realp` tunable parameter `a`, you can change the current value of `a` using:

```
M.Blocks.a.Value = -1;
```

InternalDelay

Vector storing internal delays.

Internal delays arise, for example, when closing feedback loops on systems with delays, or when connecting delayed systems in series or parallel. For more information about internal delays, see "Closing Feedback Loops with Time Delays" in the *Control System Toolbox User's Guide*.

For continuous-time models, internal delays are expressed in the time unit specified by the `TimeUnit` property of the model. For discrete-time models, internal delays are expressed as integer multiples of the sample time `Ts`. For example, `InternalDelay = 3` means a delay of three sampling periods.

You can modify the values of internal delays. However, the number of entries in `sys.InternalDelay` cannot change, because it is a structural property of the model.

InputDelay

Input delay for each input channel, specified as a scalar value or numeric vector. For continuous-time systems, specify input delays in the time unit stored in the `TimeUnit` property. For discrete-time systems, specify input delays in integer multiples of the sample time `Ts`. For example, `InputDelay = 3` means a delay of three sample times.

For a system with `Nu` inputs, set `InputDelay` to an `Nu`-by-1 vector. Each entry of this vector is a numerical value that represents the input delay for the corresponding input channel.

You can also set `InputDelay` to a scalar value to apply the same delay to all channels.

Default: 0

`OutputDelay`

Output delays. `OutputDelay` is a numeric vector specifying a time delay for each output channel. For continuous-time systems, specify output delays in the time unit stored in the `TimeUnit` property. For discrete-time systems, specify output delays in integer multiples of the sample time `Ts`. For example, `OutputDelay = 3` means a delay of three sampling periods.

For a system with `Ny` outputs, set `OutputDelay` to an `Ny`-by-1 vector, where each entry is a numerical value representing the output delay for the corresponding output channel. You can also set `OutputDelay` to a scalar value to apply the same delay to all channels.

Default: 0 for all output channels

`Ts`

Sample time. For continuous-time models, `Ts = 0`. For discrete-time models, `Ts` is a positive scalar representing the sampling period. This value is expressed in the unit specified by the `TimeUnit` property of the model. To denote a discrete-time model with unspecified sample time, set `Ts = -1`.

Changing this property does not discretize or resample the model. Use `c2d` and `d2c` to convert between continuous- and discrete-time representations. Use `d2d` to change the sample time of a discrete-time system.

Default: `0` (continuous time)

`TimeUnit`

String representing the unit of the time variable. This property specifies the units for the time variable, the sample time `Ts`, and any time delays in the model. Use any of the following values:

- `'nanoseconds'`
- `'microseconds'`
- `'milliseconds'`
- `'seconds'`

- `'minutes'`
- `'hours'`
- `'days'`
- `'weeks'`
- `'months'`
- `'years'`

Changing this property has no effect on other properties, and therefore changes the overall system behavior. Use `chgTimeUnit` to convert between time units without modifying system behavior.

Default: `'seconds'`

`InputName`

Input channel names. Set `InputName` to a string for single-input model. For a multi-input model, set `InputName` to a cell array of strings.

Alternatively, use automatic vector expansion to assign input names for multi-input models. For example, if `sys` is a two-input model, enter:

```
sys.InputName = 'controls';
```

The input names automatically expand to `{'controls(1)';'controls(2)'}`.

You can use the shorthand notation `u` to refer to the `InputName` property. For example, `sys.u` is equivalent to `sys.InputName`.

Input channel names have several uses, including:

- Identifying channels on model display and plots
- Extracting subsystems of MIMO systems
- Specifying connection points when interconnecting models

Default: Empty string `''` for all input channels

`InputUnit`

Input channel units. Use `InputUnit` to keep track of input signal units. For a single-input model, set `InputUnit` to a string. For a multi-input model, set `InputUnit` to a cell array of strings. `InputUnit` has no effect on system behavior.

Default: Empty string `''` for all input channels

InputGroup

Input channel groups. The `InputGroup` property lets you assign the input channels of MIMO systems into groups and refer to each group by name. Specify input groups as a structure. In this structure, field names are the group names, and field values are the input channels belonging to each group. For example:

```
sys.InputGroup.controls = [1 2];
sys.InputGroup.noise = [3 5];
```

creates input groups named `controls` and `noise` that include input channels 1, 2 and 3, 5, respectively. You can then extract the subsystem from the `controls` inputs to all outputs using:

```
sys(:,'controls')
```

Default: Struct with no fields

OutputName

Output channel names. Set `OutputName` to a string for single-output model. For a multi-output model, set `OutputName` to a cell array of strings.

Alternatively, use automatic vector expansion to assign output names for multi-output models. For example, if `sys` is a two-output model, enter:

```
sys.OutputName = 'measurements';
```

The output names automatically expand to `{'measurements(1)';'measurements(2)'}`.

You can use the shorthand notation `y` to refer to the `OutputName` property. For example, `sys.y` is equivalent to `sys.OutputName`.

Output channel names have several uses, including:

- Identifying channels on model display and plots
- Extracting subsystems of MIMO systems
- Specifying connection points when interconnecting models

Default: Empty string `''` for all output channels

OutputUnit

Output channel units. Use `OutputUnit` to keep track of output signal units. For a single-output model, set `OutputUnit` to a string. For a multi-output model, set `OutputUnit` to a cell array of strings. `OutputUnit` has no effect on system behavior.

Default: Empty string `''` for all output channels

OutputGroup

Output channel groups. The `OutputGroup` property lets you assign the output channels of MIMO systems into groups and refer to each group by name. Specify output groups as a structure. In this structure, field names are the group names, and field values are the output channels belonging to each group. For example:

```
sys.OutputGroup.temperature = [1];
sys.InputGroup.measurement = [3 5];
```

creates output groups named `temperature` and `measurement` that include output channels 1, and 3, 5, respectively. You can then extract the subsystem from all inputs to the `measurement` outputs using:

```
sys('measurement',:)
```

Default: Struct with no fields

Name

System name. Set `Name` to a string to label the system.

Default: `''`

Notes

Any text that you want to associate with the system. Set `Notes` to a string or a cell array of strings.

Default: `{}`

UserData

Any type of data you wish to associate with system. Set `UserData` to any MATLAB data type.

Default: [ ]

SamplingGrid

Sampling grid for model arrays, specified as a data structure.

For model arrays that are derived by sampling one or more independent variables, this property tracks the variable values associated with each model in the array. This information appears when you display or plot the model array. Use this information to trace results back to the independent variables.

Set the field names of the data structure to the names of the sampling variables. Set the field values to the sampled variable values associated with each model in the array. All sampling variables should be numeric and scalar valued, and all arrays of sampled values should match the dimensions of the model array.

For example, suppose you create a 11-by-1 array of linear models, `sysarr`, by taking snapshots of a linear time-varying system at times `t = 0:10`. The following code stores the time samples with the linear models.

```
 sysarr.SamplingGrid = struct('time',0:10)
```

Similarly, suppose you create a 6-by-9 model array, `M`, by independently sampling two variables, `zeta` and `w`. The following code attaches the `(zeta,w)` values to `M`.

```
[zeta,w] = ndgrid(<6 values of zeta>,<9 values of w>)
M.SamplingGrid = struct('zeta',zeta,'w',w)
```

When you display `M`, each entry in the array includes the corresponding `zeta` and `w` values.

```
M

M(:,:,1,1) [zeta=0.3, w=5] =

        25
  --------------
  s^2 + 3 s + 25


M(:,:,2,1) [zeta=0.35, w=5] =

         25
  ----------------
```

```
  s^2 + 3.5 s + 25

...
```

For model arrays generated by linearizing a Simulink model at multiple parameter values or operating points, the software populates `SamplingGrid` automatically with the variable values that correspond to each entry in the array. For example, the Simulink Control Design commands `linearize` and `slLinearizer` populate `SamplingGrid` in this way.

Default: `[]`

Examples

Tunable Low-Pass Filter

This example shows how to create the low-pass filter $F = a/(s + a)$ with one tunable parameter a.

You cannot use `ltiblock.tf` to represent F, because the numerator and denominator coefficients of an `ltiblock.tf` block are independent. Instead, construct F using the tunable real parameter object `realp`.

1. Create a tunable real parameter.

   ```
   a = realp('a',10);
   ```

   The `realp` object `a` is a tunable parameter with initial value 10.
2. Use `tf` to create the tunable filter `F`:

   ```
   F = tf(a,[1 a]);
   ```

`F` is a `genss` object which has the tunable parameter `a` in its `Blocks` property. You can connect `F` with other tunable or numeric models to create more complex models of control systems. For an example, see "Control System with Tunable Components".

State-Space Model With Both Fixed and Tunable Parameters

This example shows how to create a state-space (`genss`) model having both fixed and tunable parameters.

Create a state-space model having the following state-space matrices:

$$A=\begin{bmatrix}1 & a+b\\ 0 & ab\end{bmatrix},\quad B=\begin{bmatrix}-3.0\\ 1.5\end{bmatrix},\quad C=\begin{bmatrix}0.3 & 0\end{bmatrix},\quad D=0,$$

where a and b are tunable parameters, whose initial values are –1 and 3, respectively.

1 Create the tunable parameters using `realp`.

```
a = realp('a',-1);
b = realp('b',3);
```

2 Define a generalized matrix using algebraic expressions of `a` and `b`.

```
A = [1 a+b;0 a*b]
```

`A` is a generalized matrix whose `Blocks` property contains `a` and `b`. The initial value of `A` is `M = [1 2;0 -3]`, from the initial values of `a` and `b`.

3 Create the fixed-value state-space matrices.

```
B = [-3.0;1.5];
C = [0.3 0];
D = 0;
```

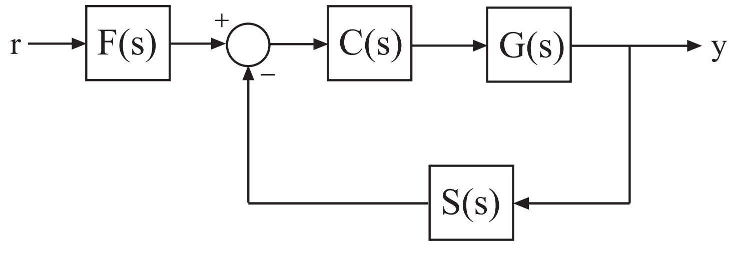
4 Use `ss` to create the state-space model.

```
sys = ss(A,B,C,D)
```

`sys` is a generalized LTI model (`genss`) with tunable parameters `a` and `b`.

Control System With Both Numeric and Tunable Components

This example shows how to create a tunable model of the control system in the following illustration.



The plant response $G(s) = 1/(s + 1)^2$. The model of sensor dynamics is $S(s) = 5/(s + 4)$. The controller C is a tunable PID controller, and the prefilter $F = a/(s + a)$ is a low-pass filter with one tunable parameter, a.

Create models representing the plant and sensor dynamics.

Because the plant and sensor dynamics are fixed, represent them using numeric LTI models `zpk` and `tf`.

```
G = zpk([],[-1,-1],1);
S = tf(5,[1 4]);
```

Create a tunable representation of the controller C.

```
C = ltiblock.pid('C','PID');
```

```
C =

  Parametric continuous-time PID controller "C" with formula:

             1          s
  Kp + Ki * --- + Kd * --------
             s          Tf*s+1

  and tunable parameters Kp, Ki, Kd, Tf.

Type "pid(C)" to see the current value and "get(C)" to see all properties.
```

`C` is a `ltiblock.pid` object, which is a Control Design Block with a predefined proportional-integral-derivative (PID) structure.

Create a model of the filter $F = a/(s + a)$ with one tunable parameter.

```
a = realp('a',10);
F = tf(a,[1 a]);
```

`a` is a `realp` (real tunable parameter) object with initial value 10. Using `a` as a coefficient in `tf` creates the tunable `genss` model object `F`.

Connect the models together to construct a model of the closed-loop response from r to y.

```
T = feedback(G*C,S)*F
```

`T` is a `genss` model object. In contrast to an aggregate model formed by connecting only Numeric LTI models, `T` keeps track of the tunable elements of the control system. The tunable elements are stored in the `Blocks` property of the `genss` model object.

Display the tunable elements of `T`.

```
T.Blocks
```

```
ans = 

    C: [1x1 ltiblock.pid]
    a: [1x1 realp]
```

If you have Robust Control Toolbox software, you can use tuning commands such as `systune` to tune the free parameters of `T` to meet design requirements you specify.

More About

Tips

- You can manipulate `genss` models as ordinary `ss` models. Analysis commands such as `bode` and `step` evaluate the model by replacing each tunable parameter with its current value.

- “Models with Tunable Coefficients”
- “Dynamic System Models”
- “Control Design Blocks”

See Also

`realp` | `genmat` | `genfrd` | `tf` | `ss` | `getValue` | `ltiblock.pid` | `feedback` | `connect`

get

Access model property values

Syntax

```
Value = get(sys,'PropertyName')
Struct = get(sys)
```

Description

`Value = get(sys,'PropertyName')` returns the current value of the property `PropertyName` of the model object `sys`. The string `'PropertyName'` can be the full property name (for example, `'UserData'`) or any unambiguous case-insensitive abbreviation (for example, `'user'`). See reference pages for the individual model object types for a list of properties available for that model.

`Struct = get(sys)` converts the TF, SS, or ZPK object `sys` into a standard MATLAB structure with the property names as field names and the property values as field values.

Without left-side argument,

```
get(sys)
```

displays all properties of `sys` and their values.

Examples

Consider the discrete-time SISO transfer function defined by

```
h = tf(1,[1 2],0.1,'inputname','voltage','user','hello')
```

You can display all properties of `h` with

```
get(h)
          num: {[0 1]}
          den: {[1 2]}
```

```
        ioDelay: 0
       Variable: 'z'
             Ts: 0.1
     InputDelay: 0
    OutputDelay: 0
      InputName: {'voltage'}
     OutputName: {''}
     InputGroup: [1x1 struct]
    OutputGroup: [1x1 struct]
           Name: ''
          Notes: {}
       UserData: 'hello'
```

or query only about the numerator and sample time values by

```
get(h,'num')

ans =
    [1x2 double]
```

and

```
get(h,'ts')

ans =
    0.1000
```

Because the numerator data (`num` property) is always stored as a cell array, the first command evaluates to a cell array containing the row vector `[0 1]`.

More About

Tips

An alternative to the syntax

```
Value = get(sys,'PropertyName')
```

is the structure-like referencing

```
Value = sys.PropertyName
```

For example,

```
sys.Ts
sys.a
sys.user
```

return the values of the sample time, A matrix, and `UserData` property of the (state-space) model `sys`.

See Also

`set` | `ssdata` | `tfdata` | `zpkdata` | `frdata` | `idssdata` | `polydata`

getBlockValue

Current value of Control Design Block in Generalized Model

Syntax

```
val = getBlockValue(M,blockname)
[val1,val2,...] = getBlockValue(M,blockname1,blockname2,...)
S = getBlockValue(M)
```

Description

`val = getBlockValue(M,blockname)` returns the current value of the Control Design Block blockname in the Generalized Model M. (For uncertain blocks, the "current value" is the nominal value of the block.)

`[val1,val2,...] = getBlockValue(M,blockname1,blockname2,...)` returns the values of the specified Control Design Blocks.

`S = getBlockValue(M)` returns the values of all Control Design Blocks of the generalized model in a structure. This syntax lets you transfer the block values from one generalized model to another model that uses the same Control Design Blocks, as follows:

```
S = getBlockValue(M1);
setBlockValue(M2,S);
```

Input Arguments

`M`

Generalized LTI (`genss`) model or generalized matrix (`genmat`).

`blockname`

Name of the Control Design Block in the model M whose current value is evaluated.

To get a list of the Control Design Blocks in M, enter `M.Blocks`.

Output Arguments

val

Numerical LTI model or numerical value, equal to the current value of the Control Design Block blockname.

S

Current values of all Control Design Blocks in M, returned as a structure. The names of the fields in S are the names of the blocks in M. The values of the fields are numerical LTI models or numerical values equal to the current values of the corresponding Control Design Blocks.

Examples

`aval` is a numeric scalar, because `a` is a real scalar parameter.

Get Current Values of Single Blocks

Create a tunable `genss` model, and evaluate the current value of the Control Design Blocks of the model.

Typically, you use `getBlockValue` to retrieve the tuned values of control design blocks after tuning the `genss` model using a tuning command such as `systune`. For this example, create the model and retrieve the initial block values.

```
G = zpk([],[-1,-1],1);
C = ltiblock.pid('C','PID');
a = realp('a',10);
F = tf(a,[1 a]);
T = feedback(G*C,1)*F;

Cval = getBlockValue(T,'C')
```

```
Continuous-time I-only controller:

      1
Ki * ---
      s
```

```
With Ki = 0.001
```

`Cval` is a numeric `pid` controller object.

```
aval = getBlockValue(T,'a')
```

```
aval =

    10
```

Get All Current Values as Structure

Using the `genss` model of the previous example, get the current values of all blocks in the model.

```
G = zpk([],[-1,-1],1);
C = ltiblock.pid('C','PID');
a = realp('a',10);
F = tf(a,[1 a]);
T = feedback(G*C,1)*F;

S = getBlockValue(T)
```

```
S =

    C: [1x1 pid]
    a: 10
```

See Also

`setBlockValue` | `showBlockValue` | `getValue`

Introduced in R2011b

getCompSensitivity

Complementary sensitivity function from generalized model of control system

Syntax

```
T = getCompSensitivity(CL,location)
T = getSensitivity(CL,location,opening)
```

Description

`T = getCompSensitivity(CL,location)` returns the complementary sensitivity measured at the specified location for a generalized model of a control system.

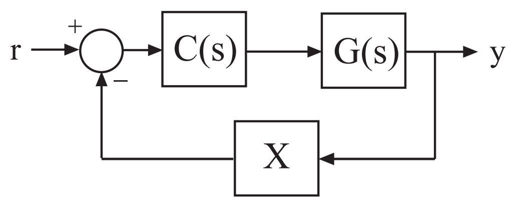
`T = getSensitivity(CL,location,opening)` specifies additional loop openings for the complementary sensitivity function calculation. Use an opening, for example, to calculate the complementary sensitivity function of an inner loop, with the outer loop open.

If opening and location list the same point, the software opens the loop after adding the disturbance signal at the point.

Examples

Complementary Sensitivity Function at a Location

Compute the complementary sensitivity at the plant output, `X`.



Create a model of the system by specifying and connecting a numeric LTI plant model `G`, a tunable controller `C`, and the `AnalysisPoint` block `X`. Use the `AnalysisPoint` block to mark the location where you assess the complementary sensitivity (plant output in this example).

```
G = tf([1],[1 5]);
C = ltiblock.pid('C','p');
C.Kp.Value = 3;
X = AnalysisPoint('X');
CL = feedback(G*C,X);
```

`CL` is a `genss` model that represents the closed-loop response of the control system from r to y. The model contains the `AnalysisPoint` block, `X`, that identifies the analysis-point location.

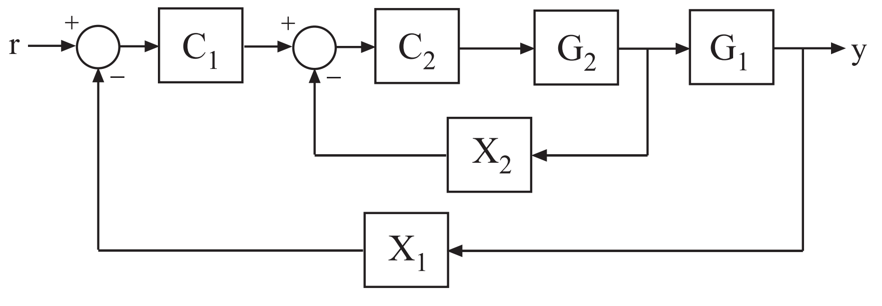
Calculate the complementary sensitivity, T, at `X`.

```
T = getCompSensitivity(CL,'X');
tf(T)
```

```
ans =

  From input "X" to output "X":
   -3
  -----
  s + 8

Continuous-time transfer function.
```

Specify Additional Loop Opening for Complementary Sensitivity Function Calculation

Calculate the inner-loop sensitivity at the output of `G2`, with the outer loop open.



Create a model of the system by specifying and connecting the numeric plant models, tunable controllers, and `AnalysisPoint` blocks. `G1` and `G2` are plant models, `C1` and `C2` are tunable controllers, and X1 and X2 are AnalysisPoint blocks that mark potential loop-opening locations.

```
G1 = tf(10,[1 10]);
G2 = tf([1 2],[1 0.2 10]);
C1 = ltiblock.pid('C','pi');
C2 = ltiblock.gain('G',1);
X1 = AnalysisPoint('X1');
X2 = AnalysisPoint('X2');
CL = feedback(G1*feedback(G2*C2,X2)*C1,X1);
```

Calculate the complementary sensitivity, T, at X2, with the outer loop open at X1.

```
T = getCompSensitivity(CL,'X2','X1');
tf(T)
```

```
ans =

  From input "X2" to output "X2":
       -s - 2
  ----------------
  s^2 + 1.2 s + 12

Continuous-time transfer function.
```

Input Arguments

CL — Model of control system

generalized state-space model

Model of a control system, specified as a Generalized State-Space Model (genss).

Locations at which you can perform sensitivity analysis or open loops are marked by AnalysisPoint blocks in CL. Use getPoints(CL) to get the list of such locations.

location — Location

string | cell array of strings

Location at which you calculate the complementary sensitivity function, specified as a string or cell array of strings. To extract the complementary sensitivity function at multiple locations, use a cell array of strings.

Each string in location must match an analysis point in CL. Analysis points are marked using `AnalysisPoint` blocks. Use `getPoints(CL)` to get the list of available analysis points in CL.

Example: `'u'` or `{'u','y'}`

`opening` — Additional loop opening

string | cell array of strings

Additional loop opening used to calculate the complementary sensitivity function, specified as a string or cell array of strings. To open the loop at multiple locations, use a cell array of strings.

Each string in opening must match an analysis point in CL. Analysis points are marked using `AnalysisPoint` blocks. Use `getPoints(CL)` to get the list of available analysis points in CL.

Use an opening, for example, to calculate the complementary sensitivity function of an inner loop, with the outer loop open.

If opening and location list the same point, the software opens the loop after adding the disturbance signal at the point.

Example: `'y_outer'` or `{'y_outer','y_outer2'}`

Output Arguments

`T` — Complementary sensitivity function

generalized state-space model

Complementary sensitivity function of the control system, T, measured at location, returned as a Generalized State-Space Model (`genss`).

- If location specifies a single analysis point, then `T` is a SISO `genss` model.
- If location is a string specifying a vector signal, or a cell array identifying multiple analysis points, then `T` is a MIMO `genss` model.

More About

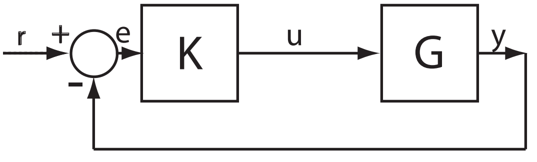
Complementary Sensitivity

The *complementary sensitivity function*, T, at a point is the closed-loop transfer function around the feedback loop measured at the specified location. It is related to the open-loop transfer function, L, and the sensitivity function, S, at the same point as follows:

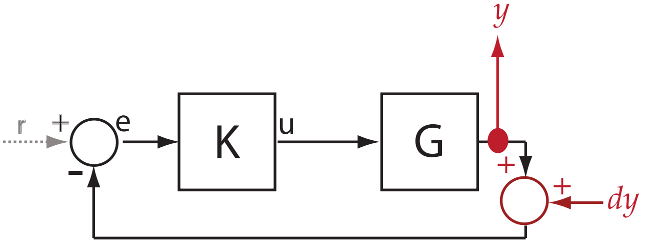
$$T = \frac{L}{1-L} = S - 1.$$

Use `getLoopTransfer` and `getSensitivity` to compute L and S.

Consider the following model:



The complementary sensitivity, T, at `y` is defined as the transfer function from `dy` to `y`.

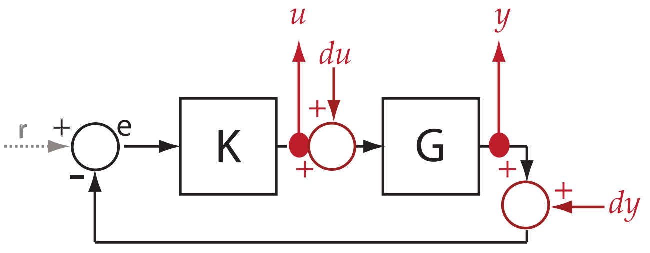


Observe that, in contrast to the sensitivity function, the disturbance, `dy`, is added *after* the measurement, `y`.

$$\begin{aligned}
&y = -GK(y + dy) \\
&\rightarrow y = -GKy - GKdy \\
&\rightarrow (I + GK)y = -GKdy \\
&\rightarrow y = \underbrace{-(I + GK)^{-1}GK}_{T}\,dy.
\end{aligned}$$

Here, I is an identity matrix of the same size as GK. The complementary sensitivity transfer function at `y` is equal to `-1` times the closed-loop transfer function from `r` to `y`.

Complementary sensitivity at multiple locations, for example, `u` and `y`, is defined as the MIMO transfer function from the disturbances to measurements:



$$T = \begin{bmatrix} T_{du \to u} & T_{dy \to u} \\ T_{du \to y} & T_{dy \to y} \end{bmatrix}.$$

See Also

| `AnalysisPoint` | `genss` | `getCompSensitivity` | `getIOTransfer` | `getLoopTransfer` | `getPoints` | `getSensitivity` | `getValue` | `systune`

getDelayModel

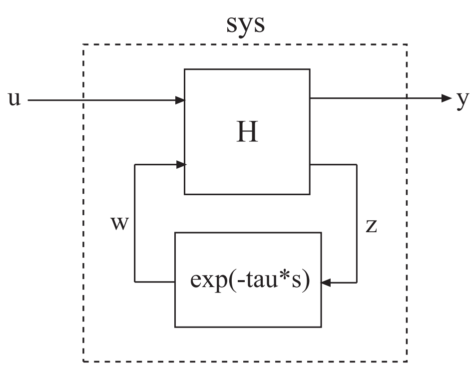
State-space representation of internal delays

Syntax

```
[H,tau] = getDelayModel(sys)
[A,B1,B2,C1,C2,D11,D12,D21,D22,E,tau] = getDelayModel(sys)
```

Description

`[H,tau] = getDelayModel(sys)` decomposes a state-space model sys with internal delays into a delay-free state-space model, H, and a vector of internal delays, tau. The relationship among sys, H, and tau is shown in the following diagram.



`[A,B1,B2,C1,C2,D11,D12,D21,D22,E,tau] = getDelayModel(sys)` returns the set of state-space matrices and internal delay vector, tau, that explicitly describe the state-space model sys. These state-space matrices are defined by the state-space equations:

- Continuous-time sys:

$$
\begin{aligned}
E\frac{dx(t)}{dt} &= Ax(t) + B_1u(t) + B_2w(t) \\
y(t) &= C_1x(t) + D_{11}u(t) + D_{12}w(t) \\
z(t) &= C_2x(t) + D_{21}u(t) + D_{22}w(t) \\
w(t) &= z(t-\tau)
\end{aligned}
$$

- Discrete-time sys:

$$
\begin{aligned}
Ex[k+1] &= Ax[k] + B_1u[k] + B_2w[k] \\
y[k] &= C_1x[k] + D_{11}u[k] + D_{12}w[k] \\
z[k] &= C_2x[k] + D_{21}u[k] + D_{22}w[k] \\
w[k] &= z[k-\tau]
\end{aligned}
$$

Input Arguments

`sys`

Any state-space (`ss`) model.

Output Arguments

`H`

Delay-free state-space model (`ss`). H results from decomposing sys into a delay-free component and a component `exp(-tau*s)` that represents all internal delays.

If sys has no internal delays, H is equal to sys.

`tau`

Vector of internal delays of sys, expressed in the time units of sys. The vector tau results from decomposing sys into a delay-free state-space model H and a component `exp(-tau*s)` that represents all internal delays.

If sys has no internal delays, tau is empty.

A,B1,B2,C1,C2,D11,D12,D21,D22,E

Set of state-space matrices that, with the internal delay vector tau, explicitly describe the state-space model sys.

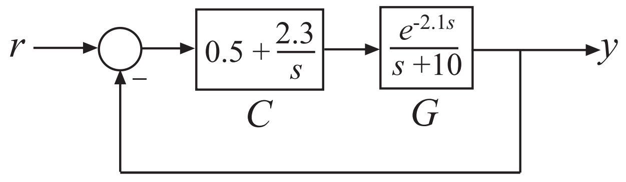
For explicit state-space models ($E = I$, or `sys.e = []`), the output `E = []`.

If sys has no internal delays, the outputs `B2`, `C2`, `D12`, `D21`, and `D22` are all empty (`[]`).

Examples

Get Delay-Free State-Space Model and Internal Delay

Decompose the following closed-loop system with internal delay into a delay-free component and a component representing the internal delay.



Create the closed-loop model sys from r to y.

```
G = tf(1,[1 10],'InputDelay',2.1);
C = pid(0.5,2.3);
sys = feedback(C*G,1);
```

`sys` is a state-space (`ss`) model with an internal delay arising from the feedback loop.

Decompose `sys` into a delay-free state-space model and the value of the internal delay.

```
[H,tau] = getDelayModel(sys);
```

More About

- "Internal Delays"

See Also

`setDelayModel`

getGainCrossover

Crossover frequencies for specified gain

Syntax

```
wc = getGainCrossover(sys,gain)
```

Description

`wc = getGainCrossover(sys,gain)` returns the vector wc of frequencies at which the frequency response of the dynamic system model, sys, has principal gain of gain. For SISO systems, the principal gain is the frequency response. For MIMO models, the principal gain is the largest singular value of sys.

Examples

Unity Gain Crossover

Find the 0dB crossover of a single-loop control system with plant

$$G(s) = \frac{1}{(s+1)^3}$$

and PI controller

$$C(s) = 1.14 + \frac{0.454}{s}.$$

```
G = zpk([],[-1,-1,-1],1);
C = pid(1.14,0.454);
sys = G*C;
wc = getGainCrossover(sys,1)
```

```
wc =
```

```
    0.5214
```

The 0 dB crossovers are the frequencies at which the open-loop response `sys = G*C` has unity gain. Because this system only crosses unity gain once, `getGainCrossover` returns a single value.

Notch Filter Stopband

Find the 20 dB stopband of

$$sys = \frac{s^2 + 0.05s + 100}{s^2 + 5s + 100}.$$

`sys` is a notch filter centered at 10 rad/s.

```
sys = tf([1 0.05 100],[1 5 100]);
gain = db2mag(-20);
wc = getGainCrossover(sys,gain)

wc =

    9.7531
   10.2531
```

The `db2mag` command converts the gain value of –20 dB to absolute units. The `getGainCrossover` command returns the two frequencies that define the stopband.

Input Arguments

`sys` — Input dynamic system

dynamic system model

Input dynamic system, specified as any SISO or MIMO dynamic system model.

`gain` — Input gain

positive real scalar

Input gain in absolute units, specified as a positive real scalar.

- If sys is a SISO model, the gain is the frequency response magnitude of sys.

- If sys is a MIMO model, gain means the largest singular value of sys.

Output Arguments

`wc` — Crossover frequencies

column vector

Crossover frequencies, returned as a column vector. This vector lists the frequencies at which the gain or largest singular value of sys is gain.

More About

Algorithms

`getGainCrossover` computes gain crossover frequencies using structure-preserving eigensolvers from the SLICOT library. For more information about the SLICOT library, see http://slicot.org.

- “Dynamic System Models”

See Also

`bandwidth` | `bode` | `freqresp` | `getPeakGain` | `sigma`

getIOTransfer

Closed-loop transfer function from generalized model of control system

Syntax

```
H = getIOTransfer(T,in,out)
H = getIOTransfer(T,in,out,openings)
```

Description

`H = getIOTransfer(T,in,out)` returns the transfer function from specified inputs to specified outputs of a control system, computed from a closed-loop generalized model of the control system.

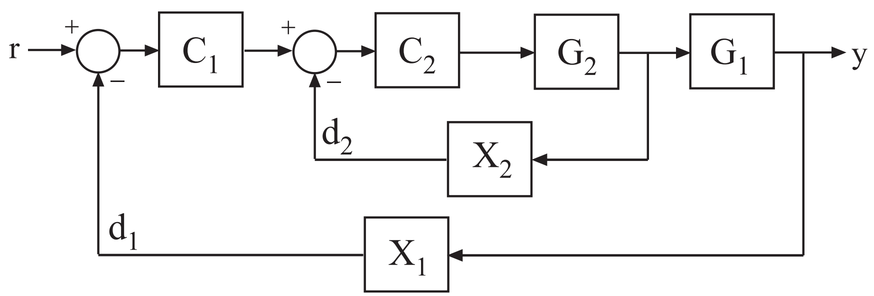
`H = getIOTransfer(T,in,out,openings)` returns the transfer function calculated with one or more loops open.

Examples

Closed-Loop Responses of Control System Model

Analyze responses of a control system by using `getIOTransfer` to compute responses between various inputs and outputs of a closed-loop model of the system.

Consider the following control system.



Create a `genss` model of the system by specifying and connecting the numeric plant models `G1` and `G2`, the tunable controllers `C1`, and the `AnalysisPoint` blocks `X1` and `X2` that mark potential loop-opening or signal injection sites.

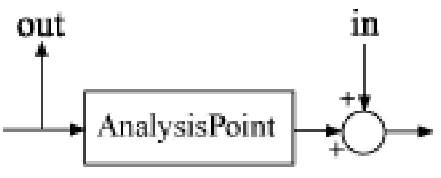
```
G1 = tf(10,[1 10]);
G2 = tf([1 2],[1 0.2 10]);
C1 = ltiblock.pid('C','pi');
C2 = ltiblock.gain('G',1);
X1 = AnalysisPoint('X1');
X2 = AnalysisPoint('X2');
T = feedback(G1*feedback(G2*C2,X2)*C1,X1);
T.InputName = 'r';
T.OutputName = 'y';
```

If you tuned the free parameters of this model (for example, using the Robust Control Toolbox tuning command `systune`), you might want to analyze the tuned system performance by examining various system responses.

For example, examine the response at the output, y, to a disturbance injected at the point d_1.

```
H1 = getIOTransfer(T,'X1','y');
```

`H1` represents the closed-loop response of the control system to a disturbance injected at the implicit input associated with the `AnalysisPoint` block `X1`, which is the location of d_1:



`H1` is a `genss` model that includes the tunable blocks of `T`. If you have tuned the free parameters of `T`, `H1` allows you to validate the disturbance response of your tuned system. For example, you can use analysis commands such as `bodeplot` or `stepplot` to analyze `H1`. You can also use `getValue` to obtain the current value of `H1`, in which all the tunable blocks are evaluated to their current numeric values.

Similarly, examine the response at the output to a disturbance injected at the point d_2.

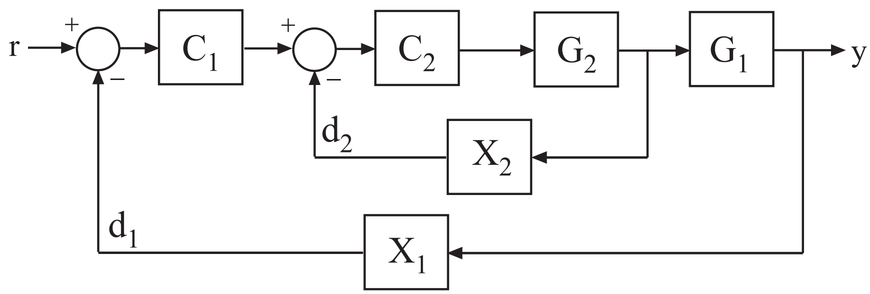
```
H2 = getIOTransfer(T,'X2','y');
```

You can also generate a two-input, one-output model representing the response of the control system to simultaneous disturbances at both d_1 and d_2. To do so, provide `getIOTransfer` with a cell array that specifies the multiple input locations.

```
H = getIOTransfer(T,{'X1','X2'},'y');
```

Responses with Some Loops Open and Others Closed

Compute the response from r to y of the following cascaded control system, with the inner loop open, and the outer loop closed.



Create a `genss` model of the system by specifying and connecting the numeric plant models `G1` and `G2`, the tunable controllers `C1`, and the `AnalysisPoint` blocks `X1` and `X2` that mark potential loop-opening or signal injection sites.

```
G1 = tf(10,[1 10]);
G2 = tf([1 2],[1 0.2 10]);
C1 = ltiblock.pid('C','pi');
C2 = ltiblock.gain('G',1);
X1 = AnalysisPoint('X1');
X2 = AnalysisPoint('X2');
T = feedback(G1*feedback(G2*C2,X2)*C1,X1);T.InputName = 'r';
T.OutputName = 'y';
```

If you tuned the free parameters of this model (for example, using the Robust Control Toolbox tuning command `systune`), you might want to analyze the tuned system performance by examining various system responses.

For example, compute the response of the system with the inner loop open, and the outer loop closed.

```
H = getIOTransfer(T,'r','y','X2');
```

By default, the loops are closed at the analysis points `X1` and `X2`. Specifying `'X2'` for the `openings` argument causes `getIOTransfer` to open the loop at `X2` for the purposes of computing the requested transfer from *r* to *y*. The switch at `X1` remains closed for this computation.

Input Arguments

`T` — Model of control system

generalized state-space model

Model of a control system, specified as a Generalized State-Space (`genss`) Model.

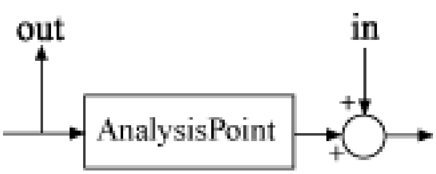
`in` — Input to extracted transfer function

string | cell array of strings

Input to extracted transfer function, specified as a string or cell array of strings. To extract a multiple-input transfer function from the control system, use a cell array of strings. Each string in in must match either:

- An input of the control system model `T` (in other words, a string contained in `T.InputName`).
- An analysis point in `T`, corresponding to a channel of an `AnalysisPoint` block in `T`. Use `getpoints(T)` to get a full list of available analysis points in `T`.

  When you specify an analysis point as an input `in`, `getIOTransfer` uses the input implicitly associated with the `AnalysisPoint` channel, arranged as follows.

  This input signal models a disturbance entering at the output of the switch.

If an analysis point has the same name as an input of `T`, then `getIOTransfer` uses the input of `T`.

Example: `{'r','X1'}`

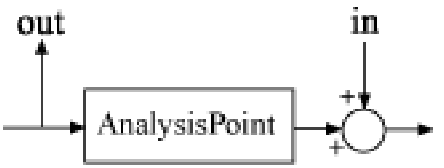
`out` — Output of extracted transfer function

string | cell array of strings

Output of extracted transfer function, specified as a string or cell array of strings. To extract a multiple-output transfer function from the control system, use a cell array of strings. Each string in out must match either:

- An output of the control system model `T` (in other words, a string contained in `T.OutputName`).
- An analysis point in `T`, corresponding to a channel of an `AnalysisPoint` block in `T`. Use `getPoints(T)` to get a full list of available analysis points in `T`.

  When you specify an analysis point as an output `out`, `getIOTransfer` uses the output implicitly associated with the `AnalysisPoint` channel, arranged as follows.



If an analysis point has the same name as an output of `T`, then `getIOTransfer` uses the output of `T`.

Example: `{'y','X2'}`

`openings` — Locations for opening feedback loops

string | cell array of strings

Locations for opening feedback loops for computation of the response from in to out, specified as string or cell array of strings that identify analysis points in T. Analysis points are marked by `AnalysisPoint` blocks in T. Use `getPoints(T)` to get a full list of available loop-opening sites in `T`.

Use `openings` when you want to compute the response from in to out with some loops in the control system open. For example, in a cascaded loop configuration, you can calculate the response from the system input to the system output with the inner loop open.

Output Arguments

H — Closed-loop transfer function
generalized state-space model

Closed-loop transfer function of the control system T from in to out, returned as a Generalized State-Space (`genss`) model.

- If both in and out specify a single signal, then `T` is a SISO `genss` model.
- If in or out identifies multiple signals, then `T` is a MIMO `genss` model.

More About

Tips

- You can use `getIOTransfer` to extract various subsystem responses, given a generalized model of the overall control system. This is useful for validating responses of a control system that you tune with the Robust Control Toolbox tuning command `systune`.

  For example, in addition to evaluating the overall response of a tuned control system from inputs to outputs, you can use `getIOTransfer` to extract the transfer function from a disturbance input to a system output. Evaluate the responses of that transfer function (such as with `step` or `bode`) to confirm that the tuned system meets your disturbance rejection requirements.
- `getIOTransfer` is the `genss` equivalent to the Simulink Control Design `getIOTransfer` command, which works with the `slTuner` and `slLinearizer` interfaces. Use the Simulink Control Design command when your control system is modeled in Simulink.

See Also
| `AnalysisPoint` | `genss` | `getIOTransfer` | `getLoopTransfer` | `getPoints` | `systune`

getLFTModel

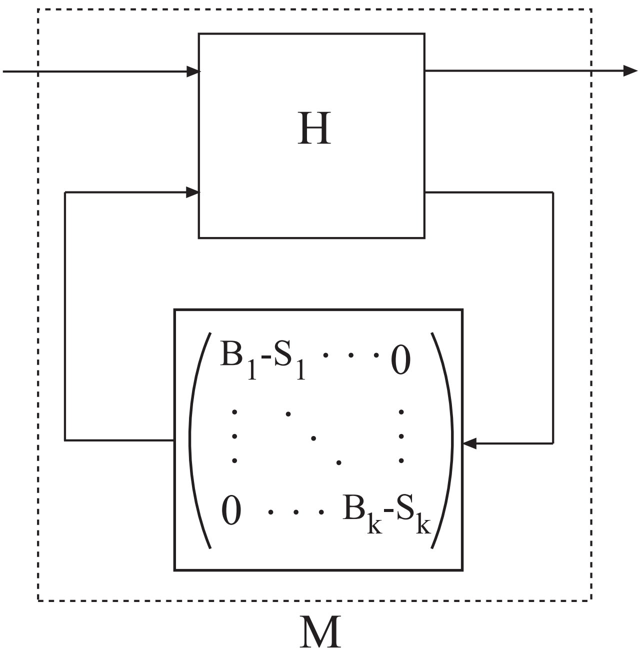
Decompose generalized LTI model

Syntax

```
[H,B,S] = getLFTModel(M)
```

Description

`[H,B,S] = getLFTModel(M)` extracts the components H, B, and S that make up the Generalized matrix or Generalized LTI model M. The model M decomposes into H, B, and S. These components are related to M as shown in the following illustration.



The cell array B contains the Control Design Blocks of M. The component H is a numeric matrix, `ss` model, or `frd` model that describes the fixed portion of M and the interconnections between the blocks of B. The matrix S = `blkdiag(S1,...,Sk)` contains numerical offsets that ensure that the interconnection is well-defined when the current (nominal) value of M is finite.

You can recombine H, B, and S into M using `lft`, as follows:

```
M = lft(H,blkdiag(B{:})-S);
```

Input Arguments

M

Generalized LTI model (`genss` or `genfrd`) or Generalized matrix (`genmat`).

Output Arguments

H

Matrix, `ss` model, or `frd` model describing the numeric portion of M and how it the numeric portion is connected to the Control Design Blocks of M.

B

Cell array of Control Design Blocks (for example, `realp` or `ltiblock.ss`) of M.

S

Matrix of offset values. The software might introduce offsets when you build a Generalized model to ensure that H is finite when the current (nominal) value of M is finite.

More About

Tips

- `getLFTModel` gives you access to the internal representation of Generalized LTI models and Generalized Matrices. For more information about this representation, see “Internal Structure of Generalized Models”.

- “Generalized Matrices”
- “Generalized and Uncertain LTI Models”
- “Models with Tunable Coefficients”
- “Internal Structure of Generalized Models”

See Also

`genfrd` | `genss` | `genmat` | `lft` | `getValue` | `nblocks`

getLoopTransfer

Open-loop transfer function of control system

Syntax

```
L = getLoopTransfer(T,Locations)
L = getLoopTransfer(T,Locations,sign)
L = getLoopTransfer(T,Locations,sign,openings)
```

Description

`L = getLoopTransfer(T,Locations)` returns the point-to-point open-loop transfer function of a control system measured at specified analysis points. The point-to-point open-loop transfer function is the open-loop response obtained by injecting signals at the specified locations and measuring the return signals at the same locations.

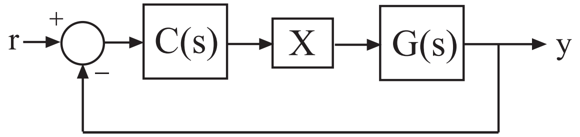
`L = getLoopTransfer(T,Locations,sign)` specifies the feedback sign for calculating the open-loop response. The relationship between the closed-loop response `T` and the open-loop response `L` is `T = feedback(L,1,sign)`.

`L = getLoopTransfer(T,Locations,sign,openings)` specifies additional loop-opening locations to open for computing the open-loop response at Locations.

Examples

Open-Loop Transfer Function at Analysis Point

Compute the open-loop response of the following control system model at an analysis point specified by an `AnalysisPoint` block, `X`.



Create a model of the system by specifying and connecting a numeric LTI plant model G, a tunable controller C, and the AnalysisPoint block X.

```
G = tf([1 2],[1 0.2 10]);
C = ltiblock.pid('C','pi');
X = AnalysisPoint('X');
T = feedback(G*X*C,1);
```

T is a genss model that represents the closed-loop response of the control system from r to y. The model contains the AnalysisPoint block X that identifies the potential loop-opening location.

Calculate the open-loop point-to-point loop transfer at the location X.

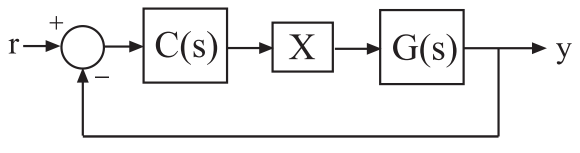
```
L = getLoopTransfer(T,'X');
```

This command computes the positive-feedback transfer function you would obtain by opening the loop at X, injecting a signal into G, and measuring the resulting response at the output of C. By default, getLoopTransfer computes the positive feedback transfer function. In this example, the positive feedback transfer function is $L(s) = -G(s)C(s)$

The output L is a genss model that includes the tunable block C. You can use getValue to obtain the current value of L, in which all the tunable blocks of L are evaluated to their current numeric value.

Negative-Feedback Open-Loop Transfer Function

Compute the negative-feedback open-loop transfer of the following control system model at an analysis point specified by an AnalysisPoint block, X.



Create a model of the system by specifying and connecting a numeric LTI plant model G, a tunable controller C, and the AnalysisPoint block X.

```
G = tf([1 2],[1 0.2 10]);
C = ltiblock.pid('C','pi');
X = AnalysisPoint('X');
T = feedback(G*X*C,1);
```

`T` is a `genss` model that represents the closed-loop response of the control system from *r* to *y*. The model contains the `AnalysisPoint` block `X` that identifies the potential loop-opening location.

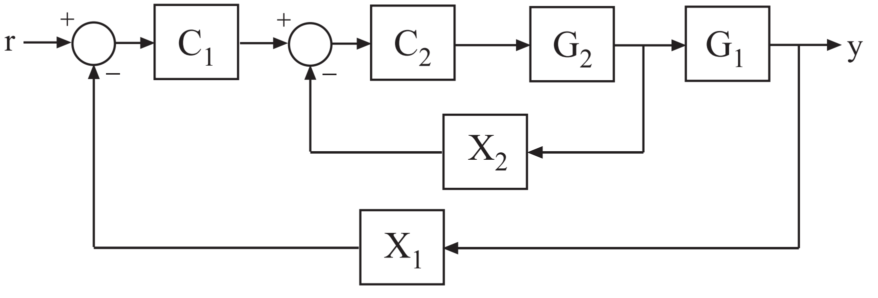
Calculate the open-loop point-to-point loop transfer at the location `X`.

```
L = getLoopTransfer(T,'X',-1);
```

This command computes the open-loop transfer function from the input of `G` to the output of `C`, assuming that the loop is closed with negative feedback. That is, the relationships between `L` and `T` is given by `T = feedback(L,1)`. In this example, the positive feedback transfer function is $L(s) = G(s)C(s)$

Transfer Function with Additional Loop Openings

Compute the open-loop response of the inner loop of the following cascaded control system, with the outer loop open.



Create a model of the system by specifying and connecting the numeric plant models `G1` and `G2`, the tunable controllers `C1`, and the `AnalysisPoint` blocks `X1` and `X2` that mark potential loop-opening locations.

```
G1 = tf(10,[1 10]);
G2 = tf([1 2],[1 0.2 10]);
C1 = ltiblock.pid('C','pi');
C2 = ltiblock.gain('G',1);
X1 = AnalysisPoint('X1');
X2 = AnalysisPoint('X2');
T = feedback(G1*feedback(G2*C2,X2)*C1,X1);
```

Compute the negative-feedback open-loop response of the inner loop, at the location `X2`, with the outer loop opened at `X1`.

```
L = getLoopTransfer(T,'X2',-1,'X1');
```

By default, the loop is closed at the analysis-point location marked by the `AnalysisPoint` block `X1`. Specifying `'X1'` for the `openings` argument causes `getLoopTransfer` to open the loop at `X1` for the purposes of computing the requested loop transfer at `X2`. In this example, the negative-feedback open-loop response $L(s) = G_2(s)C_2(s)$.

Input Arguments

`T` — Model of control system

generalized state-space model

Model of a control system, specified as a Generalized State-Space (`genss`) Model. Locations at which you can open loops and perform open-loop analysis are marked by `AnalysisPoint` blocks in `T`.

`Locations` — Analysis-point locations

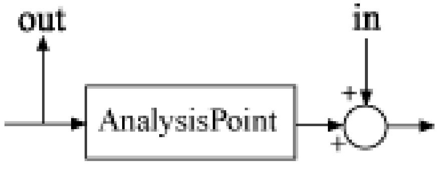
string | cell array of strings

Analysis-point locations in the control system model at which to compute the open-loop point-to-point response, specified as a string or a cell array of strings that identify analysis-point locations in T.

Analysis-point locations are marked by `AnalysisPoint` blocks in T. An `AnalysisPoint` block can have single or multiple channels. The `Location` property of an `AnalysisPoint` block gives names to these feedback channels.

The name of any channel in a `AnalysisPoint` block in T is a valid entry for the Locations argument to `getLoopTransfer`. Use `getPoints(T)` to get a full list of available analysis points in `T`.

`getLoopTransfer` computes the open-loop response you would obtain by injecting a signal at the implicit input associated with an `AnalysisPoint` channel, and measuring the response at the implicit output associated with the channel. These implicit inputs and outputs are arranged as follows.



L is the open-loop transfer function from `in` to `out`.

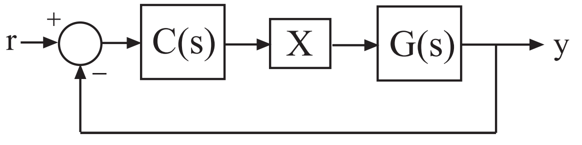
`sign` — Feedback sign

`+1` (default) | `-1`

Feedback sign, specified as `+1` or `-1` The feedback sign determines the sign of the open-loop transfer function.

- `+1` — Compute the positive-feedback loop transfer. In this case, the relationship between the closed-loop response `T` and the open-loop response `L` is `T = feedback(L,1,+1)`.
- `-1` — Compute the negative-feedback loop transfer. In this case, the relationship between the closed-loop response `T` and the open-loop response `L` is `T = feedback(L,1)`.

Choose a feedback sign that is consistent with the conventions of the analysis you intend to perform with the loop transfer function. For example, consider the following system, where `T` is the closed-loop transfer function from *r* to *y*.



To compute the stability margins of this system with the `margin` command, which assumes negative feedback, you need to use the negative-feedback open-loop response. Therefore, you can use `L = getLoopTransfer(T,'X',-1)` to obtain the negative-feedback transfer function $L = GC$.

`openings` — Additional locations for opening feedback loops

string | cell array of strings

Additional locations for opening feedback loops for computation of the open-loop response, specified as string or cell array of strings that identify analysis-point locations in T. Analysis-point locations are marked by `AnalysisPoint` blocks in T. Any channel name contained in the `Location` property of an `AnalysisPoint` block in T is a valid entry for openings.

Use `openings` when you want to compute the open-loop response at one analysis-point location with other loops also open at other locations. For example, in a cascaded loop configuration, you can calculate the inner loop open-loop response with the outer loop also open. Use `getPoints(T)` to get a full list of available analysis-point locations in `T`.

Output Arguments

`L` — Point-to-point open-loop response
generalized state-space model

Point-to-point open-loop response of the control system T measured at the analysis points specified by Locations, returned as a Generalized State-Space (`genss`) Model.

- If Locations is a string specifying a single analysis point, then `L` is a SISO `genss` model. In this case, `L` represents the response obtained by opening the loop at Locations, injecting signals and measuring the return signals at the same location.
- If Locations is a string specifying a vector signal, or a cell array identifying multiple analysis points, then `L` is a MIMO `genss` model. In this case, `L` represents the open-loop MIMO response obtained by opening loops at all locations listed in Locations, injecting signals and measuring the return signals at those locations.

More About

Tips

- You can use `getLoopTransfer` to extract open-loop responses given a generalized model of the overall control system. This is useful, for example, for validating open-loop responses of a control system that you tune with the Robust Control Toolbox tuning command `systune`.
- `getLoopTransfer` is the `genss` equivalent to the Simulink Control Design command `getLoopTransfer`, which works with the `slTuner` and `slLinearizer` interfaces. Use the Simulink Control Design command when your control system is modeled in Simulink.

See Also

`AnalysisPoint` | `genss` | `getIOTransfer` | `getLoopTransfer` | `getPoints` | `systune`

getNominal

Nominal value of Generalized LTI model or Generalized matrix

Note: `getNominal` has been removed. Use `getValue` instead.

---

getoptions

Return `@PlotOptions` handle or plot options property

Syntax

```
p = getoptions(h)
p = getoptions(h,propertyname)
```

Description

`p = getoptions(h)` returns the plot options handle associated with plot handle `h`. `p` contains all the settable options for a given response plot.

`p = getoptions(h,propertyname)` returns the specified options property, `propertyname`, for the plot with handle `h`. You can use this to interrogate a plot handle. For example,

```
p = getoptions(h,'Grid')
```

returns `'on'` if a grid is visible, and `'off'` when it is not.

For a list of the properties and values available for each plot type, see "Properties and Values Reference".

See Also

`setoptions`

getPeakGain

Peak gain of dynamic system frequency response

Syntax

```
gpeak = getPeakGain(sys)
gpeak = getPeakGain(sys,tol)
gpeak = getPeakGain(sys,tol,fband)
[gpeak,fpeak] = getPeakGain( ___ )
```

Description

`gpeak = getPeakGain(sys)` returns the peak input/output gain in absolute units of the dynamic system model, sys.

- If sys is a SISO model, then the peak gain is the largest value of the frequency response magnitude.
- If sys is a MIMO model, then the peak gain is the largest value of the frequency response 2-norm (the largest singular value across frequency) of sys. This quantity is also called the L_∞ norm of sys, and coincides with the H_∞ norm for stable systems.
- If sys is a model that has tunable or uncertain parameters, `getPeakGain` evaluates the peak gain at the current or nominal value of sys.
- If sys is a model array, `getPeakGain` returns an array of the same size as sys, where `gpeak(k) = getPeakGain(sys(:,:,k))` .

`gpeak = getPeakGain(sys,tol)` returns the peak gain of sys with relative accuracy tol.

`gpeak = getPeakGain(sys,tol,fband)` returns the peak gain in the frequency interval fband.

`[gpeak,fpeak] = getPeakGain( ___ )` also returns the frequency fpeak at which the gain achieves the peak value gpeak, and can include any of the input arguments in previous syntaxes.

Examples

Peak Gain of Transfer Function

Compute the peak gain of the resonance in the transfer function

$$sys = \frac{90}{s^2 + 1.5s + 90}.$$

```
sys = tf(90,[1,1.5,90]);
gpeak = getPeakGain(sys);
```

The `getPeakGain` command returns the peak gain in absolute units.

Peak Gain with Specified Accuracy

Compute the peak gain of the resonance in the transfer function $sys = \frac{90}{s^2 + 1.5s + 90}$. with a relative accuracy of 0.01%.

```
sys = tf(90,[1,1.5,90]);
gpeak = getPeakGain(sys,0.0001);
```

The second argument specifies a relative accuracy of 0.0001. The `getPeakGain` command returns a value that is within 0.01% of the true peak gain of the transfer function.

Peak Gain Within Specified Band

Compute the peak gain of the second resonance in the transfer function

$$sys = \left(\frac{1}{s^2 + 0.2s + 1}\right)\left(\frac{100}{s^2 + s + 100}\right).$$

`sys` is the product of resonances at 1 rad/s and 10 rad/s.

```
sys = tf(1,[1,.2,1])*tf(100,[1,1,100]);
fband = [8,12];
gpeak = getPeakGain(sys,0.01,fband);
```

The `fband` argument causes `getPeakGain` to return the local peak gain between 8 and 12 rad/s.

Frequency of Peak Gain

Identify which of the two resonances has higher gain in the transfer function

$$sys = \left(\frac{1}{s^2 + 0.2s + 1}\right)\left(\frac{100}{s^2 + s + 100}\right).$$

`sys` is the product of resonances at 1 rad/s and 10 rad/s.

```
sys = tf(1,[1,.2,1])*tf(100,[1,1,100]);
[gpeak,fpeak] = getPeakGain(sys)
```

```
gpeak =

    5.0502


fpeak =

    1.0000
```

`fpeak` is the frequency corresponding to the peak gain `gpeak`. The peak at 1 rad/s is the overall peak gain of `sys`.

Input Arguments

`sys` — Input dynamic system

dynamic system model | model array

Input dynamic system, specified as any dynamic system model or model array. sys can be SISO or MIMO.

`tol` — Relative accuracy

0.01 (default) | positive real scalar

Relative accuracy of the peak gain, specified as a positive real scalar value. `getPeakGain` calculates gpeak such that the fractional difference between gpeak and the true peak gain of sys is no greater than tol.

`fband` — Frequency interval
`[0,Inf]` (default) | 1-by-2 vector of positive real values

Frequency interval in which to calculate the peak gain, specified as a 1-by-2 vector of positive real values. Specify fband as a row vector of the form `[fmin,fmax]`.

Output Arguments

`gpeak` — Peak gain of dynamic system
scalar | array

Peak gain of the dynamic system model or model array sys, returned as a scalar value or an array.

- If sys is a single model, then gpeak is a scalar value.
- If sys is a model array, then gpeak is an array of the same size as sys, where `gpeak(k) = getPeakGain(sys(:,:,k))`.

`fpeak` — Frequency of peak gain
nonnegative real scalar | array of nonnegative real values

Frequency at which the gain achieves the peak value `gpeak`, returned as a nonnegative real scalar value or an array of nonnegative real values. The frequency is expressed in units of rad/`TimeUnit`, relative to the `TimeUnit` property of sys.

- If sys is a single model, then fpeak is a scalar.
- If sys is a model array, then fpeak is an array of the same size as sys, where `fpeak(k)` is the peak gain frequency of the *k*th model in the array.

More About

Algorithms

`getPeakGain` uses the algorithm of [1]. All eigenvalue computations are performed using structure-preserving algorithms from the SLICOT library. For more information about the SLICOT library, see http://slicot.org.

- “Dynamic System Models”

References

[1] Bruisma, N.A. and M. Steinbuch, "A Fast Algorithm to Compute the H_∞-Norm of a Transfer Function Matrix," *System Control Letters*, 14 (1990), pp. 287-293.

See Also

`bode` | `freqresp` | `getGainCrossover` | `sigma`

getSensitivity

Sensitivity function from generalized model of control system

Syntax

```
S = getSensitivity(T,location)
S = getSensitivity(T,location,opening)
```

Description

`S = getSensitivity(T,location)` returns the sensitivity function at the specified location for a generalized model of a control system.

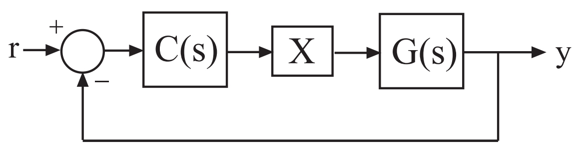
`S = getSensitivity(T,location,opening)` specifies additional loop openings for the sensitivity function calculation. Use an opening, for example, to calculate the sensitivity function of an inner loop, with the outer loop open.

If opening and location list the same point, the software opens the loop after measuring the signal at the point.

Examples

Sensitivity Function at a Location

Compute the sensitivity at the plant input, marked by the analysis point `X`.



Create a model of the system by specifying and connecting a numeric LTI plant model `G`, a tunable controller `C`, and the `AnalysisPoint` block `X`. Use the `AnalysisPoint` block to mark the location where you assess the sensitivity (plant input in this example).

```
G = tf([1],[1 5]);
C = ltiblock.pid('C','p');
C.Kp.Value = 3;
X = AnalysisPoint('X');
T = feedback(G*X*C,1);
```

`T` is a `genss` model that represents the closed-loop response of the control system from r to y. The model contains the `AnalysisPoint` block, `X`, that identifies the analysis point.

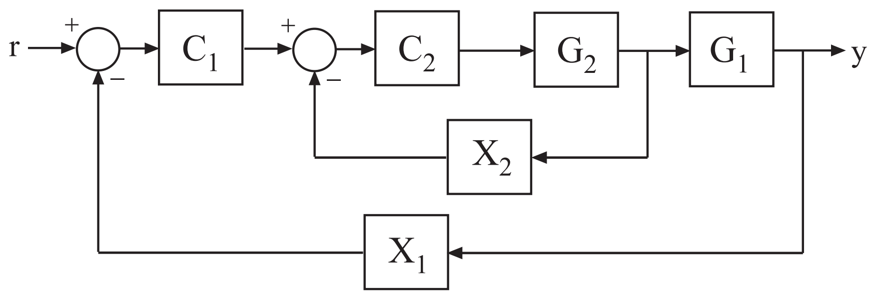
Calculate the sensitivity, S, at `X`.

```
S = getSensitivity(T,'X');
tf(S)
```

```
ans =

  From input "X" to output "X":
  s + 5
  -----
  s + 8

Continuous-time transfer function.
```

Specify Additional Loop Opening for Sensitivity Function Calculation

Calculate the inner-loop sensitivity at the output of `G2`, with the outer loop open.



Create a model of the system by specifying and connecting the numeric plant models, tunable controllers, and `AnalysisPoint` blocks. `G1` and `G2` are plant models, `C1` and `C2` are tunable controllers, and `X1` and `X2` are `AnalysisPoint` blocks that mark potential loop-opening locations.

```
G1 = tf(10,[1 10]);
```

```
G2 = tf([1 2],[1 0.2 10]);
C1 = ltiblock.pid('C','pi');
C2 = ltiblock.gain('G',1);
X1 = AnalysisPoint('X1');
X2 = AnalysisPoint('X2');
T = feedback(G1*feedback(G2*C2,X2)*C1,X1);
```

Calculate the sensitivity, S, at `X2`, with the outer loop open at `X1`.

```
S = getSensitivity(T,'X2','X1');
tf(S)
```

```
ans =

  From input "X2" to output "X2":
  s^2 + 0.2 s + 10
  ----------------
  s^2 + 1.2 s + 12

Continuous-time transfer function.
```

Input Arguments

`T` — Model of control system

generalized state-space model

Model of a control system, specified as a Generalized State-Space Model (`genss`).

Locations at which you can perform sensitivity analysis or open loops are marked by `AnalysisPoint` blocks in `T`. Use `getPoints(T)` to get the list of such locations.

`location` — Location

string | cell array of strings

Location at which you calculate the sensitivity function, specified as a string or cell array of strings. To extract the sensitivity function at multiple locations, use a cell array of strings.

Each string in location must match an analysis point in T. Analysis points are marked using `AnalysisPoint` blocks. Use `getPoints(T)` to get the list of available analysis points in T.

Example: `'u'` or `{'u','y'}`

`opening` — Additional loop opening

string | cell array of strings

Additional loop opening used to calculate the sensitivity function, specified as a string or cell array of strings. To open the loop at multiple locations, use a cell array of strings.

Each string in opening must match an analysis point in T. Analysis points are marked using `AnalysisPoint` blocks. Use `getPoints(T)` to get the list of available analysis points in T.

Use an opening, for example, to calculate the sensitivity function of an inner loop, with the outer loop open.

If opening and location list the same point, the software opens the loop after measuring the signal at the point.

Example: `'y_outer'` or `{'y_outer','y_outer2'}`

Output Arguments

`S` — Sensitivity function

generalized state-space model

Sensitivity function of the control system, T, measured at location, returned as a Generalized State-Space Model (`genss`).

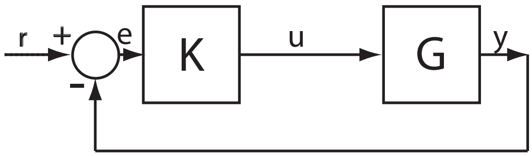
- If location specifies a single analysis point, then `S` is a SISO `genss` model.
- If location is a string specifying a vector signal, or a cell array identifying multiple analysis points, then `S` is a MIMO `genss` model.

More About

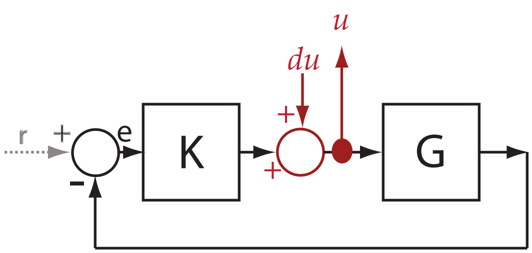
Sensitivity Function

The *sensitivity function*, also referred to simply as *sensitivity*, measures how sensitive a signal is to an added disturbance. Feedback reduces the sensitivity in the frequency band where the open-loop gain is greater than `1`.

Consider the following model:



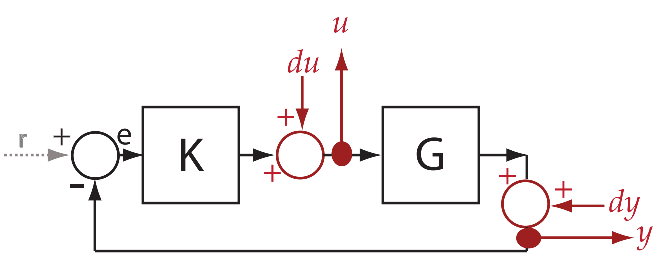
The sensitivity, S_u, at u is defined as the transfer function from du to u:



$$
\begin{aligned}
& u = du - KGu \\
& \rightarrow (I + KG)u = du \\
& \rightarrow u = \underbrace{(I + KG)^{-1}}_{S_u} du.
\end{aligned}
$$

Here, I is an identity matrix of the same size as KG.

Sensitivity at multiple locations, for example, u and y, is defined as the MIMO transfer function from the disturbances to sensitivity measurements:



$$
S = \begin{bmatrix} S_{du \rightarrow u} & S_{dy \rightarrow u} \\ S_{du \rightarrow y} & S_{dy \rightarrow y} \end{bmatrix}.
$$

See Also

| `AnalysisPoint` | `genss` | `getCompSensitivity` | `getIOTransfer` | `getLoopTransfer` | `getPoints` | `getSensitivity` | `getValue` | `systune`

getPoints

Get list of analysis points in generalized model of control system

Syntax

```
points = getPoints(T)
```

Description

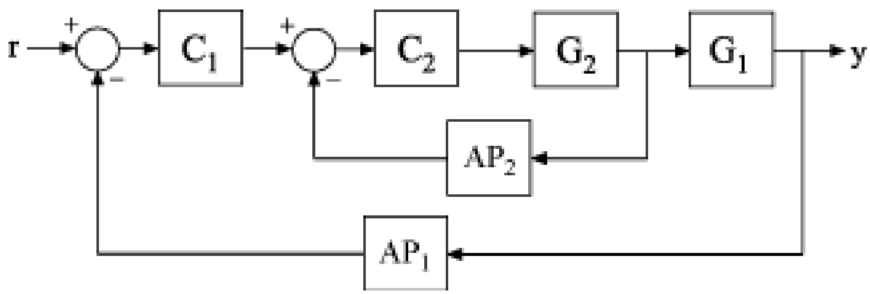
`points = getPoints(T)` returns the names of all analysis-point locations in a generalized state-space model of a control system. Use this function to query the list of available analysis points in the model for control system analysis or tuning. You can refer to the analysis-point locations by name to create design goals control system tuning or to compute open-loop and closed-loop responses using analysis commands such as `getLoopTransfer` and `getIOTransfer`.

Examples

Analysis-Point Locations in Control System Model

Build a closed-loop model of a cascaded feedback loop system, and get a list of analysis point locations in the model.

Create a model of the following cascaded feedback loop. C_1 and C_2 are tunable controllers. AP_1 and AP_2 are points of interest for analysis, which you mark with `AnalysisPoint` blocks.



```
G1 = tf(10,[1 10]);
G2 = tf([1 2],[1 0.2 10]);
C1 = ltiblock.pid('C','pi');
C2 = ltiblock.gain('G',1);
AP1 = AnalysisPoint('AP1');
AP2 = AnalysisPoint('AP2');
T = feedback(G1*feedback(G2*C2,AP2)*C1,AP1);
```

`T` is a `genss` model whose Control Design Blocks include the tunable controllers and the switches `AP1` and `AP2`.

Get a list of the loop-opening sites in `T`.

```
points = getPoints(T)
```

```
points =

    'AP1'
    'AP2'
```

`getPoints` returns a cell array listing loop-opening sites in the model.

For more complicated closed-loop models, you can use `getPoints` to keep track of a larger number of analysis points.

Input Arguments

`T` — Model of control system

generalized state-space model

Model of a control system, specified as a generalized state-space (`genss`) model. Locations in the model at which you can calculate system responses or specify design goals for tuning are marked by `AnalysisPoint` blocks in `T`.

Output Arguments

`points` — Analysis-points locations

cell array of strings

Analysis-point locations in the control system model, returned as a cell array of strings. This output is obtained by concatenating the `Location` properties of all `AnalysisPoint` blocks in the control system model.

More About

- “Generalized Models”

See Also

`AnalysisPoint` | `genss` | `getIOTransfer` | `getLoopTransfer`

getValue

Current value of Generalized Model

Syntax

```
curval = getValue(M)
curval = getValue(M,blockvalues)
curval = getValue(M,Mref)
```

Description

`curval = getValue(M)` returns the current value curval of the Generalized LTI model or Generalized matrix M. The current value is obtained by replacing all Control Design Blocks in `M` by their current value. (For uncertain blocks, the "current value" is the nominal value of the block.)

`curval = getValue(M,blockvalues)` uses the block values specified in the structure blockvalues to compute the current value. The field names and values of blockvalues specify the block names and corresponding values. Blocks of M not specified in blockvalues are replaced by their current values.

`curval = getValue(M,Mref)` inherits block values from the generalized model Mref. This syntax is equivalent to curval = getValue(M,`Mref.Blocks`). Use this syntax to evaluate the current value of M using block values computed elsewhere (for example, tuned values obtained with Robust Control Toolbox tuning commands such as `systune`, `looptune`, or `hinfstruct`).

Input Arguments

`M`

Generalized LTI model or Generalized matrix.

`blockvalues`

Structure specifying blocks of M to replace and the values with which to replace those blocks.

The field names of blockvalues match names of Control Design Blocks of M. Use the field values to specify the replacement values for the corresponding blocks of M. The field values can be numeric values, dynamic system models, or static models. If some field values are Control Design Blocks or Generalized LTI models, the current values of those models are used to compute curval.

`Mref`

Generalized LTI model. If you provide Mref, `getValue` computes curval using the current values of the blocks in Mref whose names match blocks in M.

Output Arguments

`curval`

Numeric array or Numeric LTI model representing the current value of M.

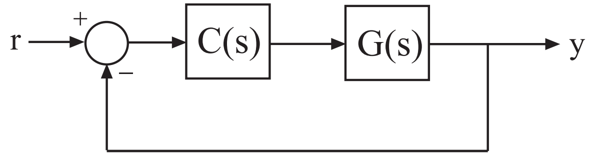
If you do not specify a replacement value for a given Control Design Block of M, `getValue` uses the current value of that block.

Examples

Evaluate Model for Specified Values of its Blocks

This example shows how to replace a Control Design Block in a Generalized LTI model with a specified replacement value using `getValue`.

Consider the following closed-loop system:



The following code creates a `genss` model of this system with $G(s) = \frac{(s-1)}{(s+1)^3}$ and a tunable PI controller C.

```
G = zpk(1,[-1,-1,-1],1);
C = ltiblock.pid('C','pi');
Try = feedback(G*C,1)
```

The `genss` model `Try` has one Control Design Block, `C`. The block `C` is initialized to default values, and the model `Try` has a current value that depends on the current value of `C`. Use `getValue` to evaluate `C` and `Try` to examine the current values.

1. Evaluate `C` to obtain its current value.

   ```
   Cnow = getValue(C)
   ```

   This command returns a numeric `pid` object whose coefficients reflect the current values of the tunable parameters in `C`.
2. Evaluate `Try` to obtain its current value.

   ```
   Tnow = getValue(Try)
   ```

   This commend returns a numeric model that is equivalent to `feedback(G*Cnow,1)`.

Access Values of Tuned Models and Blocks

Propagate changes in block values from one model to another using `getValue`.

This technique is useful for accessing values of models and blocks tuned with Robust Control Toolbox tuning commands such as `systune`, `looptune`, or `hinfstruct`. For example, if you have a closed-loop model of your control system `T0`, with two tunable blocks, `C1` and `C2`, you can tune it using:

```
[T,fSoft] = systune(T0,SoftReqs);
```

You can then access the tuned values of `C1` and `C2`, as well as any closed-loop model `H` that depends on `C1` and `C2`, using the following:

```
C1t = getValue(C1,T);
C2t = getValue(C2,T);
Ht = getValue(H,T);
```

See Also

`genss` | `replaceBlock` | `systune` | `looptune` | `hinfstruct`

gram

Controllability and observability gramians

Syntax

```
Wc = gram(sys,'c')
Wc = gram(sys,'o')
```

Description

`Wc = gram(sys,'c')` calculates the controllability gramian of the state-space (`ss`) model sys.

`Wc = gram(sys,'o')` calculates the observability gramian of the `ss` model sys.

You can use gramians to study the controllability and observability properties of state-space models and for model reduction [1] . They have better numerical properties than the controllability and observability matrices formed by `ctrb` and `obsv`.

Given the continuous-time state-space model

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$

the controllability gramian is defined by

$$W_c = \int_0^\infty e^{A\tau} BB^T e^{A^T\tau} d\tau$$

The controllability gramian is positive definite if and only if (A, B) is controllable.

The observability gramian is defined by

$$W_o = \int_0^\infty e^{A^T\tau} C^T C e^{A\tau} d\tau$$

The observability gramian is positive definite if and only if (A, C) is observable.

The discrete-time counterparts of the controllability and observability gramians are

$$W_c = \sum_{k=0}^{\infty} A^k BB^T (A^T)^k, \quad W_o = \sum_{k=0}^{\infty} (A^T)^k C^T CA^k$$

respectively.

Limitations

The A matrix must be stable (all eigenvalues have negative real part in continuous time, and magnitude strictly less than one in discrete time).

More About

Algorithms

The controllability gramian W_c is obtained by solving the continuous-time Lyapunov equation

$$AW_c + W_c A^T + BB^T = 0$$

or its discrete-time counterpart

$$AW_c A^T - W_c + BB^T = 0$$

Similarly, the observability gramian W_o solves the Lyapunov equation

$$A^T W_o + W_o A + C^T C = 0$$

in continuous time, and the Lyapunov equation

$$A^T W_o A - W_o + C^T C = 0$$

in discrete time.

References

[1] Kailath, T., *Linear Systems*, Prentice-Hall, 1980.

See Also

`balreal` | `ctrb` | `lyap` | `dlyap` | `obsv`

hasdelay

True for linear model with time delays

Syntax

```
B = hasdelay(sys)
B = hasdelay(sys,'elem')
```

Description

`B = hasdelay(sys)` returns 1 (true) if the model `sys` has input delays, output delays, I/O delays, or internal delays, and 0 (false) otherwise. If `sys` is a model array, then `B` is true if least one model in `sys` has delays.

`B = hasdelay(sys,'elem')` returns a logical array of the same size as the model array `sys`. The logical array indicates which models in `sys` have delays.

See Also

`totaldelay` | `absorbDelay`

hasInternalDelay

Determine if model has internal delays

Syntax

```
B = hasInternalDelay(sys)
B = hasInternalDelay(sys,'elem')
```

Description

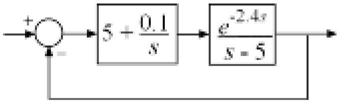
`B = hasInternalDelay(sys)` returns 1 (true) if the model sys has internal delays, and 0 (false) otherwise. If sys is a model array, then B is true if least one model in sys has delays.

`B = hasInternalDelay(sys,'elem')` checks each model in the model array sys and returns a logical array of the same size as sys. The logical array indicates which models in sys have internal delays.

Examples

Check model for internal delays

Build a dynamic system model of the following closed-loop system and check the model for internal delays.




```
s = tf('s');
G = exp(-2.4*s)/(s-5);
C = pid(5,0.1);
sys = feedback(G*C,1);
B = hasInternalDelay(sys)
```

```
B =
```

```
     1
```

The model `sys` has an internal delay because of the transfer delay in the plant `G`. Therefore, `hasInternalDelay` returns 1.

Input Arguments

`sys` — Model or array to check

dynamic system model | model array

Model or array to check for internal delays, specified as a dynamic system model or array of dynamic system models.

Output Arguments

`B` — Flag indicating presence of internal delays

logical | logical array

Flag indicating presence of internal delays in input model or array, returned as a logical value or logical array.

See Also

`getDelayModel` | `hasdelay`

hsvd

Hankel singular values of dynamic system

Syntax

```
hsv = hsvd(sys)
hsv = hsvd(sys,'AbsTol',ATOL,'RelTol',RTOL,'Offset',ALPHA)
hsv = hsvd(sys, opts)
hsvd(sys)
[hsv,baldata] = hsvd(sys)
```

Description

`hsv = hsvd(sys)` computes the Hankel singular values `hsv` of the dynamic system `sys`. In state coordinates that equalize the input-to-state and state-to-output energy transfers, the Hankel singular values measure the contribution of each state to the input/output behavior. Hankel singular values are to model order what singular values are to matrix rank. In particular, small Hankel singular values signal states that can be discarded to simplify the model (see `balred`).

For models with unstable poles, `hsvd` only computes the Hankel singular values of the stable part and entries of `hsv` corresponding to unstable modes are set to `Inf`.

`hsv = hsvd(sys,'AbsTol',ATOL,'RelTol',RTOL,'Offset',ALPHA)` specifies additional options for the stable/unstable decomposition. See the `stabsep` reference page for more information about these options. The default values are `ATOL = 0`, `RTOL = 1e-8`, and `ALPHA = 1e-8`.

`hsv = hsvd(sys, opts)` computes the Hankel singular values using the options specified in the `hsvdOptions` object `opts`.

`hsvd(sys)` displays a Hankel singular values plot.

`[hsv,baldata] = hsvd(sys)` returns additional data to speed up model order reduction with `balred`. For example

```
sys = rss(20);                % 20-th order model
[hsv,baldata] = hsvd(sys);
rsys = balred(sys,8:10,'Balancing',baldata);
bode(sys,'b',rsys,'r--')
```

computes three approximations of `sys` of orders 8, 9, 10.

There is more than one `hsvd` available. Type

```
help lti/hsvd
```

for more information.

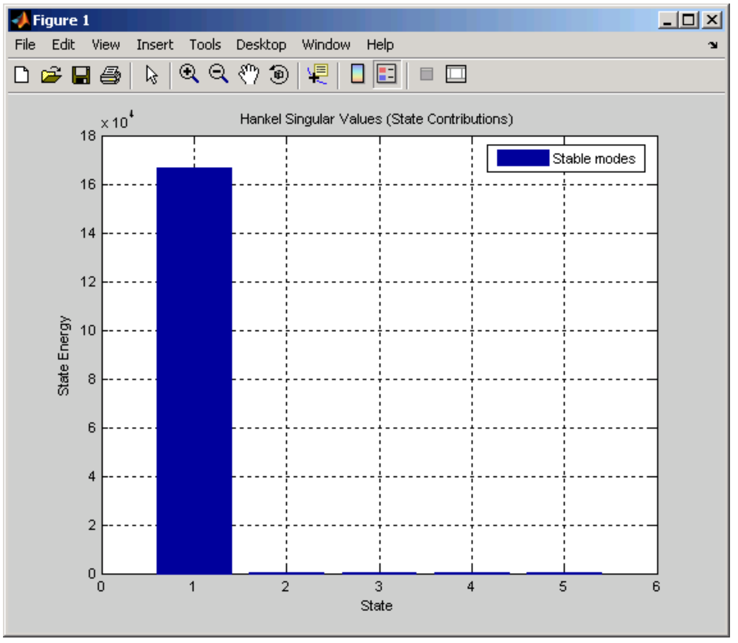
Examples

Compute Hankel Singular Values

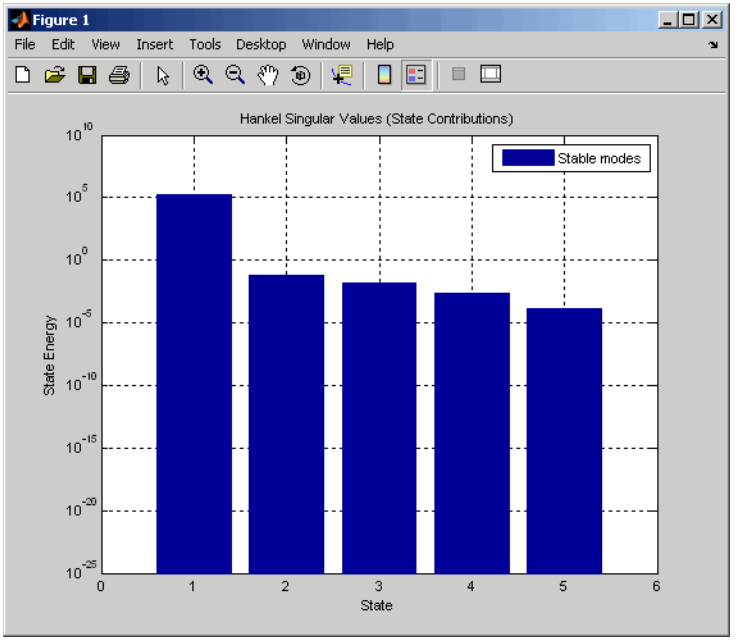
This example illustrates how to compute Hankel singular values.

First, create a system with a stable pole very near to 0, then calculate the Hankel singular values.

```
sys = zpk([1 2],[-1 -2 -3 -10 -1e-7],1)
hsvd(sys)

Zero/pole/gain:
            (s-1) (s-2)
-----------------------------------
(s+1) (s+2) (s+3) (s+10) (s+1e-007)
```

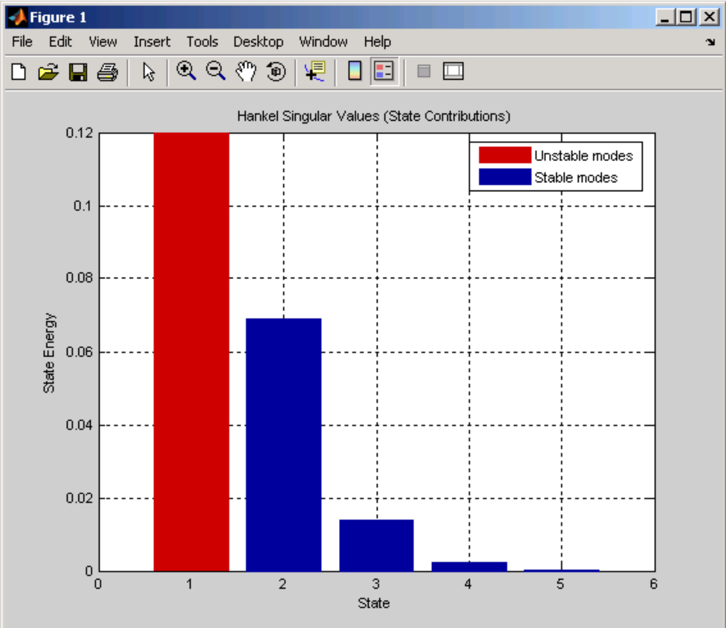


For a better view of the Hankel singular values, switch the plot to log scale by selecting **Y Scale** > **Log** from the right-click menu.



Notice the dominant Hankel singular value with 1e5 magnitude, due to the mode `s=-1e-7` near the imaginary axis. Set the `offset=1e-6` to treat this mode as unstable

```
hsvd(sys,'Offset',1e-7)
```



The dominant Hankel singular value is now shown as unstable.

More About

Tips

You can change the properties of your plot, for example the units. For information on the ways to change properties of your plots, see "Ways to Customize Plots".

Algorithms

The `AbsTol`, `RelTol`, and `ALPHA` parameters are only used for models with unstable or marginally stable dynamics. Because Hankel singular values are only meaningful for stable dynamics, `hsvd` must first split such models into the sum of their stable and unstable parts:

```
G = G_s + G_ns
```

This decomposition can be tricky when the model has modes close to the stability boundary (e.g., a pole at `s=-1e-10`), or clusters of modes on the stability boundary (e.g., double or triple integrators). While hsvd is able to overcome these difficulties in most cases, it sometimes produces unexpected results such as

1. Large Hankel singular values for the stable part.

   This happens when the stable part G_s contains some poles very close to the stability boundary. To force such modes into the unstable group, increase the 'Offset' option to slightly grow the unstable region.

2. Too many modes are labeled "unstable." For example, you see 5 red bars in the HSV plot when your model had only 2 unstable poles.

   The stable/unstable decomposition algorithm has built-in accuracy checks that reject decompositions causing a significant loss of accuracy in the frequency response. Such loss of accuracy arises, e.g., when trying to split a cluster of stable and unstable modes near s=0. Because such clusters are numerically equivalent to a multiple pole at s=0, it is actually desirable to treat the whole cluster as unstable. In some cases, however, large relative errors in low-gain frequency bands can trip the accuracy checks and lead to a rejection of valid decompositions. Additional modes are then absorbed into the unstable part G_ns, unduly increasing its order.

   Such issues can be easily corrected by adjusting the AbsTol and RelTol tolerances. By setting AbsTol to a fraction of smallest gain of interest in your model, you tell the algorithm to ignore errors below a certain gain threshold. By increasing RelTol, you tell the algorithm to sacrifice some relative model accuracy in exchange for keeping more modes in the stable part G_s.

See Also

hsvdOptions | balred | balreal

hsvdOptions

Create option set for computing Hankel singular values and input/output balancing

Syntax

```
opts = hsvdOptions
opts = hsvdOptions('OptionName', OptionValue)
```

Description

opts = hsvdOptions returns the default options for the hsvd and balreal commands.

opts = hsvdOptions('*OptionName*', *OptionValue*) accepts one or more comma-separated name/value pairs. Specify *OptionName* inside single quotes.

Input Arguments

Name-Value Pair Arguments

'AbsTol, RelTol'

Absolute and relative error tolerance for stable/unstable decomposition. Positive scalar values. For an input model G with unstable poles, hsvd and balreal first extract the stable dynamics by computing the stable/unstable decomposition $G \rightarrow GS + GU$. The AbsTol and RelTol tolerances control the accuracy of this decomposition by ensuring that the frequency responses of G and $GS + GU$ differ by no more than AbsTol + RelTol*abs(G). Increasing these tolerances helps separate nearby stable and unstable modes at the expense of accuracy. See stabsep for more information.

Default: AbsTol = 0; RelTol = 1e-8

'Offset'

Offset for the stable/unstable boundary. Positive scalar value. In the stable/unstable decomposition, the stable term includes only poles satisfying:

- `Re(s) < -Offset * max(1,|Im(s)|)` (Continuous time)
- `|z| < 1 - Offset` (Discrete time)

Increase the value of `Offset` to treat poles close to the stability boundary as unstable.

Default: `1e-8`

For additional information on the options and how to use them, see the `hsvd` and `balreal` reference pages.

Examples

Compute the Hankel singular values of the system given by:

$$sys = \frac{(s+0.5)}{\left(s+10^{-6}\right)(s+2)}$$

Use the `Offset` option to force `hsvd` to exclude the pole at $s = 10^{-6}$ from the stable term of the stable/unstable decomposition.

```
sys = zpk(-.5,[-1e-6 -2],1);
opts = hsvdOptions('Offset',.001); % create option set
hsvd(sys,opts)  % treats -1e-6 as unstable
```

See Also

`hsvd` | `balreal`

hsvoptions

Create list of Hankel singular value plot options

Syntax

```
P = hsvoptions
P = HSVOPTIONS('cstpref')
```

Description

`P = hsvoptions` returns a list of available options for Hankel singular value (HSV) plots with default values set. You can use these options to customize the Hankel singular value plot appearance using the command line.

`P = HSVOPTIONS('cstpref')` initializes the plot options you selected in the Control System Toolbox Preferences Editor dialog box. For more information about the editor, see "Toolbox Preferences Editor" in the User's Guide documentation.

This table summarizes the Hankel singular value plot options.

Option	Description
Title, XLabel, YLabel	Label text and style
TickLabel	Tick label style
Grid [off|on]	Show or hide the grid
XlimMode, YlimMode	Limit modes
Xlim, Ylim	Axes limits
YScale [linear|log]	Scale for Y-axis
AbsTol, RelTol, Offset	Parameters for the Hankel singular value computation (used only for models with unstable dynamics). See `hsvd` and `stabsep` for details.

Examples

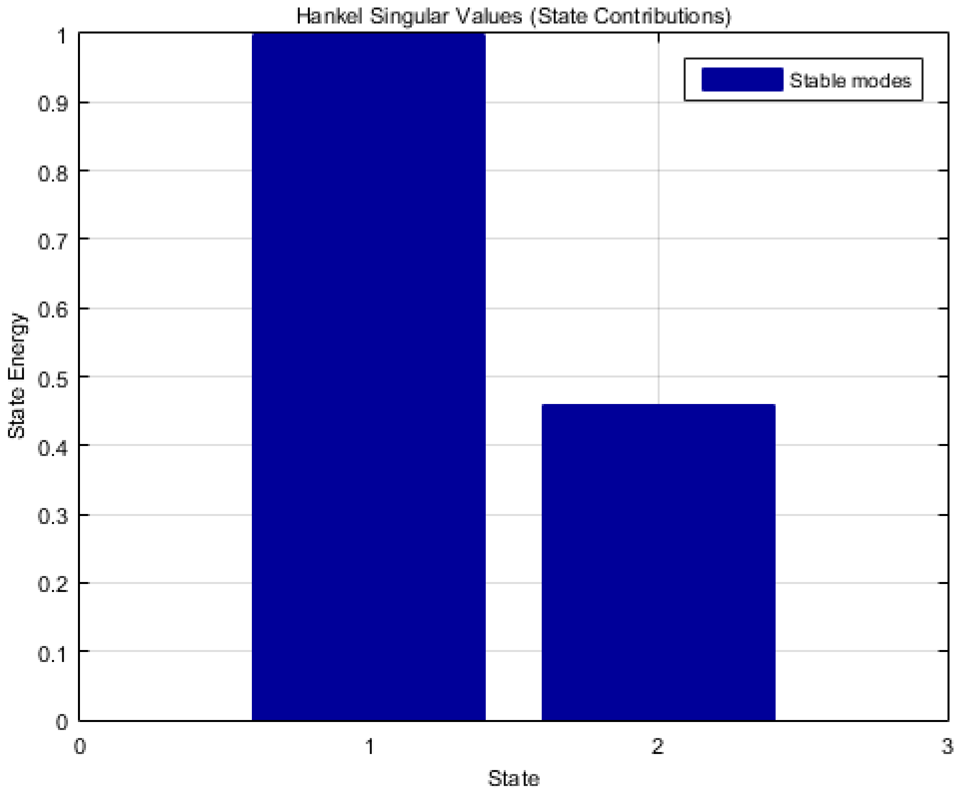
Set Scale for Y-Axis in HSV Plot

Create an options set, and set the `Yscale` property.

```
P = hsvoptions;
P.YScale = 'linear';
```

Use the options set to generate an HSV plot. Note the linear y-axis scale in the plot.

```
h = hsvplot(rss(2,2,3),P);
```



See Also

`hsvd` | `hsvplot` | `getoptions` | `setoptions` | `stabsep`

hsvplot

Plot Hankel singular values and return plot handle

Syntax

```
h = hsvplot(sys)
hsvplot(sys)
hsvplot(sys, AbsTol',ATOL,'RelTol',RTOL,'Offset',ALPHA)
hsvplot(AX,sys,...)
```

Description

`h = hsvplot(sys)` plots the Hankel singular values of an LTI system `sys` and returns the plot handle `h`. You can use this handle to customize the plot with the `getoptions` and `setoptions` commands. Type

```
help hsvoptions
```

for a list of available plot options.

`hsvplot(sys)` plots the Hankel singular values of the LTI model `sys`. See `hsvd` for details on the meaning and purpose of Hankel singular values. The Hankel singular values for the stable and unstable modes of `sys` are shown in blue and red, respectively.

`hsvplot(sys, AbsTol',ATOL,'RelTol',RTOL,'Offset',ALPHA)` specifies additional options for computing the Hankel singular values.

`hsvplot(AX,sys,...)` attaches the plot to the axes with handle `AX`.

Examples

Use the plot handle to change plot options in the Hankel singular values plot.

```
sys = rss(20);
h = hsvplot(sys,'AbsTol',1e-6);
% Switch to log scale and modify Offset parameter
```

```
setoptions(h,'Yscale','log','Offset',0.3)
```

More About

Tips

You can change the properties of your plot, for example the units. For information on the ways to change properties of your plots, see “Ways to Customize Plots”.

See Also

getoptions | hsvd | hsvoptions | setoptions

imp2exp

Convert implicit linear relationship to explicit input-output relation

Syntax

```
B = imp2exp(A,yidx,uidx)
```

Description

`B = imp2exp(A,yidx,uidx)` transforms a linear constraint between variables `Y` and `U` of the form `A(:,[yidx;uidx])*[Y;U] = 0` into an explicit input/output relationship `Y = B*U`. The vectors `yidx` and `uidx` refer to the columns (inputs) of `A` as referenced by the explicit relationship for `B`.

The constraint matrix `A` can be a `double, ss, tf, zpk` and `frd` object as well as an uncertain object, including `umat`, `uss` and `ufrd`. The result `B` will be of the same class.

Examples

Scalar Algebraic Constraint

Consider the constraint `4y + 7u = 0`. Solving for `y` gives `y = 1.75u`. You form the equation using `imp2exp`:

```
A = [4 7];
Yidx = 1;
Uidx = 2;
```

and then

```
B = imp2exp(A,Yidx,Uidx)
B =
   -1.7500
```

yields `B` equal to `-1.75`.

Matrix Algebraic Constraint

Consider two motor/generator constraints among 4 variables `[V;I;T;W]`, namely `[1 -1 0 -2e-3;0 -2e-3 1 0]*[V;I;T;W] = 0`. You can find the 2-by-2 matrix `B` so that `[V;T] = B*[W;I]` using `imp2exp`.

```
A = [1 -1 0 -2e-3;0 -2e-3 1 0];
Yidx = [1 3];
Uidx = [4 2];
B = imp2exp(A,Yidx,Uidx)
B =
    0.0020    1.0000
         0    0.0020
```

You can find the 2-by-2 matrix `C` so that `[I;W] = C*[T;V]`

```
Yidx = [2 4];
Uidx = [3 1];
C = imp2exp(A,Yidx,Uidx)
C =
         500            0
     -250000          500
```

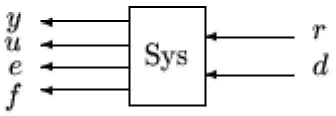
Uncertain Matrix Algebraic Constraint

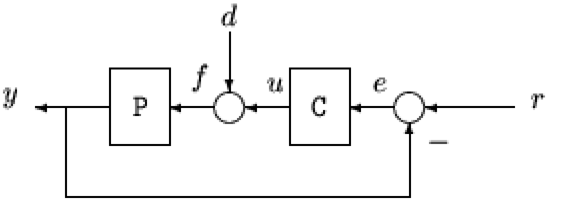
Consider two uncertain motor/generator constraints among 4 variables `[V;I;T;W]`, namely `[1 -R 0 -K;0 -K 1 0]*[V;I;T;W] = 0`. You can find the uncertain 2-by-2 matrix `B` so that `[V;T] = B*[W;I]`.

```
R = ureal('R',1,'Percentage',[-10 40]);
K = ureal('K',2e-3,'Percentage',[-30 30]);
A = [1 -R 0 -K;0 -K 1 0];
Yidx = [1 3];
Uidx = [4 2];
B = imp2exp(A,Yidx,Uidx)
UMAT: 2 Rows, 2 Columns
  K: real, nominal = 0.002, variability = [-30  30]%, 2 occurrences
  R: real, nominal = 1, variability = [-10  40]%, 1 occurrence
```

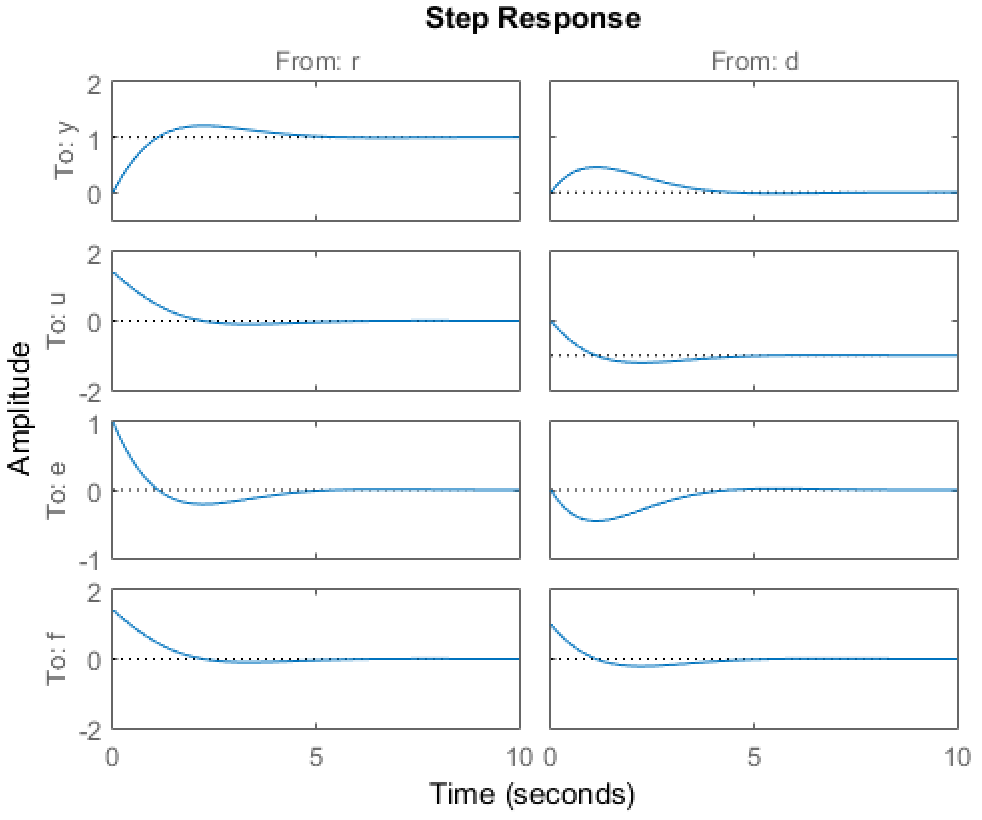
Scalar Dynamic System Constraint

Consider a standard single-loop feedback connection of controller `C` and an uncertain plant `P`, described by the equations `e = r-y; u = Ce; f = d+u; y = Pf`.






```
P = tf([1],[1 0]);
C = tf([2*.707*1 1^2],[1 0]);
A = [1 -1 0 0 0 -1;0 -C 1 0 0 0;0 0 -1 -1 1 0;0 0 0 0 -P 1];
OutputIndex = [6;3;2;5];  % [y;u;e;f]
InputIndex = [1;4];       % [r;d]
Sys = imp2exp(A,OutputIndex,InputIndex);
Sys.InputName = {'r';'d'};
Sys.OutputName = {'y';'u';'e';'f'};

pole(Sys)


ans =

  -0.7070 + 0.7072i
  -0.7070 - 0.7072i
  -0.7070 + 0.7072i
  -0.7070 - 0.7072i


stepplot(Sys)
```



More About

Algorithms

The number of rows of `A` must equal the length of `yidx`.

See Also

`iconnect` | `inv`

impulse

Impulse response plot of dynamic system; impulse response data

Syntax

```
impulse(sys)
impulse(sys,Tfinal)
impulse(sys,t)
impulse(sys1,sys2,...,sysN)
impulse(sys1,sys2,...,sysN,Tfinal)
impulse(sys1,sys2,...,sysN,t)
[y,t] = impulse(sys)
[y,t] = impulse(sys,Tfinal)
y = impulse(sys,t)
[y,t,x] = impulse(sys)
[y,t,x,ysd] = impulse(sys)
```

Description

`impulse` calculates the unit impulse response of a dynamic system model. For continuous-time dynamic systems, the impulse response is the response to a Dirac input $\delta(t)$. For discrete-time systems, the impulse response is the response to a unit area pulse of length `Ts` and height `1/Ts`, where `Ts` is the sample time of the system. (This pulse approaches $\delta(t)$ as `Ts` approaches zero.) For state-space models, `impulse` assumes initial state values are zero.

`impulse(sys)` plots the impulse response of the dynamic system model `sys`. This model can be continuous or discrete, and SISO or MIMO. The impulse response of multi-input systems is the collection of impulse responses for each input channel. The duration of simulation is determined automatically to display the transient behavior of the response.

`impulse(sys,Tfinal)` simulates the impulse response from `t = 0` to the final time `t = Tfinal`. Express `Tfinal` in the system time units, specified in the `TimeUnit` property of `sys`. For discrete-time systems with unspecified sample time (`Ts = -1`), `impulse` interprets `Tfinal` as the number of sampling periods to simulate.

`impulse(sys,t)` uses the user-supplied time vector `t` for simulation. Express `t` in the system time units, specified in the `TimeUnit` property of `sys`. For discrete-time models, `t` should be of the form `Ti:Ts:Tf`, where `Ts` is the sample time. For continuous-time models, `t` should be of the form `Ti:dt:Tf`, where `dt` becomes the sample time of a discrete approximation to the continuous system (see “Algorithms” on page 1-322). The `impulse` command always applies the impulse at `t=0`, regardless of `Ti`.

To plot the impulse responses of several models `sys1`,..., `sysN` on a single figure, use:

```
impulse(sys1,sys2,...,sysN)
```

```
impulse(sys1,sys2,...,sysN,Tfinal)
```

```
impulse(sys1,sys2,...,sysN,t)
```

As with `bode` or `plot`, you can specify a particular color, linestyle, and/or marker for each system, for example,

```
impulse(sys1,'y:',sys2,'g--')
```

See "Plotting and Comparing Multiple Systems" and the `bode` entry in this section for more details.

When invoked with output arguments:

```
[y,t] = impulse(sys)
```

```
[y,t] = impulse(sys,Tfinal)
```

```
y = impulse(sys,t)
```

`impulse` returns the output response `y` and the time vector `t` used for simulation (if not supplied as an argument to impulse). No plot is drawn on the screen. For single-input systems, `y` has as many rows as time samples (length of `t`), and as many columns as outputs. In the multi-input case, the impulse responses of each input channel are stacked up along the third dimension of `y`. The dimensions of `y` are then

For state-space models only:

```
[y,t,x] = impulse(sys)
```
(length of t) × (number of outputs) × (number of inputs)

and `y(:,:,j)` gives the response to an impulse disturbance entering the `j`th input channel. Similarly, the dimensions of `x` are
(length of t) × (number of states) × (number of inputs)

`[y,t,x,ysd] = impulse(sys)` returns the standard deviation `YSD` of the response `Y` of an identified system `SYS`. `YSD` is empty if `SYS` does not contain parameter covariance information.

Examples

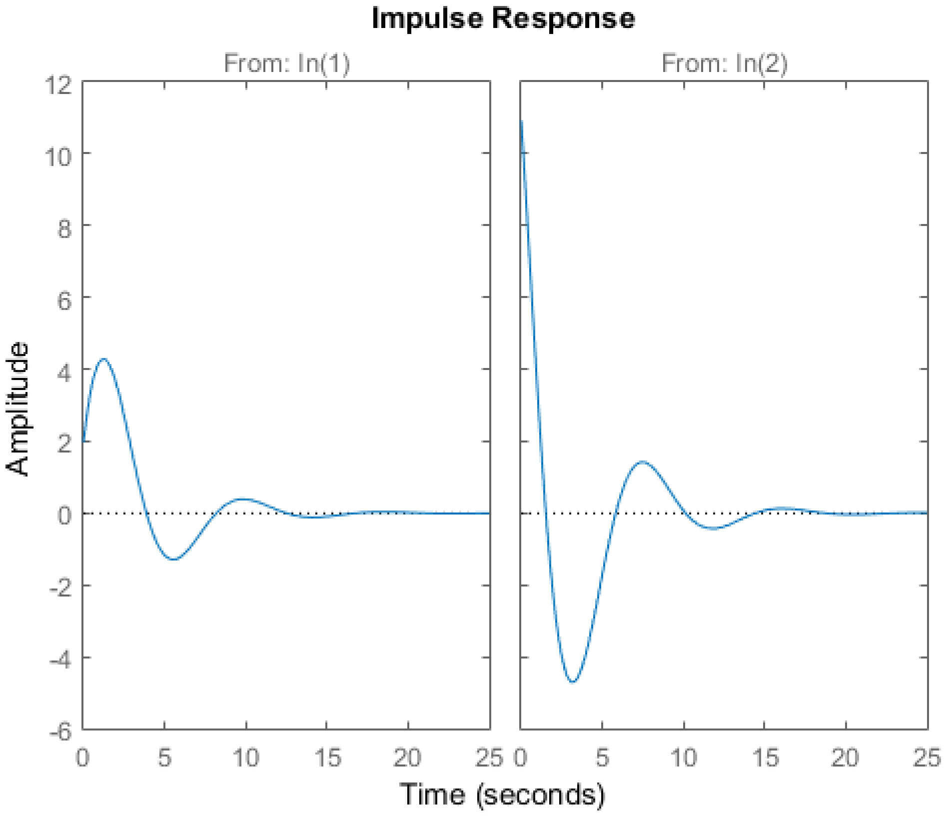
Impulse Response Plot of Second-Order State-Space Model

Plot the impulse response of the second-order state-space model

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} -0.5572 & -0.7814 \\ 0.7814 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 1 & -1 \\ 0 & 2 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix}$$

$$y = \begin{bmatrix} 1.9691 & 6.4493 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

```
a = [-0.5572 -0.7814;0.7814  0];
b = [1 -1;0 2];
c = [1.9691  6.4493];
sys = ss(a,b,c,0);
impulse(sys)
```



The left plot shows the impulse response of the first input channel, and the right plot shows the impulse response of the second input channel.

You can store the impulse response data in MATLAB arrays by

```
[y,t] = impulse(sys);
```

Because this system has two inputs, `y` is a 3-D array with dimensions

```
size(y)
```

```
ans =

   139     1     2
```

(the first dimension is the length of `t`). The impulse response of the first input channel is then accessed by

```
ch1 = y(:,:,1);
size(ch1)
```

```
ans =

   139     1
```

Impulse Data from Identified System

Fetch the impulse response and the corresponding 1 std uncertainty of an identified linear system .

```
load(fullfile(matlabroot, 'toolbox', 'ident', 'iddemos', 'data', 'dcmotordata'));
z = iddata(y, u, 0.1, 'Name', 'DC-motor');
set(z, 'InputName', 'Voltage', 'InputUnit', 'V');
set(z, 'OutputName', {'Angular position', 'Angular velocity'});
set(z, 'OutputUnit', {'rad', 'rad/s'});
set(z, 'Tstart', 0, 'TimeUnit', 's');

model = tfest(z,2);
[y,t,~,ysd] = impulse(model,2);

% Plot 3 std uncertainty
subplot(211)
plot(t,y(:,1), t,y(:,1)+3*ysd(:,1),'k:', t,y(:,1)-3*ysd(:,1),'k:')
subplot(212)
plot(t,y(:,2), t,y(:,2)+3*ysd(:,2),'k:', t,y(:,2)-3*ysd(:,2),'k:')
```

Limitations

The impulse response of a continuous system with nonzero D matrix is infinite at $t = 0$. `impulse` ignores this discontinuity and returns the lower continuity value Cb at $t = 0$.

More About

Tips

You can change the properties of your plot, for example the units. For information on the ways to change properties of your plots, see "Ways to Customize Plots".

Algorithms

Continuous-time models are first converted to state space. The impulse response of a single-input state-space model

$$\dot{x} = Ax + bu$$
$$y = Cx$$

is equivalent to the following unforced response with initial state b.

$$\dot{x} = Ax, \quad x(0) = b$$
$$y = Cx$$

To simulate this response, the system is discretized using zero-order hold on the inputs. The sample time is chosen automatically based on the system dynamics, except when a time vector `t = 0:dt:Tf` is supplied (`dt` is then used as sample time).

See Also

`linearSystemAnalyzer` | `initial` | `step` | `lsim`

impulseplot

Plot impulse response and return plot handle

Syntax

```
impulseplot(sys)
impulseplot(sys,Tfinal)
impulseplot(sys,t)
impulseplot(sys1,sys2,...,sysN)
impulseplot(sys1,sys2,...,sysN,Tfinal)
impulseplot(sys1,sys2,...,sysN,t)
impulseplot(AX,...)
impulseplot(..., plotoptions)
h = impulseplot(...)
```

Description

`impulseplot` plots the impulse response of the dynamic system model `sys`. For multi-input models, independent impulse commands are applied to each input channel. The time range and number of points are chosen automatically. For continuous systems with direct feedthrough, the infinite pulse at t=0 is disregarded. `impulseplot` can also return the plot handle, `h`. You can use this handle to customize the plot with the `getoptions` and `setoptions` commands. Type

```
help timeoptions
```

for a list of available plot options.

`impulseplot(sys)` plots the impulse response of the LTI model without returning the plot handle.

`impulseplot(sys,Tfinal)` simulates the impulse response from `t = 0` to the final time `t = Tfinal`. Express `Tfinal` in the system time units, specified in the `TimeUnit` property of `sys`. For discrete-time systems with unspecified sample time (`Ts = -1`), `impulseplot` interprets `Tfinal` as the number of sampling intervals to simulate.

`impulseplot(sys,t)` uses the user-supplied time vector `t` for simulation. Express `t` in the system time units, specified in the `TimeUnit` property of `sys`. For discrete-time models, `t` should be of the form `Ti:Ts:Tf`, where `Ts` is the sample time. For continuous-time models, `t` should be of the form `Ti:dt:Tf`, where `dt` becomes the sample time of a discrete approximation to the continuous system (see `impulse`). The `impulseplot` command always applies the impulse at `t=0`, regardless of `Ti`.

To plot the impulse response of multiple LTI models `sys1`,`sys2`,... on a single plot, use:

`impulseplot(sys1,sys2,...,sysN)`

`impulseplot(sys1,sys2,...,sysN,Tfinal)`

`impulseplot(sys1,sys2,...,sysN,t)`

You can also specify a color, line style, and marker for each system, as in

```
impulseplot(sys1,'r',sys2,'y--',sys3,'gx')
```

`impulseplot(AX,...)` plots into the axes with handle `AX`.

`impulseplot(..., plotoptions)` plots the impulse response with the options specified in `plotoptions`. Type

```
help timeoptions
```

for more detail.

`h = impulseplot(...)` plots the impulse response and returns the plot handle `h`.

Examples

Example 1

Normalize the impulse response of a third-order system.

```
sys = rss(3);
h = impulseplot(sys);
% Normalize responses
setoptions(h,'Normalize','on');
```

Example 2

Plot the impulse response and the corresponding 1 std "zero interval" of an identified linear system.

```
load(fullfile(matlabroot, 'toolbox', 'ident', 'iddemos', 'data', 'dcmotordata'));
z = iddata(y, u, 0.1, 'Name', 'DC-motor');
set(z, 'InputName', 'Voltage', 'InputUnit', 'V');
set(z, 'OutputName', {'Angular position', 'Angular velocity'});
set(z, 'OutputUnit', {'rad', 'rad/s'});
set(z, 'Tstart', 0, 'TimeUnit', 's');
model = n4sid(z,4,n4sidOptions('Focus', 'simulation'));
h = impulseplot(model,2);
showConfidence(h);
```

More About

Tips

You can change the properties of your plot, for example the units. For information on the ways to change properties of your plots, see “Ways to Customize Plots”.

See Also

`impulse` | `setoptions` | `getoptions`

initial

Initial condition response of state-space model

Syntax

```
initial(sys,x0)
initial(sys,x0,Tfinal)
initial(sys,x0,t)
initial(sys1,sys2,...,sysN,x0)
initial(sys1,sys2,...,sysN,x0,Tfinal)
initial(sys1,sys2,...,sysN,x0,t)
[y,t,x] = initial(sys,x0)
[y,t,x] = initial(sys,x0,Tfinal)
[y,t,x] = initial(sys,x0,t)
```

Description

`initial(sys,x0)` calculates the unforced response of a state-space (`ss`) model `sys` with an initial condition on the states specified by the vector `x0`:

$$\dot{x} = Ax, \quad x(0) = x_0$$
$$y = Cx$$

This function is applicable to either continuous- or discrete-time models. When invoked without output arguments, `initial` plots the initial condition response on the screen.

`initial(sys,x0,Tfinal)` simulates the response from `t = 0` to the final time `t = Tfinal`. Express `Tfinal` in the system time units, specified in the `TimeUnit` property of `sys`. For discrete-time systems with unspecified sample time (`Ts = -1`), `initial` interprets `Tfinal` as the number of sampling periods to simulate.

`initial(sys,x0,t)` uses the user-supplied time vector `t` for simulation. Express `t` in the system time units, specified in the `TimeUnit` property of `sys`. For discrete-time models, `t` should be of the form `0:Ts:Tf`, where `Ts` is the sample time. For continuous-time models, `t` should be of the form `0:dt:Tf`, where `dt` becomes the sample time of a discrete approximation to the continuous system (see `impulse`).

To plot the initial condition responses of several LTI models on a single figure, use

```
initial(sys1,sys2,...,sysN,x0)
```

```
initial(sys1,sys2,...,sysN,x0,Tfinal)
```

```
initial(sys1,sys2,...,sysN,x0,t)
```

(see `impulse` for details).

When invoked with output arguments,

```
[y,t,x] = initial(sys,x0)
```

```
[y,t,x] = initial(sys,x0,Tfinal)
```

```
[y,t,x] = initial(sys,x0,t)
```

return the output response `y`, the time vector `t` used for simulation, and the state trajectories `x`. No plot is drawn on the screen. The array `y` has as many rows as time samples (length of `t`) and as many columns as outputs. Similarly, `x` has `length(t)` rows and as many columns as states.

Examples

Response of State-Space Model to Initial Condition

Plot the response of the following state-space model:

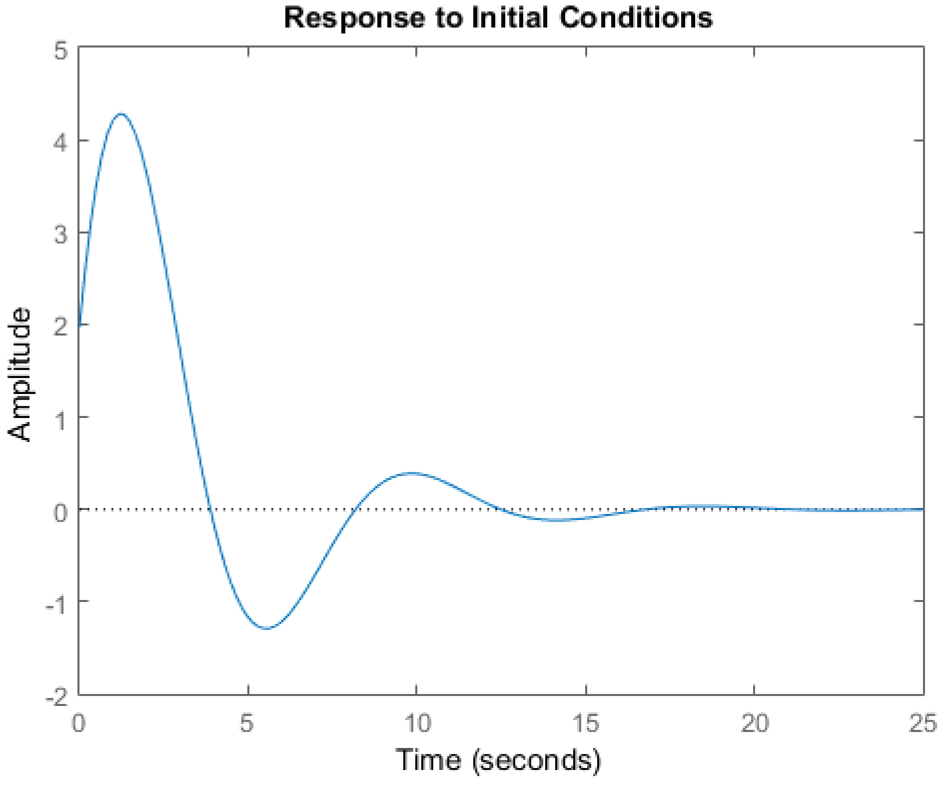
$$\begin{aligned} \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} &= \begin{bmatrix} -0.5572 & -0.7814 \\ 0.7814 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \\ y &= \begin{bmatrix} 1.9691 & 6.4493 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}. \end{aligned}$$

Take the following initial condition:

$$x(0) = \begin{bmatrix} 1 \\ 0 \end{bmatrix}.$$

```
a = [-0.5572, -0.7814; 0.7814, 0];
```

```
c = [1.9691  6.4493];
x0 = [1 ; 0];

sys = ss(a,[],c,[]);
initial(sys,x0)
```



More About

Tips

You can change the properties of your plot, for example the units. For information on the ways to change properties of your plots, see “Ways to Customize Plots”.

See Also

`impulse` | `lsim` | `linearSystemAnalyzer` | `step`

initialplot

Plot initial condition response and return plot handle

Syntax

```
initialplot(sys,x0)
initialplot(sys,x0,Tfinal)
initialplot(sys,x0,t)
initialplot(sys1,sys2,...,sysN,x0)
initialplot(sys1,sys2,...,sysN,x0,Tfinal)
initialplot(sys1,sys2,...,sysN,x0,t)
initialplot(AX,...)
initialplot(..., plotoptions)
h = initialplot(...)
```

Description

`initialplot(sys,x0)` plots the undriven response of the state-space (`ss`) model `sys` with initial condition `x0` on the states. This response is characterized by these equations:

Continuous time: x = A x, y = C x, x(0) = x0

Discrete time: x[k+1] = A x[k], y[k] = C x[k], x[0] = x0

The time range and number of points are chosen automatically. `initialplot` also returns the plot handle `h`. You can use this handle to customize the plot with the `getoptions` and `setoptions` commands. Type

```
help timeoptions
```

for a list of available plot options.

`initialplot(sys,x0,Tfinal)` simulates the response from `t = 0` to the final time `t = Tfinal`. Express `Tfinal` in the system time units, specified in the `TimeUnit` property of `sys`. For discrete-time systems with unspecified sample time (`Ts = -1`), `initialplot` interprets `Tfinal` as the number of sampling periods to simulate.

`initialplot(sys,x0,t)` uses the user-supplied time vector `t` for simulation. Express `t` in the system time units, specified in the `TimeUnit` property of `sys`. For discrete-time models, `t` should be of the form `0:Ts:Tf`, where `Ts` is the sample time. For continuous-time models, `t` should be of the form `0:dt:Tf`, where `dt` becomes the sample time of a discrete approximation to the continuous system (see `impulse`).

To plot the initial condition responses of several LTI models on a single figure, use

```
initialplot(sys1,sys2,...,sysN,x0)
```

```
initialplot(sys1,sys2,...,sysN,x0,Tfinal)
```

```
initialplot(sys1,sys2,...,sysN,x0,t)
```

You can also specify a color, line style, and marker for each system, as in

```
initialplot(sys1,'r',sys2,'y--',sys3,'gx',x0).
```

`initialplot(AX,...)` plots into the axes with handle `AX`.

`initialplot(..., plotoptions)` plots the initial condition response with the options specified in `plotoptions`. Type

```
help timeoptions
```

for more detail.

`h = initialplot(...)` plots the system response and returns the plot handle `h`.

Examples

Plot a third-order system's response to initial conditions and use the plot handle to change the plot's title.

```
sys = rss(3);
h = initialplot(sys,[1,1,1])
p = getoptions(h); % Get options for plot.
p.Title.String = 'My Title'; % Change title in options.
setoptions(h,p); % Apply options to the plot.
```

More About

Tips

You can change the properties of your plot, for example the units. For information on the ways to change properties of your plots, see “Ways to Customize Plots”.

See Also

`getoptions` | `initial` | `setoptions`

interp

Interpolate FRD model

Syntax

```
isys = interp(sys,freqs)
```

Description

`isys = interp(sys,freqs)` interpolates the frequency response data contained in the FRD model `sys` at the frequencies `freqs`. `interp`, which is an overloaded version of the MATLAB function `interp`, uses linear interpolation and returns an FRD model `isys` containing the interpolated data at the new frequencies `freqs`. If `sys` is an IDFRD model (requires System Identification Toolbox software), the noise spectrum, if non-empty, is also interpolated. The response and noise covariance data, if available, are also interpolated.

You should express the frequency values `freqs` in the same units as `sys.frequency`. The frequency values must lie between the smallest and largest frequency points in `sys` (extrapolation is not supported).

See Also

`freqresp` | `frd`

inv

Invert models

Syntax

`inv`

Description

`inv` inverts the input/output relation

$$y = G(s)u$$

to produce the model with the transfer matrix $H(s) = G(s)^{-1}$.

$$u = H(s)y$$

This operation is defined only for square systems (same number of inputs and outputs) with an invertible feedthrough matrix D. `inv` handles both continuous- and discrete-time systems.

Examples

Consider

$$H(s) = \begin{bmatrix} 1 & \frac{1}{s+1} \\ 0 & 1 \end{bmatrix}$$

At the MATLAB prompt, type

```
H = [1 tf(1,[1 1]);0 1]
Hi = inv(H)
```

to invert it. These commands produce the following result.

```
Transfer function from input 1 to output...
 #1:  1

 #2:  0

Transfer function from input 2 to output...
       -1
 #1:  -----
      s + 1

 #2:  1
```

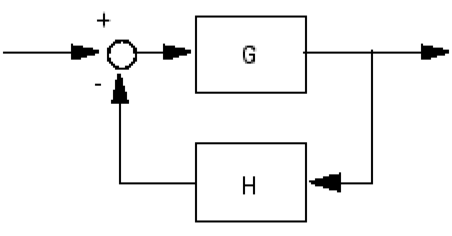
You can verify that

```
H * Hi
```

is the identity transfer function (static gain `I`).

Limitations

Do not use `inv` to model feedback connections such as



While it seems reasonable to evaluate the corresponding closed-loop transfer function $(I+GH)^{-1}G$ as

```
inv(1+g*h) * g
```

this typically leads to nonminimal closed-loop models. For example,

```
g = zpk([],1,1)
h = tf([2 1],[1 0])
cloop = inv(1+g*h) * g
```

yields a third-order closed-loop model with an unstable pole-zero cancellation at `s = 1`.

```
cloop

Zero/pole/gain:
      s (s-1)
-------------------
(s-1) (s^2 + s + 1)
```

Use `feedback` to avoid such pitfalls.

```
cloop = feedback(g,h)

Zero/pole/gain:
      s
-------------
(s^2 + s + 1)
```

iopzmap

Plot pole-zero map for I/O pairs of model

Syntax

```
iopzmap(sys)
iopzmap(sys1,sys2,...)
```

Description

`iopzmap(sys)` computes and plots the poles and zeros of each input/output pair of the dynamic system model `sys`. The poles are plotted as x's and the zeros are plotted as o's.

`iopzmap(sys1,sys2,...)` shows the poles and zeros of multiple models `sys1`,`sys2`,... on a single plot. You can specify distinctive colors for each model, as in `iopzmap(sys1,'r',sys2,'y',sys3,'g')`.

The functions `sgrid` or `zgrid` can be used to plot lines of constant damping ratio and natural frequency in the *s* or *z* plane.

For model arrays, `iopzmap` plots the poles and zeros of each model in the array on the same diagram.

Examples

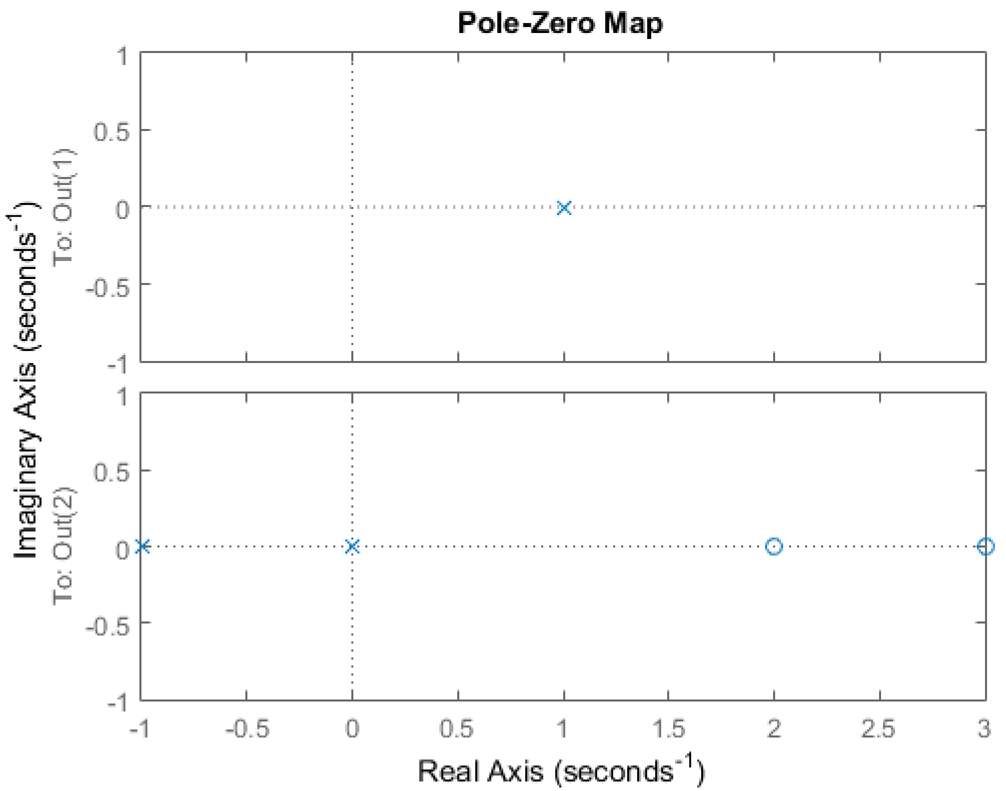
Pole-Zero Map for MIMO System

Create a one-input, two-output dynamic system.

```
H = [tf(-5 ,[1 -1]); tf([1 -5 6],[1 1 0])];
```

Plot a pole-zero map.

```
iopzmap(H)
```

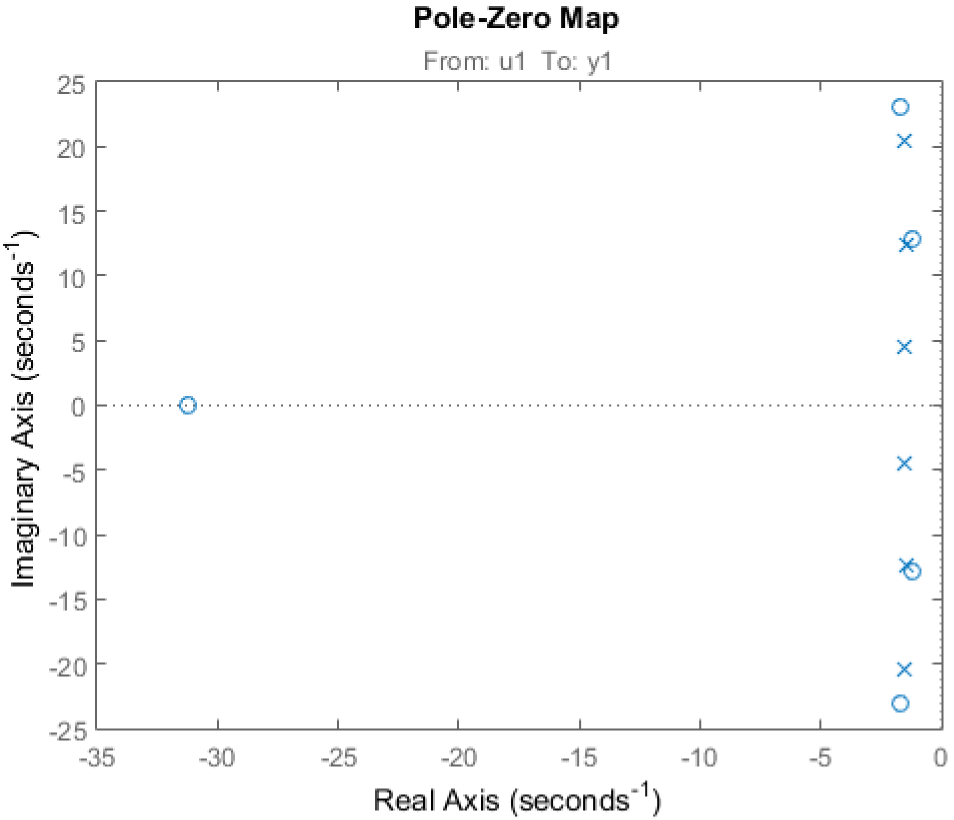


`iopzmap` generates a separate map for each I/O pair in the system.

Pole-Zero Map of Identified Model

View the poles and zeros of an over-parameterized state-space model estimated from input-output data. (Requires System Identification Toolbox™).

```
load iddata1
sys = ssest(z1,6,ssestOptions('focus','simulation'));
iopzmap(sys)
```



The plot shows that there are two pole-zero pairs that almost overlap, which hints are their potential redundancy.

More About

Tips

You can change the properties of your plot, for example the units. For information on the ways to change properties of your plots, see “Ways to Customize Plots”.

See Also

`pole` | `zero` | `sgrid` | `zgrid` | `iopzplot` | `pzmap`

iopzplot

Plot pole-zero map for I/O pairs and return plot handle

Syntax

```
h = iopzplot(sys)
iopzplot(sys1,sys2,...)
iopzplot(AX,...)
iopzplot(..., plotoptions)
```

Description

`h = iopzplot(sys)` computes and plots the poles and zeros of each input/output pair of the LTI model SYS. The poles are plotted as x's and the zeros are plotted as o's. It also returns the plot handle h. You can use this handle to customize the plot with the `getoptions` and `setoptions` commands. Type

```
help pzoptions
```

for a list of available plot options.

`iopzplot(sys1,sys2,...)` shows the poles and zeros of multiple LTI models SYS1,SYS2,... on a single plot. You can specify distinctive colors for each model, as in

```
iopzplot(sys1,'r',sys2,'y',sys3,'g')
```

`iopzplot(AX,...)` plots into the axes with handle `AX`.

`iopzplot(..., plotoptions)` plots the poles and zeros with the options specified in `plotoptions`. Type

```
help pzoptions
```

for more detail.

The function `sgrid` or `zgrid` can be used to plot lines of constant damping ratio and natural frequency in the s or z plane.

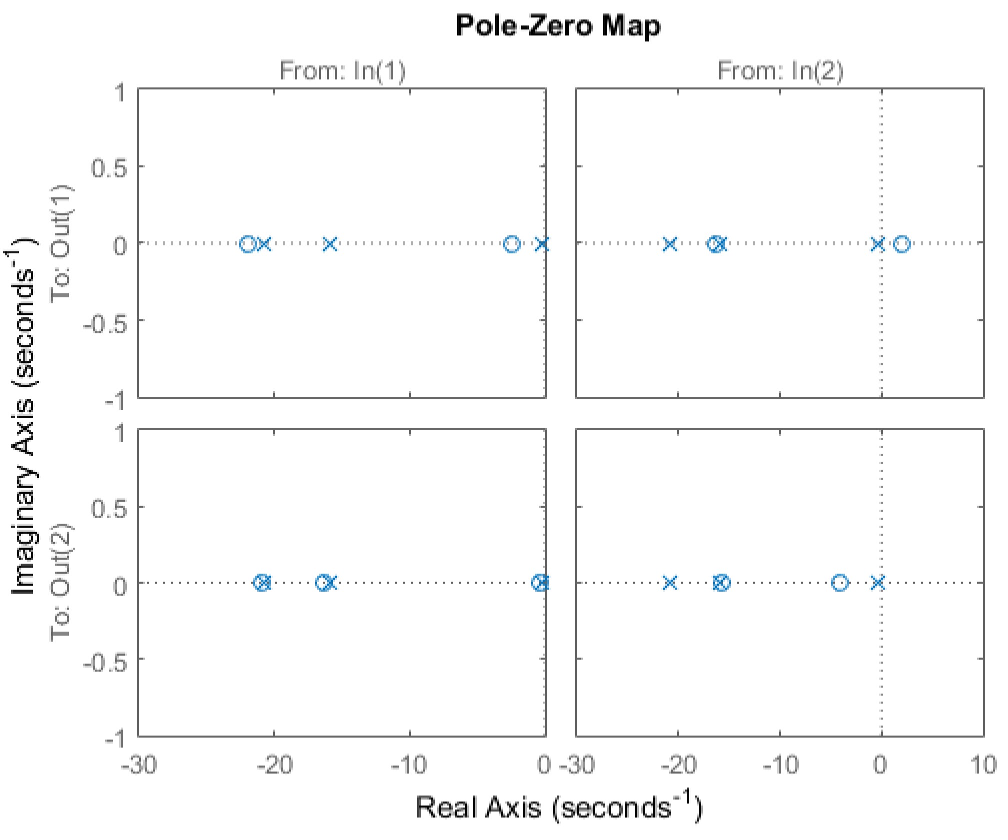
For arrays `sys` of LTI models, `iopzplot` plots the poles and zeros of each model in the array on the same diagram.

Examples

Change I/O Grouping on Pole/Zero Map

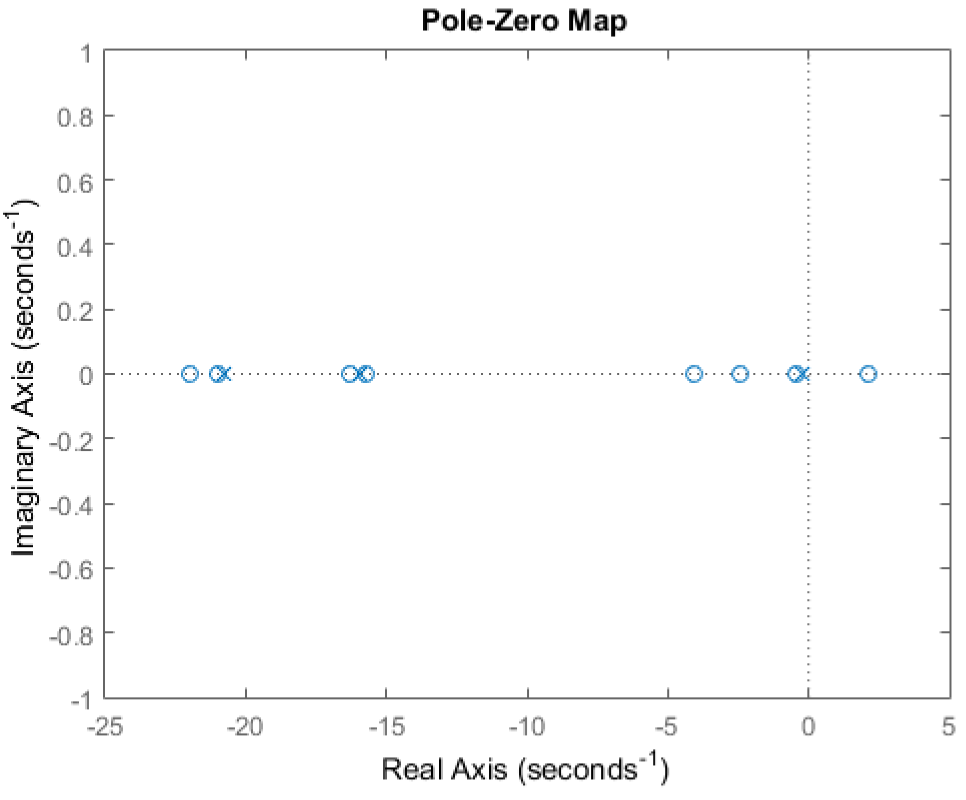
Create a pole/zero map of a two-input, two-output dynamic system.

```
sys = rss(3,2,2);
h = iopzplot(sys);
```



By default, the plot displays the poles and zeros of each I/O pair on its own axis. Use the plot handle to view all I/Os on a single axis.

```
setoptions(h,'IOGrouping','all')
```

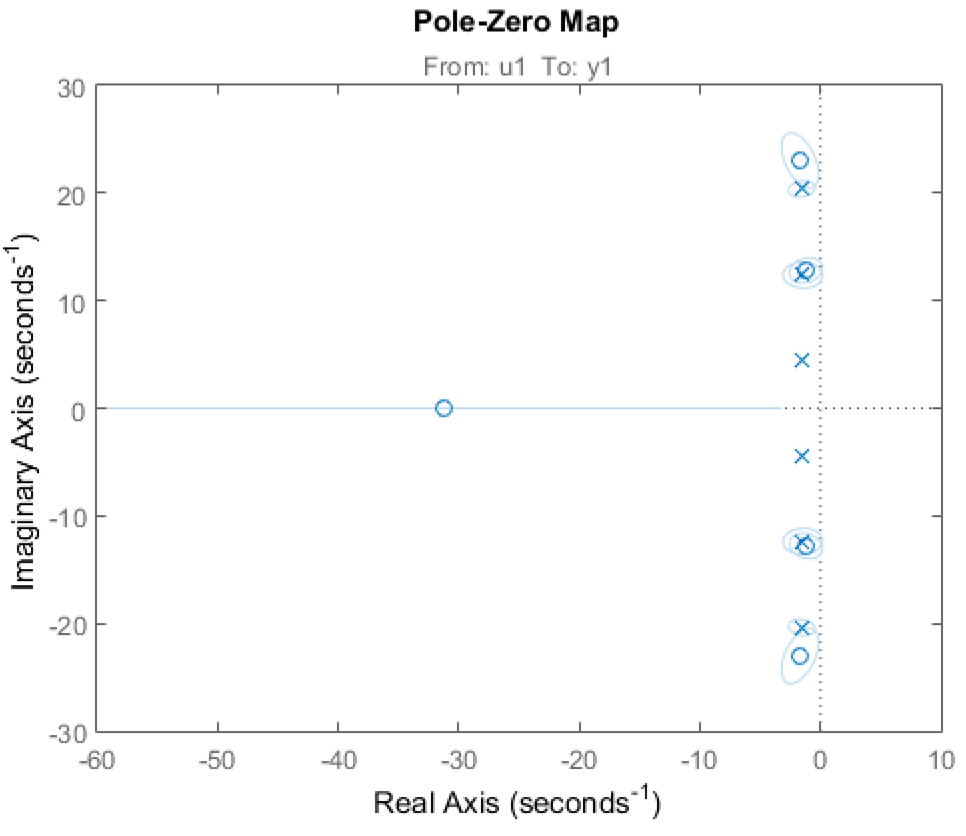


Use Pole-Zero Map to Examine Identified Model

View the poles and zeros of a sixth-order state-space model estimated from input-output data. Use the plot handle to display the confidence intervals of the identified model's pole and zero locations.

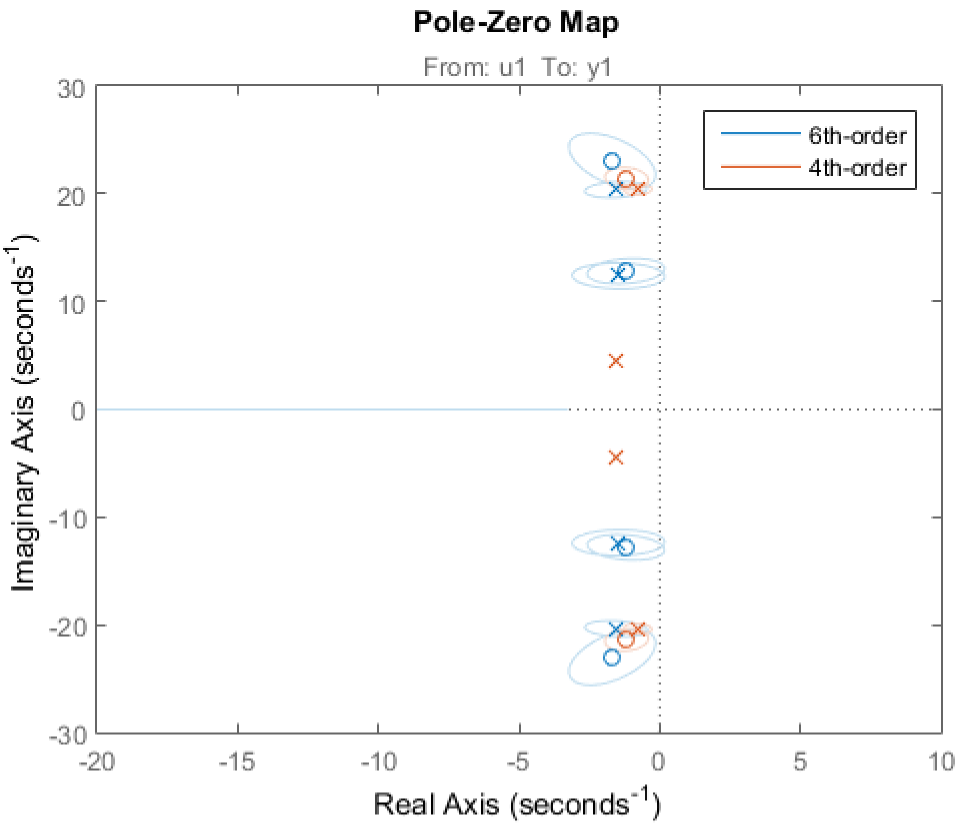
```
load iddata1
sys = ssest(z1,6,ssestOptions('focus','simulation'));
```

```
h = iopzplot(sys);
showConfidence(h)
```



There is at least one pair of complex-conjugate poles whose locations overlap with those of a complex zero, within the 1-σ confidence region. This suggests their redundancy. Hence, a lower (4th) order model might be more robust for the given data.

```
sys2 = ssest(z1,4,ssestOptions('focus','simulation'));
h = iopzplot(sys,sys2);
showConfidence(h)
legend('6th-order','4th-order')
axis([-20, 10 -30 30])
```



The fourth-order model `sys2` shows less variability in the pole-zero locations.

More About

Tips

You can change the properties of your plot, for example the units. For information on the ways to change properties of your plots, see “Ways to Customize Plots”.

See Also

`iopzmap` | `setoptions` | `getoptions`

isct

Determine if dynamic system model is in continuous time

Syntax

```
bool = isct(sys)
```

Description

`bool = isct(sys)` returns a logical value of `1` (`true`) if the dynamic system model `sys` is a continuous-time model. The function returns a logical value of `0` (`false`) otherwise.

Input Arguments

`sys`

Dynamic system model or array of such models.

Output Arguments

`bool`

Logical value indicating whether sys is a continuous-time model.

bool = `1` (`true`) if sys is a continuous-time model (`sys.Ts = 0`). If sys is a discrete-time model, bool = `0` (`false`).

For a static gain, both `isct` and `isdt` return `true` unless you explicitly set the sample time to a nonzero value. If you do so, `isdt` returns `true` and `isct` returns `false`.

For arrays of models, bool is `true` if the models in the array are continuous.

See Also

`isdt` | `isstable`

isdt

Determine if dynamic system model is in discrete time

Syntax

```
bool = isdt(sys)
```

Description

`bool = isdt(sys)` returns a logical value of `1` (`true`) if the dynamic system model `sys` is a discrete-time model. The function returns a logical value of `0` (`false`) otherwise.

Input Arguments

`sys`

Dynamic system model or array of such models.

Output Arguments

`bool`

Logical value indicating whether sys is a discrete-time model.

bool = `1` (`true`) if sys is a discrete-time model (`sys.Ts ≠ 0`). If sys is a continuous-time model, bool = `0` (`false`).

For a static gain, both `isct` and `isdt` return `true` unless you explicitly set the sample time to a nonzero value. If you do so, `isdt` returns `true` and `isct` returns `false`.

For arrays of models, bool is `true` if the models in the array are discrete.

See Also

`isct` | `isstable`

isempty

Determine whether dynamic system model is empty

Syntax

`isempty(sys)`

Description

`isempty(sys)` returns `TRUE` (logical `1`) if the dynamic system model `sys` has no input or no output, and `FALSE` (logical `0`) otherwise. Where `sys` is a FRD model, `isempty(sys)` returns `TRUE` when the frequency vector is empty. Where `sys` is a model array, `isempty(sys)` returns `TRUE` when the array has empty dimensions or when the LTI models in the array are empty.

Examples

Both commands

```
isempty(tf)   % tf by itself returns an empty transfer function
isempty(ss(1,2,[],[]))
```

return `TRUE` (logical `1`) while

```
isempty(ss(1,2,3,4))
```

returns `FALSE` (logical `0`).

See Also

`size` | `issiso`

isfinite

Determine if model has finite coefficients

Syntax

```
B = isfinite(sys)
B = isfinite(sys,'elem')
```

Description

`B = isfinite(sys)` returns 1 (true) if the model sys has finite coefficients, and 0 (false) otherwise. If sys is a model array, then B is true if all models in sys have finite coefficients.

`B = isfinite(sys,'elem')` checks each model in the model array sys and returns a logical array of the same size as sys. The logical array indicates which models in sys have finite coefficients.

Examples

Check Model for Finite Coefficients

Create model and check whether its coefficients are all finite.

```
sys = rss(3);
B = isfinite(sys)
```

```
B =

     1
```

Check Each Model in Array

Create a 1-by-5 array of models and check each model for finite coefficients.

```
sys = rss(2,2,2,1,5);
B = isfinite(sys,'elem')
```

```
B =

     1     1     1     1     1
```

When you use the `'elem'` input, `isfinite` checks each model individually and returns a logical array indicating which models have all finite coefficients.

Input Arguments

`sys` — Model or array to check

input-output model | model array

Model or array to check, specified as an input-output model or model array. Input-output models include dynamic system models such as numeric LTI models and generalized models. Input-output models also include static models such as tunable parameters or generalized matrices.

Output Arguments

`B` — Flag indicating whether model has finite coefficients

logical | logical array

Flag indicating whether model has finite coefficients, returned as a logical value or logical array.

See Also

`isreal`

isParametric

Determine if model has tunable parameters

Syntax

```
bool = isParametric(M)
```

Description

`bool = isParametric(M)` returns a logical value of `1` (`true`) if the model `M` contains parametric (tunable) “Control Design Blocks”. The function returns a logical value of `0` (`false`) otherwise.

Input Arguments

`M`

A Dynamic System model or Static model, or an array of such models.

Output Arguments

`bool`

Logical value indicating whether M contains tunable parameters.

`bool = 1` (`true`) if the model M contains parametric (tunable) “Control Design Blocks” such as `realp` or `ltiblock.ss`. If M does not contain parametric Control Design Blocks, `bool = 0` (`false`).

More About

- “Control Design Blocks”
- “Dynamic System Models”

- "Static Models"

See Also

`nblocks`

isproper

Determine if dynamic system model is proper

Syntax

```
B = isproper(sys)
B = isproper(sys,'elem')
[B, sysr] = isproper(sys)
```

Description

`B = isproper(sys)` returns `TRUE` (logical `1`) if the dynamic system model `sys` is proper and `FALSE` (logical `0`) otherwise.

A proper model has relative degree ≤ 0 and is causal. SISO transfer functions and zero-pole-gain models are proper if the degree of their numerator is less than or equal to the degree of their denominator (in other words, if they have at least as many poles as zeroes). MIMO transfer functions are proper if all their SISO entries are proper. Regular state-space models (state-space models having no `E` matrix) are always proper. A descriptor state-space model that has an invertible `E` matrix is always proper. A descriptor state-space model having a singular (non-invertible) `E` matrix is proper if the model has at least as many poles as zeroes.

If `sys` is a model array, then `B` is `TRUE` if all models in the array are proper.

`B = isproper(sys,'elem')` checks each model in a model array `sys` and returns a logical array of the same size as `sys`. The logical array indicates which models in `sys` are proper.

If `sys` is a proper descriptor state-space model with a non-invertible `E` matrix, `[B, sysr] = isproper(sys)` also returns an equivalent model `sysr` with fewer states (reduced order) and a non-singular `E` matrix. If `sys` is not proper, `sysr = sys`.

Examples

Examine Whether Models are Proper

The following commands

```
B1 = isproper(tf([1 0],1))         % transfer function s
B2 = isproper(tf([1 0],[1 1]))    % transfer function s/(s+1)
```

return FALSE (logical 0) and TRUE (logical 1), respectively.

Compute Equivalent Lower-Order Model

Combining state-space models sometimes yields results that include more states than necessary. Use `isproper` to compute an equivalent lower-order model.

```
H1 = ss(tf([1 1],[1 2 5]));
H2 = ss(tf([1 7],[1]));
H = H1*H2;
size(H)
```

```
State-space model with 1 outputs, 1 inputs, and 4 states.
```

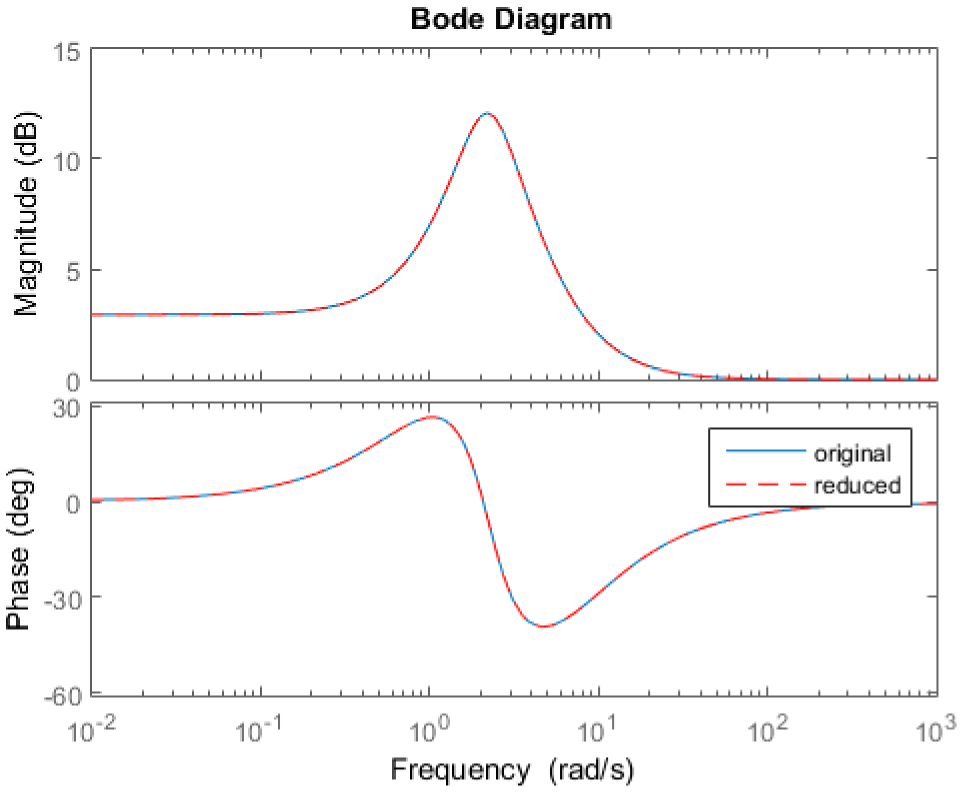
`H` is proper and reducible. `isproper` returns the reduced model.

```
[isprop,Hr] = isproper(H);
size(Hr)
```

```
State-space model with 1 outputs, 1 inputs, and 2 states.
```

`H` and `Hr` are equivalent, as a Bode plot demonstrates.

```
bodeplot(H,Hr,'r--')
legend('original','reduced')
```



See Also

ss | dss

isreal

Determine if model has real-valued coefficients

Syntax

```
B = isreal(sys)
B = isreal(sys,'elem')
```

Description

`B = isreal(sys)` returns 1 (true) if the model sys has real-valued coefficients, and 0 (false) otherwise. If sys is a model array, then B is true if all models in sys have real-valued coefficients.

`B = isreal(sys,'elem')` checks each model in the model array sys and returns a logical array of the same size as sys. The logical array indicates which models in sys have real coefficients.

Examples

Check Model for Real-Valued Coefficients

Create model and check whether its coefficients are all real-valued.

```
sys = rss(3);
B = isreal(sys)
```

```
B =

     1
```

Check Each Model in Array

Create a 1-by-5 array of models and check each model for real-valued coefficients.

```
sys = rss(2,2,2,1,5);
B = isreal(sys,'elem')
```

```
B =

     1     1     1     1     1
```

When you use the `'elem'` input, `isreal` checks each model individually and returns a logical array indicating which models have all real-valued coefficients.

Input Arguments

`sys` — Model or array to check

input-output model | model array

Model or array to check, specified as an input-output model or model array. Input-output models include dynamic system models such as numeric LTI models and generalized models. Input-output models also include static models such as tunable parameters or generalized matrices.

Output Arguments

`B` — Flag indicating whether model has real-valued coefficients

logical | logical array

Flag indicating whether model has real-valued coefficients, returned as a logical value or logical array.

See Also

`isfinite`

isstable

Determine whether system is stable

Syntax

```
B = isstable(sys)
B = isstable(sys,'elem')
```

Description

`B = isstable(sys)` returns 1 (true) if the dynamic system model `sys` has stable dynamics, and 0 (false) otherwise. If `sys` is a model array, then `B` is true only if all models in `sys` are stable.

`B = isstable(sys,'elem')` returns a logical array of the same dimensions as the model array `sys`. The logical array indicates which models in `sys` are stable.

`isstable` is only supported for analytical models with a finite number of poles.

Examples

Determine Stability of Models in Model Array

Create an array of SISO transfer function models with poles varying from 2 to -2.

```
a = [-2:2];
sys = tf(zeros(1,1,1,length(a)));
for j = 1:length(a)
    sys(1,1,1,j) = tf(1,[1 a(j)]);
end
```

Examine the stability of the model array.

```
B_all = isstable(sys)
```

```
B_all =
```

```
     0
```

By default, `isstable` returns a single Boolean value that is 1 (`true`) only if all models in the array are stable. `sys` contains some models with nonpositive poles, which are not stable. Therefore, `isstable` returns 0 (`false`).

Examine stability of each model in the array, element by element.

```
B_elem = isstable(sys,'elem')
```

```
B_elem =

     0     0     0     1     1
```

The `'elem'` flag causes `isstable` to return an array of Boolean values, which indicate the stability of the corresponding entry in the model array. For example, `B_elem(4)` = 1, which indicates that sys(1,1,1,4) is stable.

See Also

`pole`

issiso

Determine if dynamic system model is single-input/single-output (SISO)

Syntax

```
issiso(sys)
```

Description

`issiso(sys)` returns `1` (true) if the dynamic system model `sys` is SISO and `0` (false) otherwise.

See Also

`size` | `isempty`

isstatic

Determine if model is static or dynamic

Syntax

```
B = isstatic(sys)
B = isstatic(sys,'elem')
```

Description

`B = isstatic(sys)` returns 1 (true) if the model sys is a static model, and and 0 (false) if sys has dynamics such as states or delays. If sys is a model array, then B is true if all models in sys are static.

`B = isstatic(sys,'elem')` checks each model in the model array sys and returns a logical array of the same size as sys. The logical array indicates which models in sys are static.

Input Arguments

`sys` — Model or array to check

input-output model | model array

Model or array to check, specified as an input-output model or model array. Input-output models include dynamic system models such as numeric LTI models and generalized models. Input-output models also include static models such as tunable parameters or generalized matrices.

Output Arguments

`B` — Flag indicating whether input model is static

logical | logical array

Flag indicating whether input model is static, returned as a logical value or logical array.

More About

- "Types of Model Objects"

See Also

`hasdelay` | `pole` | `zero`

kalman

Kalman filter design, Kalman estimator

Syntax

```
[kest,L,P] = kalman(sys,Qn,Rn,Nn)
[kest,L,P] = kalman(sys,Qn,Rn,Nn,sensors,known)
[kest,L,P,M,Z] = kalman(sys,Qn,Rn,...,type)
```

Description

`kalman` designs a Kalman filter or Kalman state estimator given a state-space model of the plant and the process and measurement noise covariance data. The Kalman estimator provides the optimal solution to the following continuous or discrete estimation problems.

Continuous-Time Estimation

Given the continuous plant

$$\begin{aligned} \dot{x} &= Ax + Bu + Gw && \text{(state equation)} \\ y &= Cx + Du + Hw + v && \text{(measurement equation)} \end{aligned}$$

with known inputs u, white process noise w, and white measurement noise v satisfying

$$E(w) = E(v) = 0, \quad E(ww^T) = Q, \quad E(vv^T) = R, \quad E(wv^T) = N$$

construct a state estimate $\hat{x}(t)$ that minimizes the steady-state error covariance

$$P = \lim_{t \to \infty} E\left(\{x - \hat{x}\}\{x - \hat{x}\}^T\right)$$

The optimal solution is the Kalman filter with equations

$$\dot{\hat{x}} = A\hat{x} + Bu + L(y - C\hat{x} - Du)$$
$$\begin{bmatrix} \hat{y} \\ \hat{x} \end{bmatrix} = \begin{bmatrix} C \\ I \end{bmatrix} \hat{x} + \begin{bmatrix} D \\ 0 \end{bmatrix} u$$

The filter gain L is determined by solving an algebraic Riccati equation to be

$$L = (PC^T + \bar{N})\bar{R}^{-1}$$

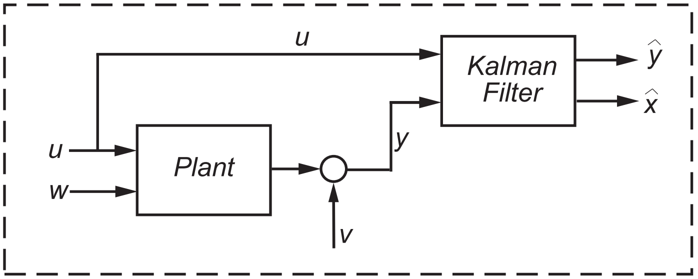
where

$$\bar{R} = R + HN + N^T H^T + HQH^T$$
$$\bar{N} = G(QH^T + N)$$

and P solves the corresponding algebraic Riccati equation.

The estimator uses the known inputs u and the measurements y to generate the output and state estimates $\hat{y}$ and $\hat{x}$. Note that $\hat{y}$ estimates the true plant output

$$y = Cx + Du + Hw + v$$



Kalman Estimator

Discrete-Time Estimation

Given the discrete plant

$$x[n+1] = Ax[n] + Bu[n] + Gw[n]$$
$$y[n] = Cx[n] + Du[n] + Hw[n] + v[n]$$

and the noise covariance data

$$E(w[n]w[n]^T) = Q, \quad E(v[n]v[n]^T) = R, \quad E(w[n]v[n]^T) = N$$

The estimator has the following state equation:

$$\hat{x}[n+1 \mid n] = A\hat{x}[n \mid n-1] + Bu[n] + L(y[n] - C\hat{x}[n \mid n-1] - Du[n])$$

The gain matrix L is derived by solving a discrete Riccati equation to be

$$L = (APC^T + \bar{N})(CPC^T + \bar{R})^{-1}$$

where

$$\bar{R} = R + HN + N^T H^T + HQH^T$$
$$\bar{N} = G(QH^T + N)$$

There are two variants of discrete-time Kalman estimators:

- The current estimator generates output estimates $\hat{y}[n \mid n]$ and state estimates $\hat{x}[n \mid n]$ using all available measurements up to $y[n]$. This estimator has the output equation

  $$\begin{bmatrix} \hat{y}[n \mid n] \\ \hat{x}[n \mid n] \end{bmatrix} = \begin{bmatrix} C(I - MC) \\ I - MC \end{bmatrix} \hat{x}[n \mid n-1] + \begin{bmatrix} (I - CM)D & CM \\ -MD & M \end{bmatrix} \begin{bmatrix} u[n] \\ y[n] \end{bmatrix}$$

  where the innovation gain M is defined as

  $$M = PC^T (CPC^T + \bar{R})^{-1}$$

  M updates the prediction $\hat{x}[n \mid n-1]$ using the new measurement $y[n]$.

  $$\hat{x}[n \mid n] = \hat{x}[n \mid n-1] + M\underbrace{(y[n] - C\hat{x}[n \mid n-1] - Du[n])}_{innovation}$$

- The delayed estimator generates output estimates $\hat{y}[n|n-1]$ and state estimates $\hat{x}[n|n-1]$ using measurements only up to $y_v[n\text{-}1]$. This estimator is easier to implement inside control loops and has the output equation

$$\begin{bmatrix} \hat{y}[n|n-1] \\ \hat{x}[n|n-1] \end{bmatrix} = \begin{bmatrix} C \\ I \end{bmatrix} \hat{x}[n|n-1] + \begin{bmatrix} D & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} u[n] \\ y[n] \end{bmatrix}$$

`[kest,L,P] = kalman(sys,Qn,Rn,Nn)` creates a state-space model `kest` of the Kalman estimator given the plant model `sys` and the noise covariance data `Qn`, `Rn`, `Nn` (matrices Q, R, N described in “Description” on page 1-363). `sys` must be a state-space model with matrices $A,[B\ G],C,[D\ H]$.

The resulting estimator `kest` has inputs $[u;y]$ and outputs $[\hat{y};\hat{x}]$ (or their discrete-time counterparts). You can omit the last input argument `Nn` when $N = 0$.

The function `kalman` handles both continuous and discrete problems and produces a continuous estimator when `sys` is continuous and a discrete estimator otherwise. In continuous time, `kalman` also returns the Kalman gain `L` and the steady-state error covariance matrix `P`. `P` solves the associated Riccati equation.

`[kest,L,P] = kalman(sys,Qn,Rn,Nn,sensors,known)` handles the more general situation when

- Not all outputs of `sys` are measured.
- The disturbance inputs w are not the last inputs of `sys`.

The index vectors `sensors` and `known` specify which outputs y of `sys` are measured and which inputs u are known (deterministic). All other inputs of `sys` are assumed stochastic.

`[kest,L,P,M,Z] = kalman(sys,Qn,Rn,...,type)` specifies the estimator type for discrete-time plants `sys`. The string `type` is either `'current'` (default) or `'delayed'`. For discrete-time plants, `kalman` returns the estimator and innovation gains L and M and the steady-state error covariances

$$P = \lim_{n\to\infty} E(e[n|n-1]e[n|n-1]^T), \quad e[n|n-1] = x[n] - x[n|n-1]$$
$$Z = \lim_{n\to\infty} E(e[n|n]e[n|n]^T), \quad e[n|n] = x[n] - x[n|n]$$

Examples

See LQG Design for the x-Axis and Kalman Filtering for examples that use the `kalman` function.

Limitations

The plant and noise data must satisfy:

- (C,A) detectable
- $\bar{R} > 0$ and $\bar{Q} - \bar{N}\bar{R}^{-1}\bar{N}^T \geq 0$
- $(A - \bar{N}\bar{R}^{-1}C, \bar{Q} - \bar{N}\bar{R}^{-1}\bar{N}^T)$ has no uncontrollable mode on the imaginary axis (or unit circle in discrete time) with the notation

$$\begin{aligned}
\bar{Q} &= GQG^T \\
\bar{R} &= R + HN + N^T H^T + HQH^T \\
\bar{N} &= G(QH^T + N)
\end{aligned}$$

References

[1] Franklin, G.F., J.D. Powell, and M.L. Workman, *Digital Control of Dynamic Systems*, Second Edition, Addison-Wesley, 1990.

[2] Lewis, F., *Optimal Estimation*, John Wiley & Sons, Inc, 1986.

See Also

`care` | `dare` | `estim` | Kalman Filter | `kalmd` | `lqg` | `lqgreg` | `ss`

kalmd

Design discrete Kalman estimator for continuous plant

Syntax

```
[kest,L,P,M,Z] = kalmd(sys,Qn,Rn,Ts)
```

Description

`kalmd` designs a discrete-time Kalman estimator that has response characteristics similar to a continuous-time estimator designed with `kalman`. This command is useful to derive a discrete estimator for digital implementation after a satisfactory continuous estimator has been designed.

`[kest,L,P,M,Z] = kalmd(sys,Qn,Rn,Ts)` produces a discrete Kalman estimator `kest` with sample time `Ts` for the continuous-time plant

$$\begin{aligned} \dot{x} &= Ax + Bu + Gw \quad &\text{(state equation)} \\ y_v &= Cx + Du + v \quad &\text{(measurement equation)} \end{aligned}$$

with process noise w and measurement noise v satisfying

$$E(w) = E(v) = 0, \quad E(ww^T) = Q_n, \quad E(vv^T) = R_n, \quad E(wv^T) = 0$$

The estimator `kest` is derived as follows. The continuous plant `sys` is first discretized using zero-order hold with sample time `Ts` (see `c2d` entry), and the continuous noise covariance matrices Q_n and R_n are replaced by their discrete equivalents

$$\begin{aligned} Q_d &= \int_0^{T_s} e^{A\tau} G Q_n G^T e^{A^T\tau} d\tau \\ R_d &= R_n / T_s \end{aligned}$$

The integral is computed using the matrix exponential formulas in [2]. A discrete-time estimator is then designed for the discretized plant and noise. See `kalman` for details on discrete-time Kalman estimation.

kalmd also returns the estimator gains L and M, and the discrete error covariance matrices P and Z (see kalman for details).

Limitations

The discretized problem data should satisfy the requirements for kalman.

References

[1] Franklin, G.F., J.D. Powell, and M.L. Workman, *Digital Control of Dynamic Systems*, Second Edition, Addison-Wesley, 1990.

[2] Van Loan, C.F., "Computing Integrals Involving the Matrix Exponential," *IEEE Trans. Automatic Control*, AC-15, October 1970.

See Also

kalman | lqrd | lqgreg

lft

Generalized feedback interconnection of two models (Redheffer star product)

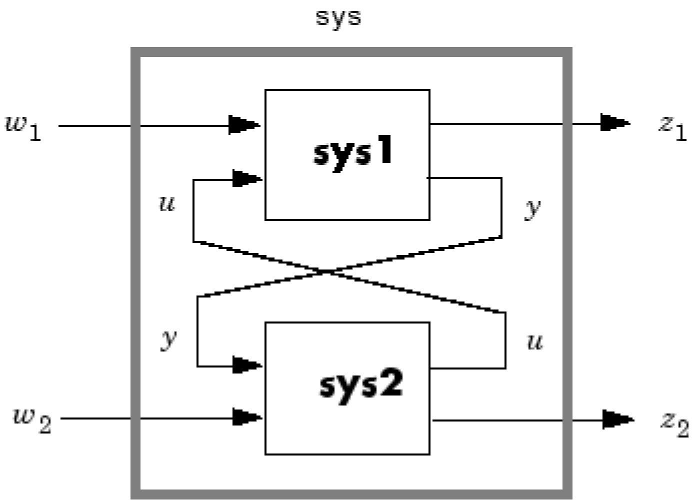
Syntax

```
lft
sys = lft(sys1,sys2,nu,ny)
```

Description

`lft` forms the star product or linear fractional transformation (LFT) of two model objects or model arrays. Such interconnections are widely used in robust control techniques.

`sys = lft(sys1,sys2,nu,ny)` forms the star product `sys` of the two models (or arrays) `sys1` and `sys2`. The star product amounts to the following feedback connection for single models (or for each model in an array).



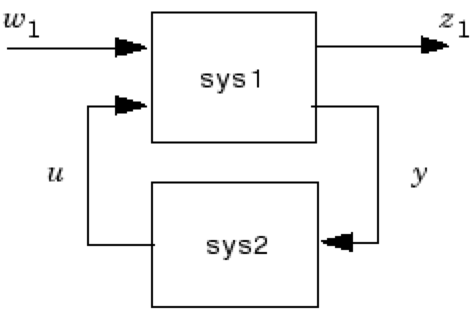
This feedback loop connects the first `nu` outputs of `sys2` to the last `nu` inputs of `sys1` (signals u), and the last `ny` outputs of `sys1` to the first `ny` inputs of `sys2` (signals y). The resulting system `sys` maps the input vector $[w_1 ; w_2]$ to the output vector $[z_1 ; z_2]$.

The abbreviated syntax

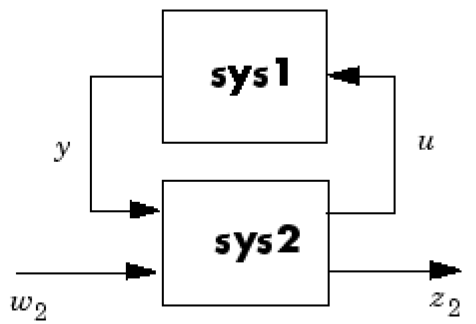
```
sys = lft(sys1,sys2)
```

produces:

- The lower LFT of `sys1` and `sys2` if `sys2` has fewer inputs and outputs than `sys1`. This amounts to deleting w_2 and z_2 in the above diagram.
- The upper LFT of `sys1` and `sys2` if `sys1` has fewer inputs and outputs than `sys2`. This amounts to deleting w_1 and z_1 in the above diagram.



Lower LFT connection



Upper LFT connection

Limitations

There should be no algebraic loop in the feedback connection.

More About

Algorithms

The closed-loop model is derived by elementary state-space manipulations.

See Also

`connect` | `feedback`

linearSystemAnalyzer

Linear System Analyzer for LTI system response analysis

Syntax

```
linearSystemAnalyzer
linearSystemAnalyzer(sys1,sys2,...,sysn)
linearSystemAnalyzer(plottype,sys1,sys2,...,sysn)
linearSystemAnalyzer(plottype,sys1,sys2,...,sysn,extras)
H = linearSystemAnalyzer(___)
linearSystemAnalyzer('clear',viewer)
linearSystemAnalyzer('current',sys1,sys2,...,sysn,viewers)
```

Description

`linearSystemAnalyzer` opens the Linear System Analyzer app. Linear System Analyzer is an interactive user interface for analyzing the time and frequency responses of linear systems and comparing such systems.

`linearSystemAnalyzer(sys1,sys2,...,sysn)` opens Linear System Analyzer and displays the step response of the LTI models `sys1,sys2,...,sysn`. You can specify a distinctive color, line style, and marker for each system, as in

```
sys1 = rss(3,2,2);
sys2 = rss(4,2,2);
linearSystemAnalyzer(sys1,'r-*',sys2,'m--');
```

`linearSystemAnalyzer(plottype,sys1,sys2,...,sysn)` further specifies which responses to display in Linear System Analyzer containing the LTI response type indicated by `plottype` for the LTI model `sys`. The string `plottype` can be any one of the following:

- `'step'` — Step response.
- `'impulse'` — Impulse response.
- `'lsim'` — Linear simulation plot. When you use this plot type, the Linear Simulation Tool dialog opens and prompts you to specify an input signal for the simulation.

- `'initial'` — Initial condition plot. This plot type is available for state-space models only. When you use this plot type without the `extras` argument, the Linear Simulation Tool dialog opens and prompts you to specify an initial state for the simulation.
- `'bode'` — Bode diagram.
- `'bodemag'` — Bode magnitude diagram.
- `'nyquist'` — Nyquist plot.
- `'nichols'` — Nichols plot.
- `'sigma'` — Singular value plot.
- `'pzmap'` — Pole/zero map.
- `'iopzmap'` — I/O pole/zero map.

Alternatively, `plottype` can be a cell vector containing up to six of these plot types. For example, the following command displays a step response plot and a Nyquist plot for a given system `sys`.

```
linearSystemAnalyzer({'step';'nyquist'},sys)
```

`linearSystemAnalyzer(plottype,sys1,sys2,...,sysn,extras)` allows the additional input arguments supported by the various LTI model response functions to be passed to the `linearSystemAnalyzer` command.

`extras` is one or more input arguments as specified by the function named in `plottype`. These arguments may be required or optional, depending on the type of LTI response. For example, if `plottype` is `'step'`, then `extras` may be the desired final time, `Tfinal`, as follows:

```
linearSystemAnalyzer('step',sys,Tfinal)
```

However, if `plottype` is `'initial'`, then `extras` must contain the initial conditions `x0`, and may contain other arguments, such as `Tfinal`.

```
linearSystemAnalyzer('initial',sys,x0,Tfinal)
```

See the individual references pages of each possible `plottype` for a list of appropriate arguments for `extras`. For example, for possible `extras` values for the `bode` plot type, see the `bode` reference page.

`H = linearSystemAnalyzer(___)` returns the handle to the Linear System Analyzer figure. You can use this syntax with any of the previous combinations of input arguments. Use the handle to modify previously opened Linear System Analyzer figures as described in the next two syntaxes.

`linearSystemAnalyzer('clear',viewer)` clears the plots and data from the Linear System Analyzer corresponding to handle `viewer`. To clear multiple Linear System Analyzers at once, set `viewer` to a vector of handles.

`linearSystemAnalyzer('current',sys1,sys2,...,sysn,viewers)` adds the responses of the systems `sys1,sys2,...,sysn` to the Linear System Analyzer corresponding to handle `viewer`. To update multiple Linear System Analyzers at once, set `viewer` to a vector of handles. If the new systems do not have the same I/O dimensions as those currently in a specified Linear System Analyzer, the Linear System Analyzer is first cleared and only the new responses are shown.

Alternatives

You can open Linear Analysis Tool from the MATLAB desktop. In the **Apps** tab, in the **Control System Design and Analysis** section of the Apps gallery, click **Linear System Analyzer**.

More About

- “Linear System Analyzer Overview”

See Also

`bode` | `impulse` | `lsim` | `initial` | `nichols` | `nyquist` | `pzmap` | `sigma` | `step`

Related Examples

- “Linear Analysis Using the Linear System Analyzer”
- “Joint Time- and Frequency-Domain Analysis”

lqg

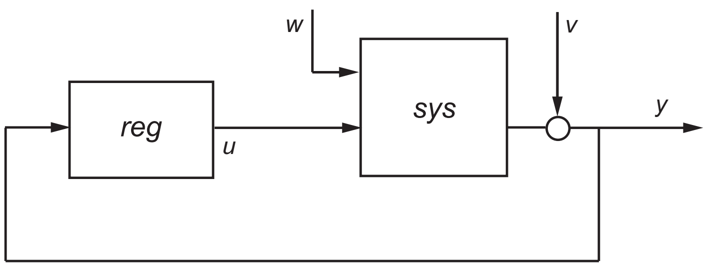
Linear-Quadratic-Gaussian (LQG) design

Syntax

```
reg = lqg(sys,QXU,QWV)
reg = lqg(sys,QXU,QWV,QI)
reg = lqg(sys,QXU,QWV,QI,'1dof')
reg = lqg(sys,QXU,QWV,QI,'2dof')
```

Description

`reg = lqg(sys,QXU,QWV)` computes an optimal linear-quadratic-Gaussian (LQG) regulator `reg` given a state-space model `sys` of the plant and weighting matrices `QXU` and `QWV`. The dynamic regulator `sys` uses the measurements y to generate a control signal u that regulates y around the zero value. Use positive feedback to connect this regulator to the plant output y.



The LQG regulator minimizes the cost function

$$J = E\left\{ \lim_{\tau \to \infty} \frac{1}{\tau} \int_0^{\tau} \left[x^T, u^T \right] Q_{xu} \begin{bmatrix} x \\ u \end{bmatrix} dt \right\}$$

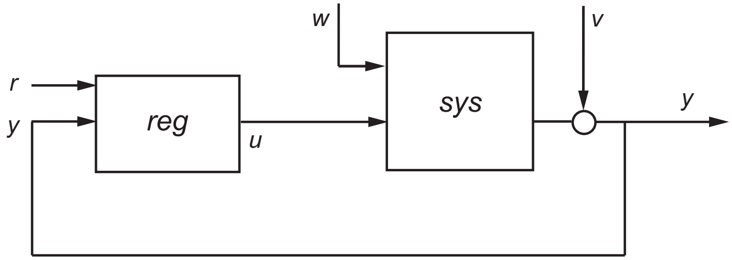
subject to the plant equations

```
dx/dt = Ax + Bu + w
y     = Cx + Du + v
```

where the process noise w and measurement noise v are Gaussian white noises with covariance:

```
E([w;v] * [w',v']) = QWV
```

`reg = lqg(sys,QXU,QWV,QI)` uses the setpoint command r and measurements y to generate the control signal u. `reg` has integral action to ensure that y tracks the command r.



The LQG servo-controller minimizes the cost function

$$J = E\left\{ \lim_{\tau\to\infty} \frac{1}{\tau} \int_0^{\tau} \left(\left[x^T, u^T \right] Q_{xu} \begin{bmatrix} x \\ u \end{bmatrix} + x_i^T Q_i x_i \right) dt \right\}$$

where x_i is the integral of the tracking error r - y. For MIMO systems, r, y, and x_i must have the same length.

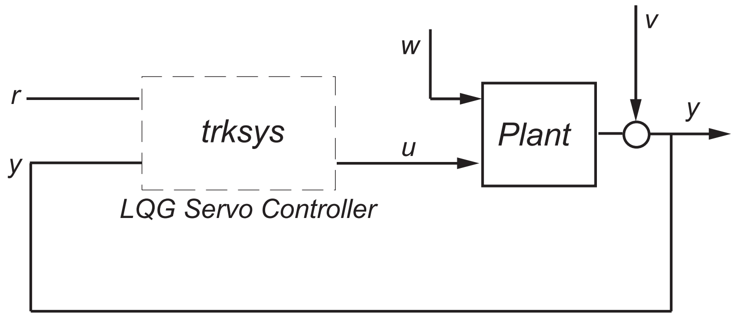
`reg = lqg(sys,QXU,QWV,QI,'1dof')` computes a one-degree-of-freedom servo controller that takes $e = r - y$ rather than $[r ; y]$ as input.

`reg = lqg(sys,QXU,QWV,QI,'2dof')` is equivalent to `LQG(sys,QXU,QWV,QI)` and produces the two-degree-of-freedom servo-controller shown previously.

Examples

Linear-Quadratic-Gaussian (LQG) Regulator and Servo Controller Design

This example shows how to design an linear-quadratic-Gaussian (LQG) regulator, a one-degree-of-freedom LQG servo controller, and a two-degree-of-freedom LQG servo controller for the following system.



The plant has three states (x), two control inputs (u), three random inputs (w), one output (y), measurement noise for the output (v), and the following state and measurement equations.

$$\frac{dx}{dt} = Ax + Bu + w$$
$$y = Cx + Du + v$$

where

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix} \qquad B = \begin{bmatrix} 0.3 & 1 \\ 0 & 1 \\ -0.3 & 0.9 \end{bmatrix}$$

$$C = \begin{bmatrix} 1.9 & 1.3 & 1 \end{bmatrix} \quad D = \begin{bmatrix} 0.53 & -0.61 \end{bmatrix}$$

The system has the following noise covariance data:

$$Q_n = E\left(\omega\omega^T\right) = \begin{bmatrix} 4 & 2 & 0 \\ 2 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$
$$R_n = E\left(vv^T\right) = 0.7$$

For the regulator, use the following cost function to define the tradeoff between regulation performance and control effort:

$$J(u) = \int_0^\infty \left(0.1x^T x + u^T \begin{bmatrix} 1 & 0 \\ 0 & 2 \end{bmatrix} u \right) dt$$

For the servo controllers, use the following cost function to define the tradeoff between tracker performance and control effort:

$$J(u) = \int_0^\infty \left(0.1x^T x + x_i^2 + u^T \begin{bmatrix} 1 & 0 \\ 0 & 2 \end{bmatrix} u \right) dt$$

To design the LQG controllers for this system:

1 Create the state-space system by typing the following in the MATLAB Command Window:

```
A = [0 1 0;0 0 1;1 0 0];
B = [0.3 1;0 1;-0.3 0.9];
C = [1.9 1.3 1];
D = [0.53 -0.61];
sys = ss(A,B,C,D);
```

2 Define the noise covariance data and the weighting matrices by typing the following commands:

```
nx = 3;    %Number of states
ny = 1;    %Number of outputs
Qn = [4 2 0; 2 1 0; 0 0 1];
Rn = 0.7;
R = [1 0;0 2]
QXU = blkdiag(0.1*eye(nx),R);
QWV = blkdiag(Qn,Rn);
QI = eye(ny);
```

3 Form the LQG regulator by typing the following command:

```
KLQG = lqg(sys,QXU,QWV)
```

This command returns the following LQG regulator:

```
a =
           x1_e    x2_e    x3_e
   x1_e  -6.212  -3.814  -4.136
   x2_e  -4.038  -3.196  -1.791
   x3_e  -1.418  -1.973  -1.766
```

```
b =
             y1
   x1_e   2.365
   x2_e   1.432
   x3_e  0.7684

c =
            x1_e       x2_e       x3_e
   u1   -0.02904  0.0008272     0.0303
   u2    -0.7147    -0.7115    -0.7132

d =
       y1
   u1   0
   u2   0

Input groups:
       Name        Channels
    Measurement       1

Output groups:
      Name      Channels
    Controls      1,2

Continuous-time model.
```

4. Form the one-degree-of-freedom LQG servo controller by typing the following command:

```
KLQG1 = lqg(sys,QXU,QWV,QI,'1dof')
```

This command returns the following LQG servo controller:

```
a =
           x1_e    x2_e    x3_e     xi1
   x1_e  -7.626  -5.068  -4.891  0.9018
   x2_e  -5.108  -4.146  -2.362  0.6762
   x3_e  -2.121  -2.604  -2.141  0.4088
   xi1        0       0       0       0

b =
              e1
   x1_e   -2.365
   x2_e   -1.432
   x3_e  -0.7684
   xi1         1
```

```
c =
          x1_e     x2_e     x3_e      xi1
   u1  -0.5388  -0.4173  -0.2481   0.5578
   u2   -1.492   -1.388   -1.131   0.5869

d =
       e1
   u1   0
   u2   0

Input groups:
    Name     Channels
    Error       1

Output groups:
      Name      Channels
    Controls      1,2

Continuous-time model.
```

5 Form the two-degree-of-freedom LQG servo controller by typing the following command:

```
KLQG2 = lqg(sys,QXU,QWV,QI,'2dof')
```

This command returns the following LQG servo controller:

```
a =
           x1_e    x2_e    x3_e     xi1
   x1_e  -7.626  -5.068  -4.891  0.9018
   x2_e  -5.108  -4.146  -2.362  0.6762
   x3_e  -2.121  -2.604  -2.141  0.4088
   xi1        0       0       0       0

b =
             r1      y1
   x1_e       0   2.365
   x2_e       0   1.432
   x3_e       0  0.7684
   xi1        1      -1

c =
          x1_e     x2_e     x3_e      xi1
   u1  -0.5388  -0.4173  -0.2481   0.5578
   u2   -1.492   -1.388   -1.131   0.5869
```

```
d =
       r1  y1
   u1   0   0
   u2   0   0

Input groups:
       Name        Channels
     Setpoint         1
    Measurement       2

Output groups:
      Name      Channels
    Controls      1,2

Continuous-time model.
```

More About

Tips

`lqg` can be used for both continuous- and discrete-time plants. In discrete-time, `lqg` uses $x[n|n\text{-}1]$ as state estimate (see `kalman` for details).

To compute the LQG regulator, `lqg` uses the commands `lqr` and `kalman`. To compute the servo-controller, `lqg` uses the commands `lqi` and `kalman`.

When you want more flexibility for designing regulators you can use the `lqr`, `kalman`, and `lqgreg` commands. When you want more flexibility for designing servo controllers, you can use the `lqi`, `kalman`, and `lqgtrack` commands. For more information on using these commands and how to decide when to use them, see “Linear-Quadratic-Gaussian (LQG) Design for Regulation” and “Linear-Quadratic-Gaussian (LQG) Design of Servo Controller with Integral Action”.

See Also

`lqr` | `lqi` | `kalman` | `lqry` | `ss` | `care` | `dare`

lqgreg

Form linear-quadratic-Gaussian (LQG) regulator

Syntax

```
rlqg = lqgreg(kest,k)
rlqg = lqgreg(kest,k,controls)
```

Description

`lqgreg` forms the linear-quadratic-Gaussian (LQG) regulator by connecting the Kalman estimator designed with `kalman` and the optimal state-feedback gain designed with `lqr`, `dlqr`, or `lqry`. The LQG regulator minimizes some quadratic cost function that trades off regulation performance and control effort. This regulator is dynamic and relies on noisy output measurements to generate the regulating commands.

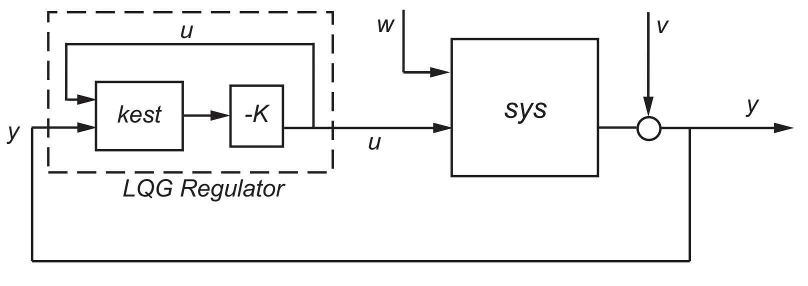
In continuous time, the LQG regulator generates the commands

$$u = -K\hat{x}$$

where $\hat{x}$ is the Kalman state estimate. The regulator state-space equations are

$$\dot{\hat{x}} = [A - LC - (B - LD)K]\hat{x} + Ly$$
$$u = -K\hat{x}$$

where y is the vector of plant output measurements (see `kalman` for background and notation). The following diagram shows this dynamic regulator in relation to the plant.



In discrete time, you can form the LQG regulator using either the delayed state estimate $\hat{x}[n \mid n-1]$ of $x[n]$, based on measurements up to $y[n\text{–}1]$, or the current state estimate $\hat{x}[n \mid n]$, based on all available measurements including $y[n]$. While the regulator

$$u[n] = -K\hat{x}[n \mid n-1]$$

is always well-defined, the *current regulator*

$$u[n] = -K\hat{x}[n \mid n]$$

is causal only when *I-KMD* is invertible (see `kalman` for the notation). In addition, practical implementations of the current regulator should allow for the processing time required to compute $u[n]$ after the measurements $y[n]$ become available (this amounts to a time delay in the feedback loop).

Examples

See the example LQG Regulation.

More About

Tips

`rlqg = lqgreg(kest,k)` returns the LQG regulator `rlqg` (a state-space model) given the Kalman estimator `kest` and the state-feedback gain matrix `k`. The same function handles both continuous- and discrete-time cases. Use consistent tools to design `kest` and `k`:

- Continuous regulator for continuous plant: use `lqr` or `lqry` and `kalman`
- Discrete regulator for discrete plant: use `dlqr` or `lqry` and `kalman`
- Discrete regulator for continuous plant: use `lqrd` and `kalmd`

In discrete time, `lqgreg` produces the regulator

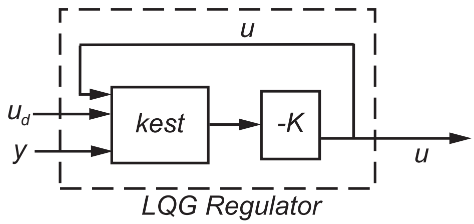
- $u[n] = -K\hat{x}[n \mid n]$ when `kest` is the "current" Kalman estimator

- $u[n] = -K\hat{x}[n \mid n-1]$ when `kest` is the “delayed” Kalman estimator

For more information on Kalman estimators, see the `kalman` reference page.

`rlqg = lqgreg(kest,k,controls)` handles estimators that have access to additional deterministic known plant inputs u_d. The index vector `controls` then specifies which estimator inputs are the controls u, and the resulting LQG regulator `rlqg` has u_d and y as inputs (see the next figure).

Note Always use *positive* feedback to connect the LQG regulator to the plant.



See Also

`kalman` | `kalmd` | `lqr` | `dlqr` | `lqrd` | `lqry` | `reg`

lqgtrack

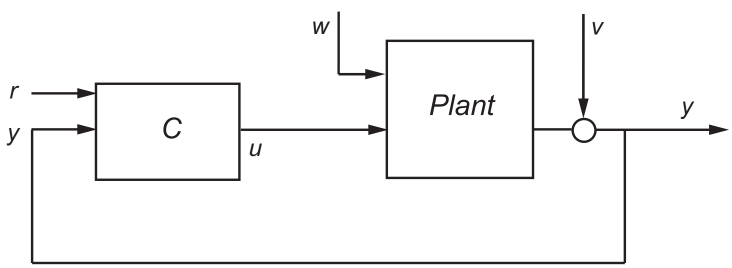
Form Linear-Quadratic-Gaussian (LQG) servo controller

Syntax

```
C = lqgtrack(kest,k)
C = lqgtrack(kest,k,'2dof')
C = lqgtrack(kest,k,'1dof')
C = lqgtrack(kest,k,...CONTROLS)
```

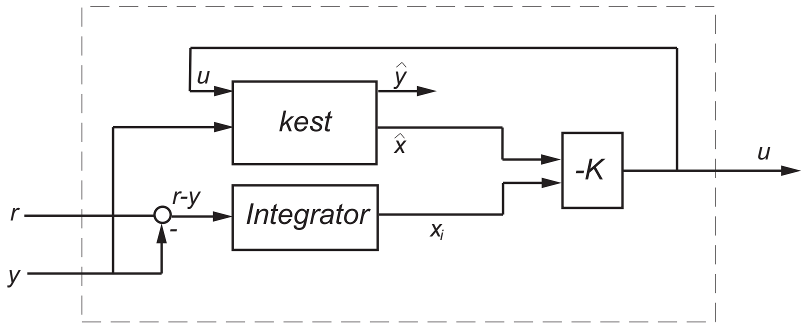
Description

`lqgtrack` forms a Linear-Quadratic-Gaussian (LQG) servo controller with integral action for the loop shown in the following figure. This compensator ensures that the output y tracks the reference command r and rejects process disturbances w and measurement noise v. `lqgtrack` assumes that r and y have the same length.



Note: Always use positive feedback to connect the LQG servo controller C to the plant output y.

`C = lqgtrack(kest,k)` forms a two-degree-of-freedom LQG servo controller `C` by connecting the Kalman estimator `kest` and the state-feedback gain `k`, as shown in the following figure. `C` has inputs $[r;y]$ and generates the command $u = -K[\hat{x};x_i]$, where $\hat{x}$ is the Kalman estimate of the plant state, and x_i is the integrator output.



LQG Servo Controller

The size of the gain matrix `k` determines the length of x_i. x_i, y, and r all have the same length.

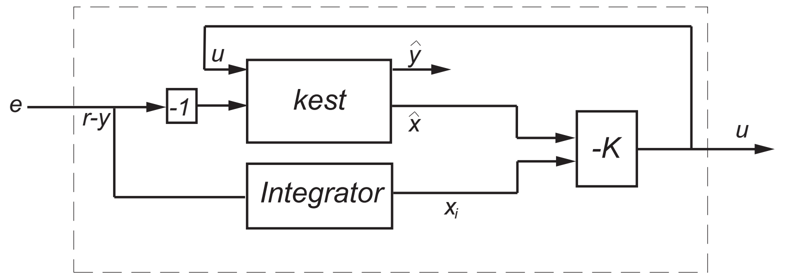
The two-degree-of-freedom LQG servo controller state-space equations are

$$\begin{bmatrix} \dot{\hat{x}} \\ \dot{x}_i \end{bmatrix} = \begin{bmatrix} A - BK_x - LC + LDK_x & -BK_i + LDK_i \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \hat{x} \\ x_i \end{bmatrix} + \begin{bmatrix} 0 & L \\ I & -I \end{bmatrix} \begin{bmatrix} r \\ y \end{bmatrix}$$

$$u = \begin{bmatrix} -K_x & -K_i \end{bmatrix} \begin{bmatrix} \hat{x} \\ x_i \end{bmatrix}$$

Note: The syntax `C = lqgtrack(kest,k,'2dof')` is equivalent to `C = lqgtrack(kest,k)`.

`C = lqgtrack(kest,k,'1dof')` forms a one-degree-of-freedom LQG servo controller `C` that takes the tracking error $e = r - y$ as input instead of $[r\ ;\ y]$, as shown in the following figure.



LQG Servo Controller

The one-degree-of-freedom LQG servo controller state-space equations are

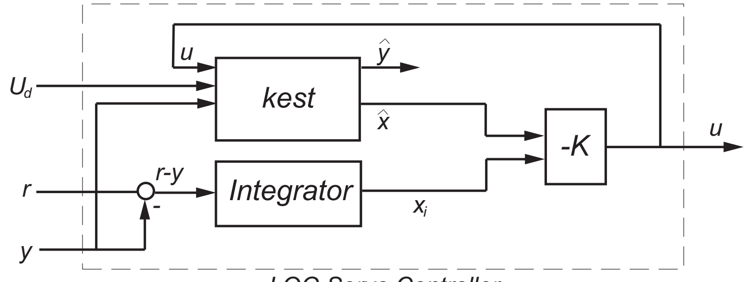
$$\begin{bmatrix} \dot{\hat{x}} \\ \dot{x}_i \end{bmatrix} = \begin{bmatrix} A - BK_x - LC + LDK_x & -BK_i + LDK_i \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \hat{x} \\ x_i \end{bmatrix} + \begin{bmatrix} -L \\ I \end{bmatrix} e$$

$$u = \begin{bmatrix} -K_x & -K_i \end{bmatrix} \begin{bmatrix} \hat{x} \\ x_i \end{bmatrix}$$

`C = lqgtrack(kest,k,...CONTROLS)` forms an LQG servo controller `C` when the Kalman estimator `kest` has access to additional known (deterministic) commands U_d of the plant. In the index vector `CONTROLS`, specify which inputs of `kest` are the control channels u. The resulting compensator C has inputs

- $[U_d \,;\, r \,;\, y]$ in the two-degree-of-freedom case
- $[U_d \,;\, e]$ in the one-degree-of-freedom case

The corresponding compensator structure for the two-degree-of-freedom cases appears in the following figure.



LQG Servo Controller

Examples

See the example "Design an LQG Servo Controller".

More About

Tips

You can use `lqgtrack` for both continuous- and discrete-time systems.

In discrete-time systems, integrators are based on forward Euler (see `lqi` for details). The state estimate $\hat{x}$ is either $x[n|n]$ or $x[n|n–1]$, depending on the type of estimator (see `kalman` for details).

See Also

`lqg` | `lqi` | `kalman` | `lqr` | `lqgreg`

lqi

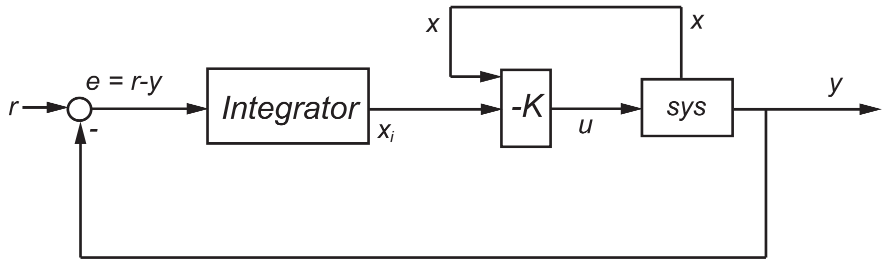
Linear-Quadratic-Integral control

Syntax

```
[K,S,e] = lqi(SYS,Q,R,N)
```

Description

`lqi` computes an optimal state-feedback control law for the tracking loop shown in the following figure.



For a plant `sys` with the state-space equations (or their discrete counterpart):

$$\frac{dx}{dt} = Ax + Bu$$
$$y = Cx + Du$$

the state-feedback control is of the form

$$u = -K[x; x_i]$$

where x_i is the integrator output. This control law ensures that the output y tracks the reference command r. For MIMO systems, the number of integrators equals the dimension of the output y.

`[K,S,e] = lqi(SYS,Q,R,N)` calculates the optimal gain matrix `K`, given a state-space model `SYS` for the plant and weighting matrices `Q`, `R`, `N`. The control law $u = -Kz = -K[x;x_i]$ minimizes the following cost functions (for $r = 0$)

- $$J(u) = \int_0^\infty \{z^T Qz + u^T Ru + 2z^T Nu\} dt$$ for continuous time
- $$J(u) = \sum_{n=0}^{\infty} \{z^T Qz + u^T Ru + 2z^T Nu\}$$ for discrete time

In discrete time, `lqi` computes the integrator output x_i using the forward Euler formula

$$x_i[n+1] = x_i[n] + Ts(r[n] - y[n])$$

where Ts is the sample time of `SYS`.

When you omit the matrix `N`, `N` is set to 0. `lqi` also returns the solution `S` of the associated algebraic Riccati equation and the closed-loop eigenvalues `e`.

Limitations

For the following state-space system with a plant with augmented integrator:

$$\frac{\delta z}{\delta t} = A_a z + B_a u$$
$$y = C_a z + D_a u$$

The problem data must satisfy:

- The pair (A_a, B_a) is stabilizable.
- $R > 0$ and $Q - NR^{-1}N^T \geq 0$.
- $\left(Q - NR^{-1}N^T, A_a - B_a R^{-1} N^T\right)$ has no unobservable mode on the imaginary axis (or unit circle in discrete time).

More About

Tips

`lqi` supports descriptor models with nonsingular E. The output `S` of `lqi` is the solution of the Riccati equation for the equivalent explicit state-space model

$$\frac{dx}{dt} = E^{-1}Ax + E^{-1}Bu$$

References

[1] P. C. Young and J. C. Willems, "An approach to the linear multivariable servomechanism problem", *International Journal of Control*, Volume 15, Issue 5, May 1972 , pages 961–979.

See Also

`lqr` | `lqgreg` | `lqg` | `care` | `dare` | `lqgtrack`

lqr

Linear-Quadratic Regulator (LQR) design

Syntax

```
[K,S,e] = lqr(SYS,Q,R,N)
[K,S,e] = LQR(A,B,Q,R,N)
```

Description

`[K,S,e] = lqr(SYS,Q,R,N)` calculates the optimal gain matrix `K`.

For a continuous time system, the state-feedback law $u = -Kx$ minimizes the quadratic cost function

$$J(u) = \int_0^\infty (x^T Q x + u^T R u + 2x^T N u)dt$$

subject to the system dynamics

$$\dot{x} = Ax + Bu.$$

In addition to the state-feedback gain `K`, `lqr` returns the solution `S` of the associated Riccati equation

$$A^T S + SA - (SB + N)R^{-1}(B^T S + N^T) + Q = 0$$

and the closed-loop eigenvalues `e = eig(A-B*K)`. K is derived from S using

$$K = R^{-1}(B^T S + N^T)$$

For a discrete-time state-space model, $u[n] = -Kx[n]$ minimizes

$$J = \sum_{n=0}^{\infty} \{x^T Q x + u^T R u + 2x^T N u\}$$

subject to $x[n + 1] = Ax[n] + Bu[n]$.

`[K,S,e] = LQR(A,B,Q,R,N)` is an equivalent syntax for continuous-time models with dynamics $\dot{x} = Ax + Bu$.

In all cases, when you omit the matrix `N`, `N` is set to 0.

Limitations

The problem data must satisfy:

- The pair (A,B) is stabilizable.
- $R > 0$ and $Q - NR^{-1}N^T \geq 0$.
- $(Q - NR^{-1}N^T, A - BR^{-1}N^T)$ has no unobservable mode on the imaginary axis (or unit circle in discrete time).

More About

Tips

`lqr` supports descriptor models with nonsingular E. The output `S` of `lqr` is the solution of the Riccati equation for the equivalent explicit state-space model:

$$\frac{dx}{dt} = E^{-1}Ax + E^{-1}Bu$$

See Also

`care` | `dlqr` | `lqgreg` | `lqrd` | `lqry` | `lqi`

lqrd

Design discrete linear-quadratic (LQ) regulator for continuous plant

Syntax

```
lqrd
[Kd,S,e] = lqrd(A,B,Q,R,Ts)
[Kd,S,e] = lqrd(A,B,Q,R,N,Ts)
```

Description

`lqrd` designs a discrete full-state-feedback regulator that has response characteristics similar to a continuous state-feedback regulator designed using `lqr`. This command is useful to design a gain matrix for digital implementation after a satisfactory continuous state-feedback gain has been designed.

`[Kd,S,e] = lqrd(A,B,Q,R,Ts)` calculates the discrete state-feedback law

$$u[n] = -K_d x[n]$$

that minimizes a discrete cost function equivalent to the continuous cost function

$$J = \int_0^\infty \left(x^T Q x + u^T R u\right) dt$$

The matrices `A` and `B` specify the continuous plant dynamics

$$\dot{x} = Ax + Bu$$

and `Ts` specifies the sample time of the discrete regulator. Also returned are the solution `S` of the discrete Riccati equation for the discretized problem and the discrete closed-loop eigenvalues `e = eig(Ad-Bd*Kd)`.

`[Kd,S,e] = lqrd(A,B,Q,R,N,Ts)` solves the more general problem with a cross-coupling term in the cost function.

$$J = \int_0^\infty \left(x^T Qx + u^T Ru + 2x^T Nu \right) dt$$

Limitations

The discretized problem data should meet the requirements for `dlqr`.

More About

Algorithms

The equivalent discrete gain matrix `Kd` is determined by discretizing the continuous plant and weighting matrices using the sample time `Ts` and the zero-order hold approximation.

With the notation

$$\Phi(\tau) = e^{A\tau}, \qquad A_d = \Phi(T_s)$$
$$\Gamma(\tau) = \int_0^\tau e^{A\eta} B d\eta, \quad B_d = \Gamma(T_s)$$

the discretized plant has equations

$$x[n+1] = A_d x[n] + B_d u[n]$$

and the weighting matrices for the equivalent discrete cost function are

$$\begin{bmatrix} Q_d & N_d \\ N_d^T & R_d \end{bmatrix} = \int_0^{T_s} \begin{bmatrix} \Phi^T(\tau) & 0 \\ \Gamma^T(\tau) & I \end{bmatrix} \begin{bmatrix} Q & N \\ N^T & R \end{bmatrix} \begin{bmatrix} \Phi(\tau) & \Gamma(\tau) \\ 0 & I \end{bmatrix} d\tau$$

The integrals are computed using matrix exponential formulas due to Van Loan (see [2]). The plant is discretized using `c2d` and the gain matrix is computed from the discretized data using `dlqr`.

References

[1] Franklin, G.F., J.D. Powell, and M.L. Workman, *Digital Control of Dynamic Systems*, Second Edition, Addison-Wesley, 1980, pp. 439-440.

[2] Van Loan, C.F., "Computing Integrals Involving the Matrix Exponential," *IEEE Trans. Automatic Control*, AC-23, June 1978.

See Also

`c2d` | `dlqr` | `kalmd` | `lqr`

lqry

Form linear-quadratic (LQ) state-feedback regulator with output weighting

Syntax

```
[K,S,e] = lqry(sys,Q,R,N)
```

Description

Given the plant

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$

or its discrete-time counterpart, `lqry` designs a state-feedback control

$$u = -Kx$$

that minimizes the quadratic cost function with output weighting

$$J(u) = \int_0^\infty (y^T Q y + u^T R u + 2 y^T N u) dt$$

(or its discrete-time counterpart). The function `lqry` is equivalent to `lqr` or `dlqr` with weighting matrices:

$$\begin{bmatrix} \bar{Q} & \bar{N} \\ \bar{N}^T & \bar{R} \end{bmatrix} = \begin{bmatrix} C^T & 0 \\ D^T & I \end{bmatrix} \begin{bmatrix} Q & N \\ N^T & R \end{bmatrix} \begin{bmatrix} C & D \\ 0 & I \end{bmatrix}$$

`[K,S,e] = lqry(sys,Q,R,N)` returns the optimal gain matrix `K`, the Riccati solution `S`, and the closed-loop eigenvalues `e = eig(A-B*K)`. The state-space model `sys` specifies the continuous- or discrete-time plant data (A, B, C, D). The default value `N=0` is assumed when `N` is omitted.

Examples

See LQG Design for the x-Axis for an example.

Limitations

The data $A, B, \bar{Q}, \bar{R}, \bar{N}$ must satisfy the requirements for `lqr` or `dlqr`.

See Also

`lqr` | `dlqr` | `kalman` | `lqgreg`

lsim

Simulate time response of dynamic system to arbitrary inputs

Syntax

```
lsim(sys,u,t)
lsim(sys,u,t,x0)
lsim(sys,u,t,x0,method)
lsim(sys1,...,sysn,u,t)
lsim(sys1,PlotStyle1,...,sysN,PlotStyleN,u,t)
y = lsim(___)
[y,t,x] = lsim(___)
lsim(sys)
```

Description

`lsim` simulates the (time) response of continuous or discrete linear systems to arbitrary inputs. When invoked without left-hand arguments, `lsim` plots the response on the screen.

`lsim(sys,u,t)` produces a plot of the time response of the dynamic system model `sys` to the input history, `t`,`u`. The vector `t` specifies the time samples for the simulation (in system time units, specified in the TimeUnit property of sys), and consists of regularly spaced time samples:

```
t = 0:dt:Tfinal
```

The input `u` is an array having as many rows as time samples (`length(t)`) and as many columns as system inputs. For instance, if `sys` is a SISO system, then `u` is a t-by-1 vector. If `sys` has three inputs, then `u` is a t-by-3 array. Each row `u(i,:)` specifies the input value(s) at the time sample `t(i)`. The signal `u` also appears on the plot.

The model `sys` can be continuous or discrete, SISO or MIMO. In discrete time, `u` must be sampled at the same rate as the system. In this case, the input `t` is redundant and can be omitted or set to an empty matrix. In continuous time, the time sampling `dt = t(2)-`

`t(1)` is used to discretize the continuous model. If `dt` is too large (undersampling), `lsim` issues a warning suggesting that you use a more appropriate sample time, but will use the specified sample time. See “Algorithms” on page 1-403 for a discussion of sample times.

`lsim(sys,u,t,x0)` further specifies an initial condition `x0` for the system states. This syntax applies only when `sys` is a state-space model. `x0` is a vector whose entries are the initial values of the corresponding states of `sys`.

`lsim(sys,u,t,x0,method)` explicitly specifies how the input values should be interpolated between samples, when `sys` is a continuous-time system. The string `method` can take one of the following values:

- `'zoh'` — Use zero-order hold
- `'foh'` — Use linear interpolation (first-order hold)

If you do not specify a method, `lsim` selects the interpolation method automatically based on the smoothness of the signal `u`.

`lsim(sys1,...,sysn,u,t)` simulates the responses of several dynamic system models to the same input history `t`,`u` and plots these responses on a single figure. You can also use the `x0` and `method` input arguments when computing the responses of multiple models.

`lsim(sys1,PlotStyle1,...,sysN,PlotStyleN,u,t)` specifies the line style, marker, and color of each of the system responses in the plot. (You can also use the `x0` and `method` input arguments with this syntax.) Each `PlotStyle` entry is a one-part, two-part, or three-part string enclosed in single quotes `(' ')`. The elements of the string can appear in any order. The string can specify only the line style, the marker, or the color. For example, the following code plots the response of `sys1` as a yellow dotted line and the response of `sys2` ad a green dashed line:

```
lsim(sys1,'y:',sys2,'g--',u,t,x0)
```

For more information about configuring the PlotStyle string, see “Specify Line Style, Color, and Markers” in the MATLAB documentation.

`y = lsim( ___ )` returns the system response `y`, sampled at the same times as the input (`t`). The output `y` is an array having as many rows as time samples (`length(t)`) and as many columns as system outputs. No plot is drawn on the screen. You can use this syntax with any of the input arguments described in previous syntaxes except the `PlotStyle` strings.

`[y,t,x] = lsim(___)` also returns the time vector `t` used for simulation and the state trajectories `x` (for state-space models only). The output `x` has as many rows as time samples (`length(t)`) and as many columns as system states. You can use this syntax with any of the input arguments described in previous syntaxes except the `PlotStyle` strings.

`lsim(sys)` opens the Linear Simulation Tool GUI. For more information about working with this GUI, see Working with the Linear Simulation Tool.

Examples

Simulate Response to Square Wave

Simulate and plot the response of the following system to a square wave with period of four seconds:

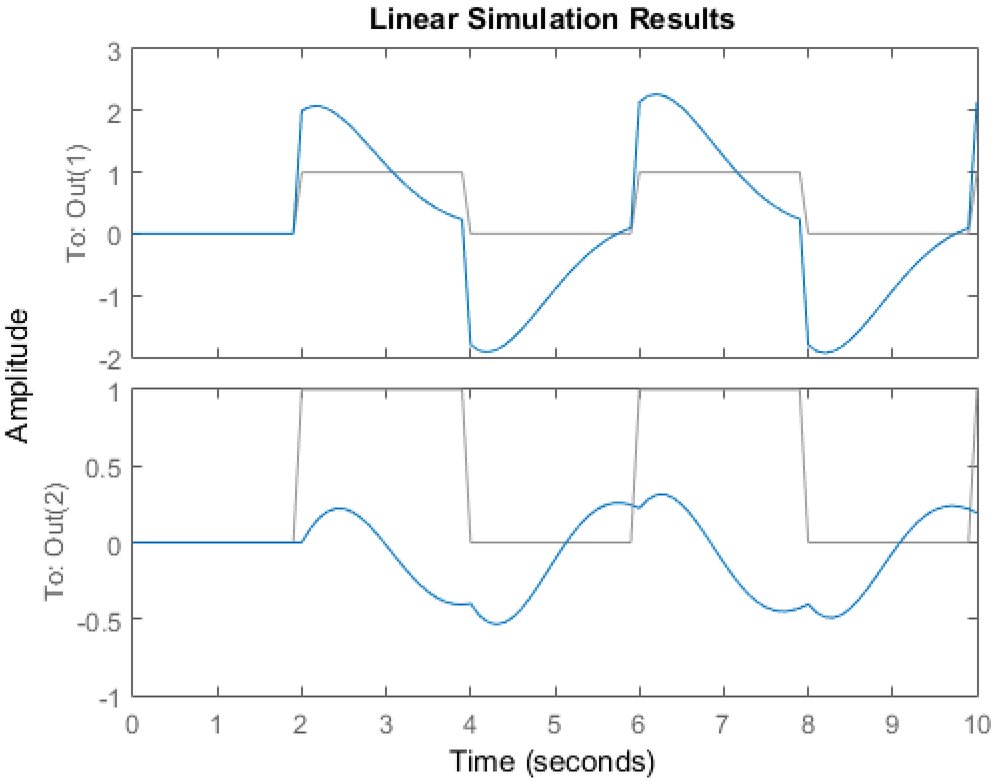
$$H(s) = \begin{bmatrix} \dfrac{2s^2+5s+1}{s^2+2s+3} \\ \dfrac{s-1}{s^2+s+5} \end{bmatrix}.$$

Create the transfer function, and generate the square wave with `gensig`. Sample every 0.1 second during 10 seconds.

```
H = [tf([2 5 1],[1 2 3]);tf([1 -1],[1 1 5])];
[u,t] = gensig('square',4,10,0.1);
```

Then simulate with `lsim`.

```
lsim(H,u,t)
```



The plot displays both the applied signal and the response.

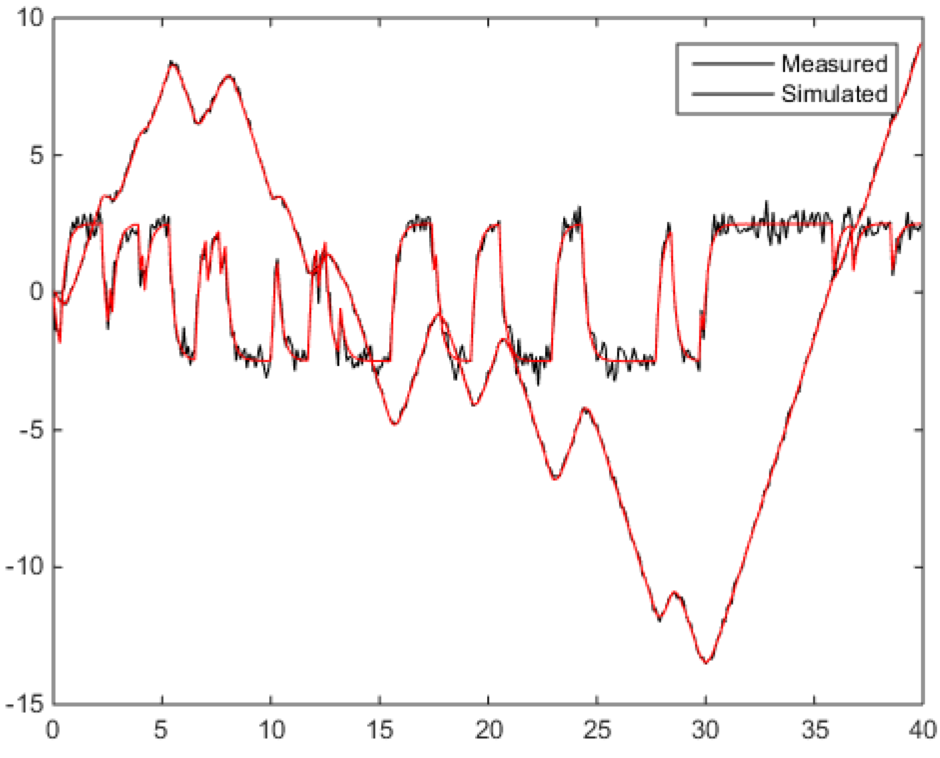
Simulate Response of Identified Model

Simulate the response of an identified linear model using the same input signal as the one used for estimation and the initial states returned by the estimation command.

```
load(fullfile(matlabroot,'toolbox','ident','iddemos','data','dcmotordata'));
z = iddata(y,u,0.1,'Name','DC-motor');

[sys,x0] = n4sid(z,4);
[y,t,x] = lsim(sys, z.InputData, [], x0);
```

Compare the simulated response `y` to measured response `z.OutputData`.

```
plot(t,z.OutputData,'k',t,y,'r')
legend('Measured','Simulated')
```



More About

Algorithms

Discrete-time systems are simulated with `ltitr` (state space) or `filter` (transfer function and zero-pole-gain).

Continuous-time systems are discretized with `c2d` using either the `'zoh'` or `'foh'` method (`'foh'` is used for smooth input signals and `'zoh'` for discontinuous signals such as pulses or square waves). The sample time is set to the spacing `dt` between the user-supplied time samples `t`.

The choice of sample time can drastically affect simulation results. To illustrate why, consider the second-order model

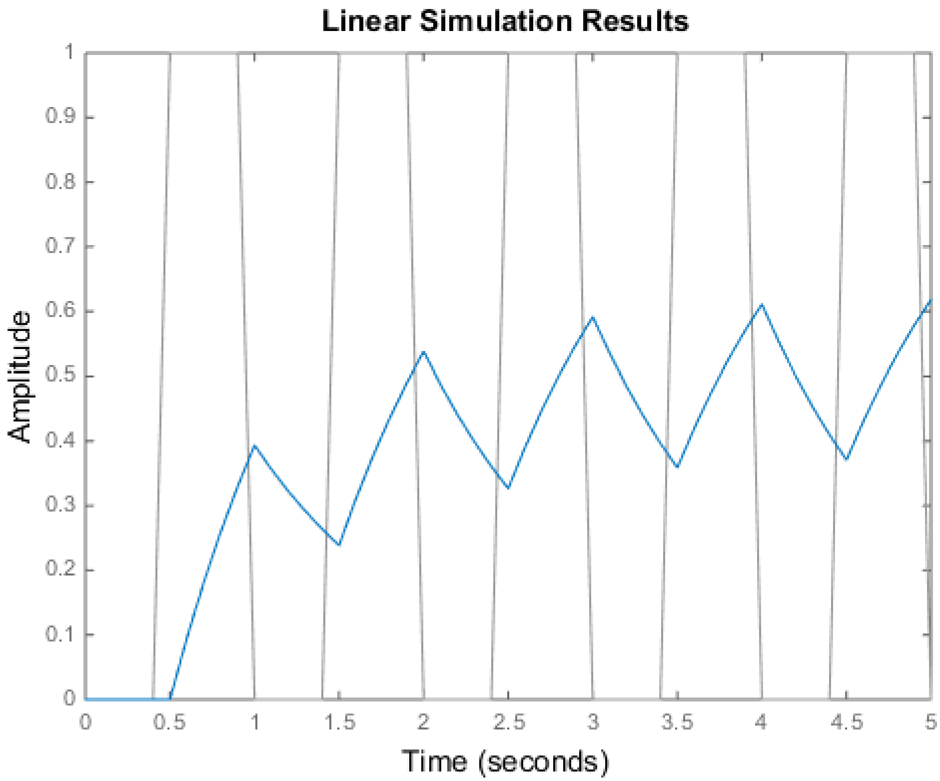
$$H(s) = \frac{\omega^2}{s^2 + 2s + \omega^2}, \quad \omega = 62.83$$

To simulate its response to a square wave with period 1 second, you can proceed as follows:

```
w2 = 62.83^2;
h = tf(w2,[1 2 w2]);
t = 0:0.1:5;                % vector of time samples
u = (rem(t,1) >= 0.5);        % square wave values
lsim(h,u,t)
```

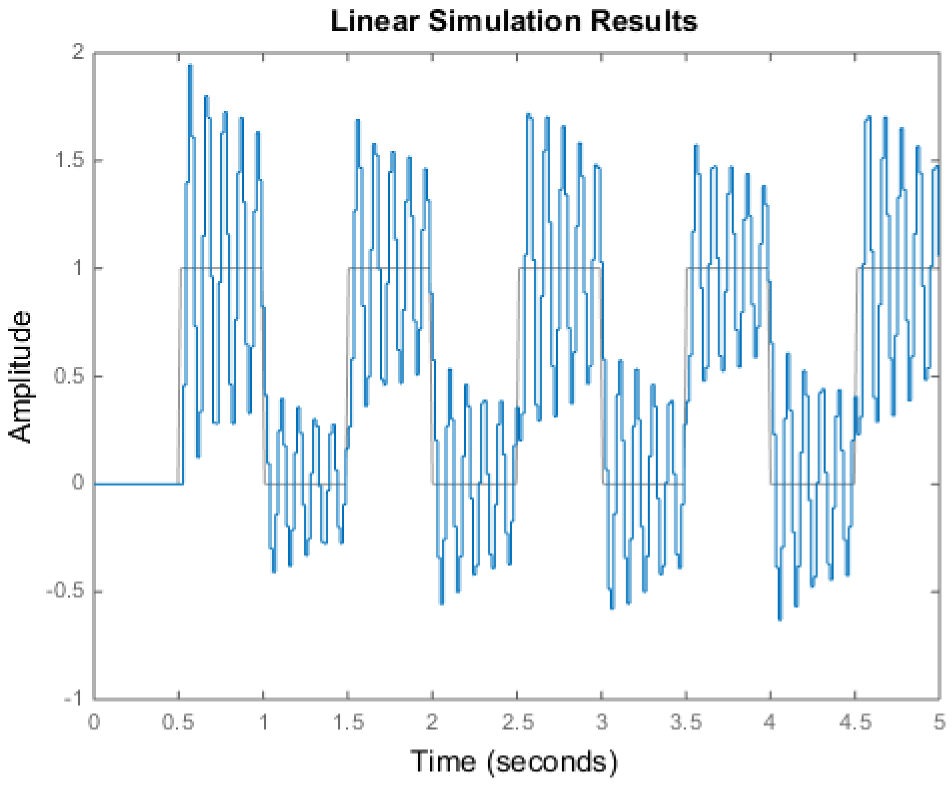
`lsim` evaluates the specified sample time, and issues a warning:

```
Warning: Input signal is undersampled. Sample every 0.016 sec or
faster.
```



To improve on this response, discretize $H(s)$ using the recommended sample time:

```
dt = 0.016;
ts = 0:dt:5;
us = (rem(ts,1) >= 0.5);
hd = c2d(h,dt);
lsim(hd,us,ts)
```



This response exhibits strong oscillatory behavior that is hidden in the undersampled version.

See Also

`gensig` | `initial` | `step` | `lsiminfo` | `impulse` | `linearSystemAnalyzer` | `sim`

lsiminfo

Compute linear response characteristics

Syntax

```
S = lsiminfo(y,t,yfinal)
S = lsiminfo(y,t)
S = lsiminfo(...,'SettlingTimeThreshold',ST)
```

Description

`S = lsiminfo(y,t,yfinal)` takes the response data `(t,y)` and a steady-state value `yfinal` and returns a structure `S` containing the following performance indicators:

- `SettlingTime` — Settling time
- `Min` — Minimum value of Y
- `MinTime` — Time at which the min value is reached
- `Max` — Maximum value of Y
- `MaxTime` — Time at which the max value is reached

For SISO responses, `t` and `y` are vectors with the same length NS. For responses with NY outputs, you can specify `y` as an NS-by-NY array and `yfinal` as a NY-by-1 array. `lsiminfo` then returns an NY-by-1 structure array `S` of performance metrics for each output channel.

`S = lsiminfo(y,t)` uses the last sample value of `y` as steady-state value `yfinal`. `s = lsiminfo(y)` assumes `t = 1:NS`.

`S = lsiminfo(...,'SettlingTimeThreshold',ST)` lets you specify the threshold `ST` used in the settling time calculation. The response has settled when the error `|y(t) - yfinal|` becomes smaller than a fraction `ST` of its peak value. The default value is `ST=0.02` (2%).

Examples

Create a fourth order transfer function and ascertain the response characteristics.

```
sys = tf([1 -1],[1 2 3 4]);
[y,t] = impulse(sys);
s = lsiminfo(y,t,0)  % final value is 0
s =

    SettlingTime: 22.8626
             Min: -0.4270
         MinTime: 2.0309
             Max: 0.2845
         MaxTime: 4.0619
```

See Also

impulse | stepinfo | lsim | initial

lsimplot

Simulate response of dynamic system to arbitrary inputs and return plot handle

Syntax

```
h = lsimplot(sys)
lsimplot(sys1,sys2,...)
lsimplot(sys,u,t)
lsimplot(sys,u,t,x0)
lsimplot(sys1,sys2,...,u,t,x0)
lsimplot(AX,...)
lsimplot(..., plotoptions)
lsimplot(sys,u,t,x0,'zoh')
lsimplot(sys,u,t,x0,'foh')
```

Description

`h = lsimplot(sys)` opens the Linear Simulation Tool for the dynamic system model `sys`, which enables interactive specification of driving input(s), the time vector, and initial state. It also returns the plot handle h. You can use this handle to customize the plot with the `getoptions` and `setoptions` commands. Type

```
help timeoptions
```

for a list of available plot options.

`lsimplot(sys1,sys2,...)` opens the Linear Simulation Tool for multiple models `sys1`,`sys2`,.... Driving inputs are common to all specified systems but initial conditions can be specified separately for each.

`lsimplot(sys,u,t)` plots the time response of the model `sys` to the input signal described by `u` and `t`. The time vector `t` consists of regularly spaced time samples (in system time units, specified in the TimeUnit property of sys). For MIMO systems, `u` is a matrix with as many columns as inputs and whose `i`th row specifies the input value at time `t(i)`. For SISO systems `u` can be specified either as a row or column vector. For example,

```
t = 0:0.01:5;
u = sin(t);
lsimplot(sys,u,t)
```

simulates the response of a single-input model `sys` to the input `u(t)=sin(t)` during 5 seconds.

For discrete-time models, `u` should be sampled at the same rate as `sys` (`t` is then redundant and can be omitted or set to the empty matrix).

For continuous-time models, choose the sampling period `t(2)-t(1)` small enough to accurately describe the input `u`. `lsim` issues a warning when `u` is undersampled, and hidden oscillations can occur.

`lsimplot(sys,u,t,x0)` specifies the initial state vector `x0` at time `t(1)` (for state-space models only). `x0` is set to zero when omitted.

`lsimplot(sys1,sys2,...,u,t,x0)` simulates the responses of multiple LTI models `sys1`,`sys2`,... on a single plot. The initial condition `x0` is optional. You can also specify a color, line style, and marker for each system, as in

```
lsimplot(sys1,'r',sys2,'y--',sys3,'gx',u,t)
```

`lsimplot(AX,...)` plots into the axes with handle `AX`.

`lsimplot(..., plotoptions)` plots the initial condition response with the options specified in `plotoptions`. Type

```
help timeoptions
```

for more detail.

For continuous-time models, `lsimplot(sys,u,t,x0,'zoh')` or `lsimplot(sys,u,t,x0,'foh')` explicitly specifies how the input values should be interpolated between samples (zero-order hold or linear interpolation). By default, `lsimplot` selects the interpolation method automatically based on the smoothness of the signal `u`.

See Also

`lsim` | `setoptions` | `getoptions`

ltiblock.gain

Tunable static gain block

Syntax

```
blk = ltiblock.gain(name,Ny,Nu)
blk = ltiblock.gain(name,G)
```

Description

Model object for creating tunable static gains. `ltiblock.gain` lets you parametrize tunable static gains for parameter studies or for automatic tuning with Robust Control Toolbox tuning commands such as `systune` or `looptune`.

`ltiblock.gain` is part of the Control Design Block family of parametric models. Other Control Design Blocks include`ltiblock.pid`, `ltiblock.ss`, and `ltiblock.tf`.

Construction

`blk = ltiblock.gain(name,Ny,Nu)` creates a parametric static gain block named name. This block has Ny outputs and Nu inputs. The tunable parameters are the gains across each of the Ny-by-Nu I/O channels.

`blk = ltiblock.gain(name,G)` uses the double array G to dimension the block and initialize the tunable parameters.

Input Arguments

`name`

String specifying the block `Name`. (See “Properties” on page 1-412.)

`Ny`

Non-negative integer specifying the number of outputs of the parametric static gain block blk.

Nu

Non-negative integer specifying the number of inputs of the parametric static gain block blk.

G

Double array of static gain values. The number of rows and columns of G determine the number of inputs and outputs of blk. The entries G are the initial values of the parametric gain block parameters.

Properties

Gain

Parametrization of the tunable gain.

`blk.Gain` is a `param.Continuous` object. For general information about the properties of the `param.Continuous` object `blk.Gain`, see the param.Continuous object reference page.

The following fields of `blk.Gain` are used when you tune `blk` using `hinfstruct`:

Field	Description
`Value`	Current value of the gain matrix. For a block that has Ny outputs and Nu inputs, `blk.Gain.Value` is a Ny-by-Nu matrix. If you use the G input argument to create blk, `blk.Gain.Value` initializes to the values of G. Otherwise, all entries of `blk.Gain.Value` initialize to zero. `hinfstruct` tunes all entries in `blk.Gain.Value` except those whose values are fixed by `blk.Gain.Free`. Default: Array of zero values.
`Free`	Array of logical values determining whether the gain entries in `blk.Gain.Value` are fixed or free parameters.

Field	Description
	• If `blk.Gain.Free(i,j) = 1`, then `blk.Gain.Value(i,j)` is a tunable parameter. • If `blk.Gain.Free(i,j) = 0`, then `blk.Gain.Value(i,j)` is fixed. Default: Array of 1 (`true`) values.
`Minimum`	Minimum value of the parameter. This property places a lower bound on the tuned value of the parameter. For example, setting `blk.Gain.Minimum = 1` ensures that all entries in the gain matrix have gain greater than 1. Default: `-Inf`.
`Maximum`	Maximum value of the parameter. This property places an upper bound on the tuned value of the parameter. For example, setting `blk.Gain.Maximum = 100` ensures that all entries in the gain matrix have gain less than 100. Default: `Inf`.

`Ts`

Sample time. For continuous-time models, `Ts = 0`. For discrete-time models, `Ts` is a positive scalar representing the sampling period. This value is expressed in the unit specified by the `TimeUnit` property of the model. To denote a discrete-time model with unspecified sample time, set `Ts = -1`.

Changing this property does not discretize or resample the model. Use `c2d` and `d2c` to convert between continuous- and discrete-time representations. Use `d2d` to change the sample time of a discrete-time system.

Default: `0` (continuous time)

TimeUnit

String representing the unit of the time variable. This property specifies the units for the time variable, the sample time `Ts`, and any time delays in the model. Use any of the following values:

- `'nanoseconds'`
- `'microseconds'`
- `'milliseconds'`
- `'seconds'`
- `'minutes'`
- `'hours'`
- `'days'`
- `'weeks'`
- `'months'`
- `'years'`

Changing this property has no effect on other properties, and therefore changes the overall system behavior. Use `chgTimeUnit` to convert between time units without modifying system behavior.

Default: `'seconds'`

InputName

Input channel names. Set `InputName` to a string for single-input model. For a multi-input model, set `InputName` to a cell array of strings.

Alternatively, use automatic vector expansion to assign input names for multi-input models. For example, if `sys` is a two-input model, enter:

```
sys.InputName = 'controls';
```

The input names automatically expand to `{'controls(1)';'controls(2)'}`.

You can use the shorthand notation `u` to refer to the `InputName` property. For example, `sys.u` is equivalent to `sys.InputName`.

Input channel names have several uses, including:

- Identifying channels on model display and plots
- Extracting subsystems of MIMO systems
- Specifying connection points when interconnecting models

Default: Empty string `''` for all input channels

InputUnit

Input channel units. Use `InputUnit` to keep track of input signal units. For a single-input model, set `InputUnit` to a string. For a multi-input model, set `InputUnit` to a cell array of strings. `InputUnit` has no effect on system behavior.

Default: Empty string `''` for all input channels

InputGroup

Input channel groups. The `InputGroup` property lets you assign the input channels of MIMO systems into groups and refer to each group by name. Specify input groups as a structure. In this structure, field names are the group names, and field values are the input channels belonging to each group. For example:

```
sys.InputGroup.controls = [1 2];
sys.InputGroup.noise = [3 5];
```

creates input groups named `controls` and `noise` that include input channels 1, 2 and 3, 5, respectively. You can then extract the subsystem from the `controls` inputs to all outputs using:

```
sys(:,'controls')
```

Default: Struct with no fields

OutputName

Output channel names. Set `OutputName` to a string for single-output model. For a multi-output model, set `OutputName` to a cell array of strings.

Alternatively, use automatic vector expansion to assign output names for multi-output models. For example, if `sys` is a two-output model, enter:

```
sys.OutputName = 'measurements';
```

The output names automatically expand to
`{'measurements(1)';'measurements(2)'}`.

You can use the shorthand notation `y` to refer to the `OutputName` property. For example, `sys.y` is equivalent to `sys.OutputName`.

Output channel names have several uses, including:

- Identifying channels on model display and plots
- Extracting subsystems of MIMO systems
- Specifying connection points when interconnecting models

Default: Empty string `''` for all output channels

OutputUnit

Output channel units. Use `OutputUnit` to keep track of output signal units. For a single-output model, set `OutputUnit` to a string. For a multi-output model, set `OutputUnit` to a cell array of strings. `OutputUnit` has no effect on system behavior.

Default: Empty string `''` for all output channels

OutputGroup

Output channel groups. The `OutputGroup` property lets you assign the output channels of MIMO systems into groups and refer to each group by name. Specify output groups as a structure. In this structure, field names are the group names, and field values are the output channels belonging to each group. For example:

```
sys.OutputGroup.temperature = [1];
sys.InputGroup.measurement = [3 5];
```

creates output groups named `temperature` and `measurement` that include output channels 1, and 3, 5, respectively. You can then extract the subsystem from all inputs to the `measurement` outputs using:

```
sys('measurement',:)
```

Default: Struct with no fields

Name

System name. Set `Name` to a string to label the system.

Default: `''`

Notes

Any text that you want to associate with the system. Set `Notes` to a string or a cell array of strings.

Default: {}

UserData

Any type of data you wish to associate with system. Set `UserData` to any MATLAB data type.

Default: [ ]

Examples

Create a 2-by-2 parametric gain block of the form

$$\begin{bmatrix} g_1 & 0 \\ 0 & g_2 \end{bmatrix}$$

where g_1 and g_2 are tunable parameters, and the off-diagonal elements are fixed to zero.

```
blk = ltiblock.gain('gainblock',2,2);  % 2 outputs, 2 inputs
blk.Gain.Free = [1 0; 0 1];    % fix off-diagonal entries to zero
```

All entries in `blk.Gain.Value` initialize to zero. Initialize the diagonal values to 1 as follows.

```
blk.Gain.Value = eye(2);    % set diagonals to 1
```

Create a two-input, three-output parametric gain block and initialize all the parameter values to 1.

To do so, create a matrix to dimension the parametric gain block and initialize the parameter values.

```
G = ones(3,2);
blk = ltiblock.gain('gainblock',G);
```

Create a 2–by-2 parametric gain block and assign names to the inputs.

```
blk = ltiblock.gain('gainblock',2,2)   % 2 outputs, 2 inputs
blk.InputName = {'Xerror','Yerror'}    % assign input names
```

More About

Tips

- Use the `blk.Gain.Free` field of blk to specify additional structure or fix the values of specific entries in the block. To fix the gain value from input `i` to output `j`, set `blk.Gain.Free(i,j) = 0`. To allow `hinfstruct` to tune this gain value, set `blk.Gain.Free(i,j) = 1`.
- To convert an `ltiblock.gain` parametric model to a numeric (non-tunable) model object, use model commands such as `tf`, `zpk`, or `ss`.

- "Control Design Blocks"
- "Models with Tunable Coefficients"

See Also

`ltiblock.pid` | `ltiblock.pid2` | `ltiblock.ss` | `ltiblock.tf` | `genss` | `systune` | `looptune` | `hinfstruct`

ltiblock.pid

Tunable PID controller

Syntax

```
blk = ltiblock.pid(name,type)
blk = ltiblock.pid(name,type,Ts)
blk = ltiblock.pid(name,sys)
```

Description

Model object for creating tunable one-degree-of-freedom PID controllers. `ltiblock.pid` lets you parametrize a tunable SISO PID controller for parameter studies or for automatic tuning with requires Robust Control Toolbox tuning commands such as `systune`, `looptune`, or `hinfstruct`.

`ltiblock.pid2` is part of the family of parametric Control Design Blocks. Other parametric Control Design Blocks include `ltiblock.gain`, `ltiblock.ss`, and `ltiblock.tf`.

Construction

`blk = ltiblock.pid(name,type)` creates the one-degree-of-freedom continuous-time PID controller:

$$blk = K_p + \frac{K_i}{s} + \frac{K_d s}{1 + T_f s},$$

with tunable parameters `Kp`, `Ki`, `Kd`, and `Tf`. The string type sets the controller type by fixing some of these values to zero (see "Input Arguments" on page 1-420).

`blk = ltiblock.pid(name,type,Ts)` creates a discrete-time PID controller with sample time Ts:

$$blk = K_p + K_i IF(z) + \frac{K_d}{T_f + DF(z)},$$

where $IF(z)$ and $DF(z)$ are the discrete integrator formulas for the integral and derivative terms, respectively. The values of the `IFormula` and `DFormula` properties set the discrete integrator formulas (see “Properties” on page 1-421).

`blk = ltiblock.pid(name,sys)` uses the dynamic system model, sys, to set the sample time, `Ts`, and the initial values of the parameters `Kp`, `Ki`, `Kd`, and `Tf`.

Input Arguments

`name`

PID controller `Name`, specified as a string. (See “Properties” on page 1-421.)

`type`

String specifying controller type. Specifying a controller type fixes up to three of the PID controller parameters. type can take the following values:

String	Controller Type	Effect on PID Parameters
`'P'`	Proportional only	`Ki` and `Kd` are fixed to zero; `Tf` is fixed to 1; `Kp` is free
`'PI'`	Proportional-integral	`Kd` is fixed to zero; `Tf` is fixed to 1; `Kp` and `Ki` are free
`'PD'`	Proportional-derivative with first-order filter on derivative action	`Ki` is fixed to zero; `Kp`, `Kd`, and `Tf` are free
`'PID'`	Proportional-integral-derivative with first-order filter on derivative action	`Kp`, `Ki`, `Kd`, and `Tf` are free

`Ts`

Sample time, specified as a scalar.

`sys`

Dynamic system model representing a PID controller.

Properties

Kp, Ki, Kd, Tf

Parametrization of the PID gains Kp, Ki, Kd, and filter time constant Tf of the tunable PID controller blk.

The following fields of blk.Kp, blk.Ki, blk.Kd, and blk.Tf are used when you tune blk using a tuning command such as systune:

Field	Description
Value	Current value of the parameter.
Free	Logical value determining whether the parameter is fixed or tunable. For example, • If blk.Kp.Free = 1, then blk.Kp.Value is tunable. • If blk.Kp.Free = 0, then blk.Kp.Value is fixed.
Minimum	Minimum value of the parameter. This property places a lower bound on the tuned value of the parameter. For example, setting blk.Kp.Minimum = 0 ensures that Kp remains positive. blk.Tf.Minimum must always be positive.
Maximum	Maximum value of the parameter. This property places an upper bound on the tuned value of the parameter. For example, setting blk.Tf.Maximum = 100 ensures that the filter time constant does not exceed 100.

blk.Kp, blk.Ki, blk.Kd, and blk.Tf are param.Continuous objects. For general information about the properties of these param.Continuous objects, see the param.Continuous object reference page.

IFormula, DFormula

Strings setting the discrete integrator formulas $IF(z)$ and $DF(z)$ for the integral and derivative terms, respectively. IFormula and DFormula can have the following values:

String	IF(z) or DF(z) Formula
`'ForwardEuler'`	$\frac{T_s}{z-1}$
`'BackwardEuler'`	$\frac{T_s z}{z-1}$
`'Trapezoidal'`	$\frac{T_s}{2}\frac{z+1}{z-1}$

Default: `'ForwardEuler'`

`Ts`

Sample time. For continuous-time models, `Ts = 0`. For discrete-time models, `Ts` is a positive scalar representing the sampling period. This value is expressed in the unit specified by the `TimeUnit` property of the model. To denote a discrete-time model with unspecified sample time, set `Ts = -1`.

Changing this property does not discretize or resample the model. Use `c2d` and `d2c` to convert between continuous- and discrete-time representations. Use `d2d` to change the sample time of a discrete-time system.

Default: `0` (continuous time)

`TimeUnit`

String representing the unit of the time variable. This property specifies the units for the time variable, the sample time `Ts`, and any time delays in the model. Use any of the following values:

- `'nanoseconds'`
- `'microseconds'`
- `'milliseconds'`
- `'seconds'`
- `'minutes'`
- `'hours'`
- `'days'`

- 'weeks'
- 'months'
- 'years'

Changing this property has no effect on other properties, and therefore changes the overall system behavior. Use chgTimeUnit to convert between time units without modifying system behavior.

Default: 'seconds'

InputName

Input channel names. Set InputName to a string for single-input model. For a multi-input model, set InputName to a cell array of strings.

Alternatively, use automatic vector expansion to assign input names for multi-input models. For example, if sys is a two-input model, enter:

```
sys.InputName = 'controls';
```

The input names automatically expand to {'controls(1)';'controls(2)'}.

You can use the shorthand notation u to refer to the InputName property. For example, sys.u is equivalent to sys.InputName.

Input channel names have several uses, including:

- Identifying channels on model display and plots
- Extracting subsystems of MIMO systems
- Specifying connection points when interconnecting models

Default: Empty string '' for all input channels

InputUnit

Input channel units. Use InputUnit to keep track of input signal units. For a single-input model, set InputUnit to a string. For a multi-input model, set InputUnit to a cell array of strings. InputUnit has no effect on system behavior.

Default: Empty string '' for all input channels

InputGroup

Input channel groups. The `InputGroup` property lets you assign the input channels of MIMO systems into groups and refer to each group by name. Specify input groups as a structure. In this structure, field names are the group names, and field values are the input channels belonging to each group. For example:

```
sys.InputGroup.controls = [1 2];
sys.InputGroup.noise = [3 5];
```

creates input groups named `controls` and `noise` that include input channels 1, 2 and 3, 5, respectively. You can then extract the subsystem from the `controls` inputs to all outputs using:

```
sys(:,'controls')
```

Default: Struct with no fields

OutputName

Output channel names. Set `OutputName` to a string for single-output model. For a multi-output model, set `OutputName` to a cell array of strings.

Alternatively, use automatic vector expansion to assign output names for multi-output models. For example, if `sys` is a two-output model, enter:

```
sys.OutputName = 'measurements';
```

The output names automatically expand to
`{'measurements(1)';'measurements(2)'}`.

You can use the shorthand notation `y` to refer to the `OutputName` property. For example, `sys.y` is equivalent to `sys.OutputName`.

Output channel names have several uses, including:

- Identifying channels on model display and plots
- Extracting subsystems of MIMO systems
- Specifying connection points when interconnecting models

Default: Empty string `''` for all output channels

OutputUnit

Output channel units. Use `OutputUnit` to keep track of output signal units. For a single-output model, set `OutputUnit` to a string. For a multi-output model, set `OutputUnit` to a cell array of strings. `OutputUnit` has no effect on system behavior.

Default: Empty string `''` for all output channels

OutputGroup

Output channel groups. The `OutputGroup` property lets you assign the output channels of MIMO systems into groups and refer to each group by name. Specify output groups as a structure. In this structure, field names are the group names, and field values are the output channels belonging to each group. For example:

```
sys.OutputGroup.temperature = [1];
sys.InputGroup.measurement = [3 5];
```

creates output groups named `temperature` and `measurement` that include output channels 1, and 3, 5, respectively. You can then extract the subsystem from all inputs to the `measurement` outputs using:

```
sys('measurement',:)
```

Default: Struct with no fields

Name

System name. Set `Name` to a string to label the system.

Default: `''`

Notes

Any text that you want to associate with the system. Set `Notes` to a string or a cell array of strings.

Default: `{}`

UserData

Any type of data you wish to associate with system. Set `UserData` to any MATLAB data type.

Default: [ ]

Examples

Tunable Controller with a Fixed Parameter

Create a tunable PD controller. Then, initialize the parameter values, and fix the filter time constant.

```
blk = ltiblock.pid('pdblock','PD');
blk.Kp.Value = 4;        % initialize Kp to 4
blk.Kd.Value = 0.7;      % initialize Kd to 0.7
blk.Tf.Value = 0.01;     % set parameter Tf to 0.01
blk.Tf.Free = false;     % fix parameter Tf to this value
blk
```

```
blk =

  Parametric continuous-time PID controller "pdblock" with formula:

               s
  Kp + Kd * --------
             Tf*s+1

  and tunable parameters Kp, Kd.

Type "pid(blk)" to see the current value and "get(blk)" to see all properties.
```

Controller Initialized by Dynamic System Model

Create a tunable discrete-time PI controller. Use a `pid` object to initialize the parameters and other properties.

```
C = pid(5,2.2,'Ts',0.1,'IFormula','BackwardEuler');
blk = ltiblock.pid('piblock',C)
```

```
blk =

  Parametric discrete-time PID controller "piblock" with formula:

             Ts*z
  Kp + Ki * ------
              z-1
```

```
  and tunable parameters Kp, Ki.

Type "pid(blk)" to see the current value and "get(blk)" to see all properties.
```

`blk` takes the value of properties, such as `Ts` and `IFormula`, from `C`.

Controller with Named Input and Output

Create a tunable PID controller, and assign names to the input and output.

```
blk = ltiblock.pid('pidblock','pid')
blk.InputName = {'error'}       % assign input name
blk.OutputName = {'control'}    % assign output name
```

More About

Tips

- You can modify the PID structure by fixing or freeing any of the parameters `Kp`, `Ki`, `Kd`, and `Tf`. For example, `blk.Tf.Free = false` fixes `Tf` to its current value.
- To convert an `ltiblock.pid` parametric model to a numeric (nontunable) model object, use model commands such as `pid`, `pidstd`, `tf`, or `ss`. You can also use `getValue` to obtain the current value of a tunable model.

- “Control Design Blocks”
- “Models with Tunable Coefficients”

See Also

`ltiblock.pid2` | `ltiblock.ss` | `ltiblock.tf` | `systune` | `looptune` | `hinfstruct` | `getValue`

ltiblock.pid2

Tunable two-degree-of-freedom PID controller

Syntax

```
blk = ltiblock.pid2(name,type)
blk = ltiblock.pid2(name,type,Ts)
blk = ltiblock.pid2(name,sys)
```

Description

Model object for creating tunable two-degree-of-freedom PID controllers. `ltiblock.pid2` lets you parametrize a tunable SISO two-degree-of-freedom PID controller. You can use this parametrized controller for parameter studies or for automatic tuning with Robust Control Toolbox tuning commands such as `systune`, `looptune`, or `hinfstruct`.

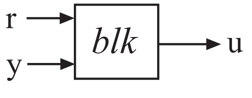
`ltiblock.pid2` is part of the family of parametric Control Design Blocks. Other parametric Control Design Blocks include `ltiblock.gain`, `ltiblock.ss`, and `ltiblock.tf`.

Construction

`blk = ltiblock.pid2(name,type)` creates the two-degree-of-freedom continuous-time PID controller described by the equation:

$$u = K_p\left(br - y\right) + \frac{K_i}{s}\left(r - y\right) + \frac{K_d s}{1 + T_f s}\left(cr - y\right).$$

r is the setpoint command, y is the measured response to that setpoint, and u is the control signal, as shown in the following illustration.



The tunable parameters of the block are:

- Scalar gains `Kp`, `Ki`, and `Kd`
- Filter time constant `Tf`
- Scalar weights `b` and `c`

The string type sets the controller type by fixing some of these values to zero (see “Input Arguments” on page 1-429).

`blk = ltiblock.pid2(name,type,Ts)` creates a discrete-time PID controller with sample time Ts. The equation describing this controller is:

$$u = K_p\left(br - y\right) + K_i IF\left(z\right)\left(r - y\right) + \frac{K_d}{T_f + DF\left(z\right)}\left(cr - y\right).$$

IF(*z*) and *DF*(*z*) are the discrete integrator formulas for the integral and derivative terms, respectively. The values of the `IFormula` and `DFormula` properties set the discrete integrator formulas (see “Properties” on page 1-430).

`blk = ltiblock.pid2(name,sys)` uses the dynamic system model, sys, to set the sample time, `Ts`, and the initial values of all the tunable parameters. The model sys must be compatible with the equation of a two-degree-of-freedom PID controller.

Input Arguments

`name`

PID controller `Name`, specified as a string. (See “Properties” on page 1-430.)

`type`

Controller type, specified as a string. Specifying a controller type fixes up to three of the PID controller parameters. type can take the following values:

String	Controller Type	Effect on PID Parameters
`'P'`	Proportional only	`Ki` and `Kd` are fixed to zero; `Tf` is fixed to 1; `Kp` is free
`'PI'`	Proportional-integral	`Kd` is fixed to zero; `Tf` is fixed to 1; `Kp` and `Ki` are free

String	Controller Type	Effect on PID Parameters
'PD'	Proportional-derivative with first-order filter on derivative action	Ki is fixed to zero; Kp, Kd, and Tf are free
'PID'	Proportional-integral-derivative with first-order filter on derivative action	Kp, Ki, Kd, and Tf are free

Ts

Sample time, specified as a scalar.

sys

Dynamic system model representing a two-degree-of-freedom PID controller.

Properties

Kp,Ki,Kd,Tf,b,c

Parametrization of the PID gains Kp, Ki, Kd, the filter time constant, Tf, and the scalar gains, b and c.

The following fields of blk.Kp, blk.Ki, blk.Kd, blk.Tf, blk.b, and blk.c are used when you tune blk using a tuning command such as systune:

Field	Description
Value	Current value of the parameter. blk.b.Value, and blk.c.Value are always nonnegative.
Free	Logical value determining whether the parameter is fixed or tunable. For example, • If blk.Kp.Free = 1, then blk.Kp.Value is tunable. • If blk.Kp.Free = 0, then blk.Kp.Value is fixed.

Field	Description
`Minimum`	Minimum value of the parameter. This property places a lower bound on the tuned value of the parameter. For example, setting `blk.Kp.Minimum = 0` ensures that `Kp` remains positive. `blk.Tf.Minimum` must always be positive.
`Maximum`	Maximum value of the parameter. This property places an upper bound on the tuned value of the parameter. For example, setting `blk.c.Maximum = 1` ensures that `c` does not exceed unity.

`blk.Kp`, `blk.Ki`, `blk.Kd`, `blk.Tf`, `blk.b`, and `blk.c` are `param.Continuous` objects. For more information about the properties of these `param.Continuous` objects, see the `param.Continuous` object reference page.

IFormula, DFormula

Strings setting the discrete integrator formulas $IF(z)$ and $DF(z)$ for the integral and derivative terms, respectively. `IFormula` and `DFormula` can have the following values:

String	IF(z) or DF(z) Formula
`'ForwardEuler'`	$\frac{T_s}{z-1}$
`'BackwardEuler'`	$\frac{T_s z}{z-1}$
`'Trapezoidal'`	$\frac{T_s}{2}\frac{z+1}{z-1}$

Default: `'ForwardEuler'`

Ts

Sample time. For continuous-time models, `Ts = 0`. For discrete-time models, `Ts` is a positive scalar representing the sampling period. This value is expressed in the unit specified by the `TimeUnit` property of the model. To denote a discrete-time model with unspecified sample time, set `Ts = -1`.

Changing this property does not discretize or resample the model. Use `c2d` and `d2c` to convert between continuous- and discrete-time representations. Use `d2d` to change the sample time of a discrete-time system.

Default: `0` (continuous time)

`TimeUnit`

String representing the unit of the time variable. This property specifies the units for the time variable, the sample time `Ts`, and any time delays in the model. Use any of the following values:

- `'nanoseconds'`
- `'microseconds'`
- `'milliseconds'`
- `'seconds'`
- `'minutes'`
- `'hours'`
- `'days'`
- `'weeks'`
- `'months'`
- `'years'`

Changing this property has no effect on other properties, and therefore changes the overall system behavior. Use `chgTimeUnit` to convert between time units without modifying system behavior.

Default: `'seconds'`

`InputName`

Input channel names. Set `InputName` to a string for single-input model. For a multi-input model, set `InputName` to a cell array of strings.

Alternatively, use automatic vector expansion to assign input names for multi-input models. For example, if `sys` is a two-input model, enter:

```
sys.InputName = 'controls';
```

The input names automatically expand to `{'controls(1)';'controls(2)'}`.

You can use the shorthand notation `u` to refer to the `InputName` property. For example, `sys.u` is equivalent to `sys.InputName`.

Input channel names have several uses, including:

- Identifying channels on model display and plots
- Extracting subsystems of MIMO systems
- Specifying connection points when interconnecting models

Default: Empty string `''` for all input channels

InputUnit

Input channel units. Use `InputUnit` to keep track of input signal units. For a single-input model, set `InputUnit` to a string. For a multi-input model, set `InputUnit` to a cell array of strings. `InputUnit` has no effect on system behavior.

Default: Empty string `''` for all input channels

InputGroup

Input channel groups. The `InputGroup` property lets you assign the input channels of MIMO systems into groups and refer to each group by name. Specify input groups as a structure. In this structure, field names are the group names, and field values are the input channels belonging to each group. For example:

```
sys.InputGroup.controls = [1 2];
sys.InputGroup.noise = [3 5];
```

creates input groups named `controls` and `noise` that include input channels 1, 2 and 3, 5, respectively. You can then extract the subsystem from the `controls` inputs to all outputs using:

```
sys(:,'controls')
```

Default: Struct with no fields

OutputName

Output channel names. Set `OutputName` to a string for single-output model. For a multi-output model, set `OutputName` to a cell array of strings.

Alternatively, use automatic vector expansion to assign output names for multi-output models. For example, if `sys` is a two-output model, enter:

```
sys.OutputName = 'measurements';
```

The output names automatically expand to
`{'measurements(1)';'measurements(2)'}`.

You can use the shorthand notation `y` to refer to the `OutputName` property. For example, `sys.y` is equivalent to `sys.OutputName`.

Output channel names have several uses, including:

- Identifying channels on model display and plots
- Extracting subsystems of MIMO systems
- Specifying connection points when interconnecting models

Default: Empty string `''` for all output channels

`OutputUnit`

Output channel units. Use `OutputUnit` to keep track of output signal units. For a single-output model, set `OutputUnit` to a string. For a multi-output model, set `OutputUnit` to a cell array of strings. `OutputUnit` has no effect on system behavior.

Default: Empty string `''` for all output channels

`OutputGroup`

Output channel groups. The `OutputGroup` property lets you assign the output channels of MIMO systems into groups and refer to each group by name. Specify output groups as a structure. In this structure, field names are the group names, and field values are the output channels belonging to each group. For example:

```
sys.OutputGroup.temperature = [1];
sys.InputGroup.measurement = [3 5];
```

creates output groups named `temperature` and `measurement` that include output channels 1, and 3, 5, respectively. You can then extract the subsystem from all inputs to the `measurement` outputs using:

```
sys('measurement',:)
```

Default: Struct with no fields

`Name`

System name. Set `Name` to a string to label the system.

Default: `''`

`Notes`

Any text that you want to associate with the system. Set `Notes` to a string or a cell array of strings.

Default: `{}`

`UserData`

Any type of data you wish to associate with system. Set `UserData` to any MATLAB data type.

Default: `[]`

Examples

Tunable Two-Degree-of-Freedom Controller with a Fixed Parameter

Create a tunable two-degree-of-freedom PD controller. Then, initialize the parameter values, and fix the filter time constant.

```
blk = ltiblock.pid2('pdblock','PD');
blk.b.Value = 1;
blk.c.Value = 0.5;
blk.Tf.Value = 0.01;
blk.Tf.Free = false;
blk
```

```
blk =

  Parametric continuous-time 2-DOF PID controller "pdblock" with equation:

                       s
  u = Kp (b*r-y) + Kd -------- (c*r-y)
```

```
                     Tf*s+1

  where r,y are the controller inputs and Kp, Kd, b, c are tunable gains.

Type "showBlockValue(blk)" to see the current value and "get(blk)" to see all
properties.
```

Controller Initialized by Dynamic System Model

Create a tunable two-degree-of-freedom PI controller. Use a two-input, one-output `tf` model to initialize the parameters and other properties.

```
s = tf('s');
Kp = 10;
Ki = 0.1;
b = 0.7;
sys = [(b*Kp + Ki/s), (-Kp - Ki/s)];
blk = ltiblock.pid2('PI2dof',sys)
```

```
blk =

  Parametric continuous-time 2-DOF PID controller "PI2dof" with equation:

                      1
  u = Kp (b*r-y) + Ki --- (r-y)
                      s

  where r,y are the controller inputs and Kp, Ki, b are tunable gains.

Type "showBlockValue(blk)" to see the current value and "get(blk)" to see all
properties.
```

`blk` takes initial parameter values from `sys`.

If `sys` is a discrete-time system, `blk` takes the value of properties, such as `Ts` and `IFormula`, from `sys`.

Controller with Named Inputs and Output

Create a tunable PID controller, and assign names to the inputs and output.

```
blk = ltiblock.pid2('pidblock','pid');
blk.InputName = {'reference','measurement'};
blk.OutputName = {'control'};
```

`blk.InputName` is a cell array containing two strings, because a two-degree-of-freedom PID controller has two inputs.

More About

Tips

- You can modify the PID structure by fixing or freeing any of the parameters. For example, `blk.Tf.Free = false` fixes `Tf` to its current value.
- To convert a `ltiblock.pid2` parametric model to a numeric (nontunable) model object, use model commands such as `tf` or `ss`. You can also use `getValue` to obtain the current value of a tunable model.

- “Control Design Blocks”
- “Models with Tunable Coefficients”

See Also

`ltiblock.pid` | `ltiblock.ss` | `ltiblock.tf` | `systune` | `looptune` | `hinfstruct` | `getValue`

ltiblock.ss

Tunable fixed-order state-space model

Syntax

```
blk = ltiblock.ss(name,Nx,Ny,Nu)
blk = ltiblock.ss(name,Nx,Ny,Nu,Ts)
blk = ltiblock.ss(name,sys)
blk = ltiblock.ss(...,Astruct)
```

Description

Model object for creating tunable fixed-order state-space models. `ltiblock.ss` lets you parametrize a state-space model of a given order for parameter studies or for automatic tuning with Robust Control Toolbox tuning commands such as `systune` or `looptune`.

`ltiblock.ss` is part of the Control Design Block family of parametric models. Other Control Design Blocks include`ltiblock.pid`, `ltiblock.gain`, and `ltiblock.tf`.

Construction

`blk = ltiblock.ss(name,Nx,Ny,Nu)` creates the continuous-time parametric state-space model named name. The state-space model blk has Nx states,Ny outputs, and Nu inputs. The tunable parameters are the entries in the *A*, *B*, *C*, and *D* matrices of the state-space model.

`blk = ltiblock.ss(name,Nx,Ny,Nu,Ts)` creates a discrete-time parametric state-space model with sample time Ts.

`blk = ltiblock.ss(name,sys)` uses the dynamic system sys to dimension the parametric state-space model, set its sample time, and initialize the tunable parameters.

`blk = ltiblock.ss(...,Astruct)` creates a parametric state-space model whose `A` matrix is restricted to the structure specified in Astruct.

Input Arguments

`name`

String specifying the `Name` of the parametric state-space model blk. (See "Properties" on page 1-440.)

`Nx`

Nonnegative integer specifying the number of states (order) of the parametric state-space model blk.

`Ny`

Nonnegative integer specifying the number of outputs of the parametric state-space model blk.

`Nu`

Nonnegative integer specifying the number of inputs of the parametric state-space model blk.

`Ts`

Scalar sample time.

`Astruct`

String specifying constraints on the form of the `A` matrix of the parametric state-space model blk. Astruct can take the following values:

String	Structure of A matrix
`'tridiag'`	`A` is tridiagonal. In tridiagonal form, `A` has free elements only in the main diagonal, the first diagonal below the main diagonal, and the first diagonal above the main diagonal. The remaining elements of `A` are fixed to zero.
`'full'`	`A` is full (every entry in `A` is a free parameter).
`'companion'`	`A` is in companion form. In companion form, the characteristic polynomial of the

String	Structure of A matrix
	system appears explicitly in the rightmost column of the A matrix. See `canon` for more information.

If you do not specify Astruct, blk defaults to `'tridiag'` form.

`sys`

Dynamic system model providing number of states, number of inputs and outputs, sample time, and initial values of the parameters of blk. To obtain the dimensions and initial parameter values, `ltiblock.ss` converts sys to a state-space model with the structure specified in Astruct. If you omit Astruct, `ltiblock.ss` converts sys into tridiagonal state-space form.

Properties

`a, b, c, d`

Parametrization of the state-space matrices A, B, C, and D of the tunable state-space model blk.

`blk.a`, `blk.b`, `blk.c`, and `blk.d` are `param.Continuous` objects. For general information about the properties of these `param.Continuous` objects, see the param.Continuous object reference page.

The following fields of `blk.a`, `blk.b`, `blk.c`, and `blk.d` are used when you tune `blk` using `hinfstruct`:

Field	Description
`Value`	Current values of the entries in the parametrized state-space matrix. For example, `blk.a.Value` contains the values of the `A` matrix of blk. `hinfstruct` tunes all entries in `blk.a.Value`, `blk.b.Value`, `blk.c.Value`, and `blk.d.Value` except those whose values are fixed by `blk.Gain.Free`.

Field	Description
`Free`	2-D array of logical values determining whether the corresponding state-space matrix parameters are fixed or free parameters. For example: • If `blk.a.Free(i,j) = 1`, then `blk.a.Value(i,j)` is a tunable parameter. • If `blk.a.Free(i,j) = 0`, then `blk.a.Value(i,j)` is fixed. Defaults: By default, all entries in `b`, `c`, and `c` are tunable. The default free entries in `a` depend upon the value of Astruct: • `'tridiag'` — entries on the three diagonals of `blk.a.Free` are `1`; the rest are `0`. • `'full'` — all entries in `blk.a.Free` are `0`. • `'companion'` — `blk.a.Free(1,:) = 1` and `blk.a.Free(j,j-1) = 1`; all other entries are `0`.
`Minimum`	Minimum value of the parameter. This property places a lower bound on the tuned value of the parameter. For example, setting `blk.a.Minimum(1,1) = 0` ensures that the first entry in the `A` matrix remains positive. Default: `-Inf`.
`Maximum`	Maximum value of the parameter. This property places an upper bound on the tuned value of the parameter. For example, setting `blk.a.Maximum(1,1) = 0` ensures that the first entry in the `A` matrix remains negative. Default: `Inf`.

`StateName`

State names. For first-order models, set `StateName` to a string. For models with two or more states, set `StateName` to a cell array of strings . Use an empty string `''` for unnamed states.

Default: Empty string `''` for all states

`StateUnit`

State units. Use `StateUnit` to keep track of the units each state is expressed in. For first-order models, set `StateUnit` to a string. For models with two or more states, set `StateUnit` to a cell array of strings. `StateUnit` has no effect on system behavior.

Default: Empty string `''` for all states

`Ts`

Sample time. For continuous-time models, `Ts = 0`. For discrete-time models, `Ts` is a positive scalar representing the sampling period. This value is expressed in the unit specified by the `TimeUnit` property of the model. To denote a discrete-time model with unspecified sample time, set `Ts = -1`.

Changing this property does not discretize or resample the model. Use `c2d` and `d2c` to convert between continuous- and discrete-time representations. Use `d2d` to change the sample time of a discrete-time system.

Default: `0` (continuous time)

`TimeUnit`

String representing the unit of the time variable. This property specifies the units for the time variable, the sample time `Ts`, and any time delays in the model. Use any of the following values:

- `'nanoseconds'`
- `'microseconds'`
- `'milliseconds'`
- `'seconds'`
- `'minutes'`

- 'hours'
- 'days'
- 'weeks'
- 'months'
- 'years'

Changing this property has no effect on other properties, and therefore changes the overall system behavior. Use `chgTimeUnit` to convert between time units without modifying system behavior.

Default: 'seconds'

InputName

Input channel names. Set `InputName` to a string for single-input model. For a multi-input model, set `InputName` to a cell array of strings.

Alternatively, use automatic vector expansion to assign input names for multi-input models. For example, if `sys` is a two-input model, enter:

```
sys.InputName = 'controls';
```

The input names automatically expand to `{'controls(1)';'controls(2)'}`.

You can use the shorthand notation `u` to refer to the `InputName` property. For example, `sys.u` is equivalent to `sys.InputName`.

Input channel names have several uses, including:

- Identifying channels on model display and plots
- Extracting subsystems of MIMO systems
- Specifying connection points when interconnecting models

Default: Empty string '' for all input channels

InputUnit

Input channel units. Use `InputUnit` to keep track of input signal units. For a single-input model, set `InputUnit` to a string. For a multi-input model, set `InputUnit` to a cell array of strings. `InputUnit` has no effect on system behavior.

Default: Empty string `''` for all input channels

`InputGroup`

Input channel groups. The `InputGroup` property lets you assign the input channels of MIMO systems into groups and refer to each group by name. Specify input groups as a structure. In this structure, field names are the group names, and field values are the input channels belonging to each group. For example:

```
sys.InputGroup.controls = [1 2];
sys.InputGroup.noise = [3 5];
```

creates input groups named `controls` and `noise` that include input channels 1, 2 and 3, 5, respectively. You can then extract the subsystem from the `controls` inputs to all outputs using:

```
sys(:,'controls')
```

Default: Struct with no fields

`OutputName`

Output channel names. Set `OutputName` to a string for single-output model. For a multi-output model, set `OutputName` to a cell array of strings.

Alternatively, use automatic vector expansion to assign output names for multi-output models. For example, if `sys` is a two-output model, enter:

```
sys.OutputName = 'measurements';
```

The output names automatically expand to `{'measurements(1)';'measurements(2)'}`.

You can use the shorthand notation `y` to refer to the `OutputName` property. For example, `sys.y` is equivalent to `sys.OutputName`.

Output channel names have several uses, including:

- Identifying channels on model display and plots
- Extracting subsystems of MIMO systems
- Specifying connection points when interconnecting models

Default: Empty string `''` for all output channels

OutputUnit

Output channel units. Use `OutputUnit` to keep track of output signal units. For a single-output model, set `OutputUnit` to a string. For a multi-output model, set `OutputUnit` to a cell array of strings. `OutputUnit` has no effect on system behavior.

Default: Empty string `''` for all output channels

OutputGroup

Output channel groups. The `OutputGroup` property lets you assign the output channels of MIMO systems into groups and refer to each group by name. Specify output groups as a structure. In this structure, field names are the group names, and field values are the output channels belonging to each group. For example:

```
sys.OutputGroup.temperature = [1];
sys.InputGroup.measurement = [3 5];
```

creates output groups named `temperature` and `measurement` that include output channels 1, and 3, 5, respectively. You can then extract the subsystem from all inputs to the `measurement` outputs using:

```
sys('measurement',:)
```

Default: Struct with no fields

Name

System name. Set `Name` to a string to label the system.

Default: `''`

Notes

Any text that you want to associate with the system. Set `Notes` to a string or a cell array of strings.

Default: `{}`

UserData

Any type of data you wish to associate with system. Set `UserData` to any MATLAB data type.

Default: `[]`

Examples

Create a parametrized 5th-order SISO model with zero D matrix.

```
blk = ltiblock.ss('ssblock',5,1,1);
blk.d.Value = 0;      % set D = 0
blk.d.Free = false;   % fix D to zero
```

By default, the A matrix is in tridiagonal form. To parametrize the model in companion form, use the `'companion'` input argument:

```
blk = ltiblock.ss('ssblock',5,1,1,'companion');
blk.d.Value = 0;      % set D = 0
blk.d.Free = false;   % fix D to zero
```

Create a parametric state-space model, and assign names to the inputs.

```
blk = ltiblock.ss('ssblock',5,2,2) % 5 states, 2 outputs, 2 inputs
blk.InputName = {'Xerror','Yerror'} % assign input names
```

More About

Tips

- Use the Astruct input argument to constrain the structure of the A matrix of the parametric state-space model. To impose additional structure constrains on the state-space matrices, use the fields `blk.a.Free`, `blk.b.Free`, `blk.c.Free`, and `blk.d.Free` to fix the values of specific entries in the parameter matrices.

  For example, to fix the value of `blk.b(i,j)`, set `blk.b.Free(i,j) = 0`. To allow `hinfstruct` to tune `blk.b(i,j)`, set `blk.b.Free(i,j) = 1`.
- To convert an `ltiblock.ss` parametric model to a numeric (non-tunable) model object, use model commands such as `ss`, `tf`, or `zpk`.

- "Control Design Blocks"
- "Models with Tunable Coefficients"

See Also

`ltiblock.pid` | `ltiblock.pid2` | `ltiblock.ss` | `ltiblock.tf` | `genss` | `systune` | `looptune` | `hinfstruct`

ltiblock.tf

Tunable transfer function with fixed number of poles and zeros

Syntax

```
blk = ltiblock.tf(name,Nz,Np)
blk = ltiblock.tf(name,Nz,Np,Ts)
blk = ltiblock.tf(name,sys)
```

Description

Model object for creating tunable SISO transfer function models of fixed order. `ltiblock.tf` lets you parametrize a transfer function of a given orderfor parameter studies or for automatic tuning with Robust Control Toolbox tuning commands such as `systune` or `looptune`.

`ltiblock.tf` is part of the Control Design Block family of parametric models. Other Control Design Blocks include`ltiblock.pid`, `ltiblock.ss`, and `ltiblock.gain`.

Construction

`blk = ltiblock.tf(name,Nz,Np)` creates the parametric SISO transfer function:

$$blk = \frac{a_m s^m + a_{m-1} s^{m-1} + \ldots + a_1 s + a_0}{s^n + b_{n-1} s^{n-1} + \ldots + b_1 s + b_0}.$$

`n = ` Np is the maximum number of poles of blk, and `m = ` Nz is the maximum number of zeros. The tunable parameters are the numerator and denominator coefficients a_0, ..., a_m and b_0, ..., b_{n-1}. The leading coefficient of the denominator is fixed to 1.

`blk = ltiblock.tf(name,Nz,Np,Ts)` creates a discrete-time parametric transfer function with sample time Ts.

`blk = ltiblock.tf(name,sys)` uses the `tf` model sys to set the number of poles, number of zeros, sample time, and initial parameter values.

Input Arguments

`name`

String specifying the `Name` of the parametric transfer function blk. (See "Properties" on page 1-448.)

`Nz`

Nonnegative integer specifying the number of zeros of the parametric transfer function blk.

`Np`

Nonnegative integer specifying the number of poles of the parametric transfer function blk.

`Ts`

Scalar sample time.

`sys`

`tf` model providing number of poles, number of zeros, sample time, and initial values of the parameters of blk.

Properties

`num, den`

Parametrization of the numerator coefficients a_m, ..., a_0 and the denominator coefficients 1,b_{n-1}, ..., b_0 of the tunable transfer function blk.

`blk.num` and `blk.den` are `param.Continuous` objects. For general information about the properties of these `param.Continuous` objects, see the param.Continuous object reference page.

The following fields of `blk.num` and `blk.den` are used when you tune `blk` using `hinfstruct`:

Field	Description
`Value`	Array of current values of the numerator a_m, ..., a_0 or the denominator coefficients $1, b_{n-1}$, ..., b_0. `blk.num.Value` has length `Nz + 1`. `blk.den.Value` has length `Np + 1`. The leading coefficient of the denominator (`blk.den.Value(1)`) is always fixed to 1. By default, the coefficients initialize to values that yield a stable, strictly proper transfer function. Use the input sys to initialize the coefficients to different values. `hinfstruct` tunes all values except those whose `Free` field is zero.
`Free`	Array of logical values determining whether the coefficients are fixed or tunable. For example, • If `blk.num.Free(j) = 1`, then `blk.num.Value(j)` is tunable. • If `blk.num.Free(j) = 0`, then `blk.num.Value(j)` is fixed. Default: `blk.den.Free(1) = 0`; all other entries are 1.
`Minimum`	Minimum value of the parameter. This property places a lower bound on the tuned value of the parameter. For example, setting `blk.num.Minimum(1) = 0` ensures that the leading coefficient of the numerator remains positive. Default: `-Inf`.
`Maximum`	Maximum value of the parameter. This property places an upper bound on the

Field	Description
	tuned value of the parameter. For example, setting `blk.num.Maximum(1) = 1` ensures that the leading coefficient of the numerator does not exceed 1. Default: `Inf`.

`Ts`

Sample time. For continuous-time models, `Ts = 0`. For discrete-time models, `Ts` is a positive scalar representing the sampling period. This value is expressed in the unit specified by the `TimeUnit` property of the model. To denote a discrete-time model with unspecified sample time, set `Ts = -1`.

Changing this property does not discretize or resample the model. Use `c2d` and `d2c` to convert between continuous- and discrete-time representations. Use `d2d` to change the sample time of a discrete-time system.

Default: `0` (continuous time)

`TimeUnit`

String representing the unit of the time variable. This property specifies the units for the time variable, the sample time `Ts`, and any time delays in the model. Use any of the following values:

- `'nanoseconds'`
- `'microseconds'`
- `'milliseconds'`
- `'seconds'`
- `'minutes'`
- `'hours'`
- `'days'`
- `'weeks'`
- `'months'`
- `'years'`

Changing this property has no effect on other properties, and therefore changes the overall system behavior. Use `chgTimeUnit` to convert between time units without modifying system behavior.

Default: `'seconds'`

`InputName`

Input channel names. Set `InputName` to a string for single-input model. For a multi-input model, set `InputName` to a cell array of strings.

Alternatively, use automatic vector expansion to assign input names for multi-input models. For example, if `sys` is a two-input model, enter:

```
sys.InputName = 'controls';
```

The input names automatically expand to `{'controls(1)';'controls(2)'}`.

You can use the shorthand notation `u` to refer to the `InputName` property. For example, `sys.u` is equivalent to `sys.InputName`.

Input channel names have several uses, including:

- Identifying channels on model display and plots
- Extracting subsystems of MIMO systems
- Specifying connection points when interconnecting models

Default: Empty string `''` for all input channels

`InputUnit`

Input channel units. Use `InputUnit` to keep track of input signal units. For a single-input model, set `InputUnit` to a string. For a multi-input model, set `InputUnit` to a cell array of strings. `InputUnit` has no effect on system behavior.

Default: Empty string `''` for all input channels

`InputGroup`

Input channel groups. The `InputGroup` property lets you assign the input channels of MIMO systems into groups and refer to each group by name. Specify input groups as a structure. In this structure, field names are the group names, and field values are the input channels belonging to each group. For example:

```
sys.InputGroup.controls = [1 2];
sys.InputGroup.noise = [3 5];
```

creates input groups named `controls` and `noise` that include input channels 1, 2 and 3, 5, respectively. You can then extract the subsystem from the `controls` inputs to all outputs using:

```
sys(:,'controls')
```

Default: Struct with no fields

OutputName

Output channel names. Set `OutputName` to a string for single-output model. For a multi-output model, set `OutputName` to a cell array of strings.

Alternatively, use automatic vector expansion to assign output names for multi-output models. For example, if `sys` is a two-output model, enter:

```
sys.OutputName = 'measurements';
```

The output names automatically expand to `{'measurements(1)';'measurements(2)'}`.

You can use the shorthand notation `y` to refer to the `OutputName` property. For example, `sys.y` is equivalent to `sys.OutputName`.

Output channel names have several uses, including:

- Identifying channels on model display and plots
- Extracting subsystems of MIMO systems
- Specifying connection points when interconnecting models

Default: Empty string `''` for all output channels

OutputUnit

Output channel units. Use `OutputUnit` to keep track of output signal units. For a single-output model, set `OutputUnit` to a string. For a multi-output model, set `OutputUnit` to a cell array of strings. `OutputUnit` has no effect on system behavior.

Default: Empty string `''` for all output channels

OutputGroup

Output channel groups. The `OutputGroup` property lets you assign the output channels of MIMO systems into groups and refer to each group by name. Specify output groups as a structure. In this structure, field names are the group names, and field values are the output channels belonging to each group. For example:

```
sys.OutputGroup.temperature = [1];
sys.InputGroup.measurement = [3 5];
```

creates output groups named `temperature` and `measurement` that include output channels 1, and 3, 5, respectively. You can then extract the subsystem from all inputs to the `measurement` outputs using:

```
sys('measurement',:)
```

Default: Struct with no fields

Name

System name. Set `Name` to a string to label the system.

Default: `''`

Notes

Any text that you want to associate with the system. Set `Notes` to a string or a cell array of strings.

Default: `{}`

UserData

Any type of data you wish to associate with system. Set `UserData` to any MATLAB data type.

Default: `[]`

Examples

Create a parametric SISO transfer function with two zeros, four poles, and at least one integrator.

A transfer function with an integrator includes a factor of 1/*s*. Therefore, to ensure that a parametrized transfer function has at least one integrator regardless of the parameter values, fix the lowest-order coeffiecient of the denominator to zero.

```
blk = ltiblock.tf('tfblock',2,4);  % two zeros, four poles
blk.den.Value(end) = 0;   % set last denominator entry to zero
blk.den.Free(end) = 0;    % fix it to zero
```

Create a parametric transfer function, and assign names to the input and output.

```
blk = ltiblock.tf('tfblock',2,3);
blk.InputName = {'error'};      % assign input name
blk.OutputName = {'control'};    % assign output name
```

More About

Tips

- To convert an `ltiblock.tf` parametric model to a numeric (non-tunable) model object, use model commands such as `tf`, `zpk`, or `ss`.

- “Control Design Blocks”
- “Models with Tunable Coefficients”

See Also

`ltiblock.pid` | `ltiblock.pid2` | `ltiblock.ss` | `ltiblock.tf` | `genss` | `systune` | `looptune` | `hinfstruct`

lyap

Continuous Lyapunov equation solution

Syntax

```
lyap
X = lyap(A,Q)
X = lyap(A,B,C)
X = lyap(A,Q,[],E)
```

Description

`lyap` solves the special and general forms of the Lyapunov equation. Lyapunov equations arise in several areas of control, including stability theory and the study of the RMS behavior of systems.

`X = lyap(A,Q)` solves the Lyapunov equation

$$AX + XA^T + Q = 0$$

where A and Q represent square matrices of identical sizes. If Q is a symmetric matrix, the solution `X` is also a symmetric matrix.

`X = lyap(A,B,C)` solves the Sylvester equation

$$AX + XB + C = 0$$

The matrices `A`, `B`, and `C` must have compatible dimensions but need not be square.

`X = lyap(A,Q,[],E)` solves the generalized Lyapunov equation

$$AXE^T + EXA^T + Q = 0$$

where Q is a symmetric matrix. You must use empty square brackets `[]` for this function. If you place any values inside the brackets, the function errors out.

Limitations

The continuous Lyapunov equation has a unique solution if the eigenvalues $\alpha_1, \alpha_2, \ldots, \alpha_n$ of A and $\beta_1, \beta_2, \ldots, \beta_n$ of B satisfy

$$\alpha_i + \beta_j \neq 0 \quad for\, all\, pairs(i, j)$$

If this condition is violated, `lyap` produces the error message:

```
Solution does not exist or is not unique.
```

Examples

Example 1

Solve Lyapunov Equation

Solve the Lyapunov equation

$$AX + XA^T + Q = 0$$

where

$$A = \begin{bmatrix} 1 & 2 \\ -3 & -4 \end{bmatrix} \qquad Q = \begin{bmatrix} 3 & 1 \\ 1 & 1 \end{bmatrix}$$

The A matrix is stable, and the Q matrix is positive definite.

```
A = [1 2; -3 -4];
Q = [3 1; 1 1];
X = lyap(A,Q)
```

These commands return the following X matrix:

```
X =

    6.1667   -3.8333
   -3.8333    3.0000
```

You can compute the eigenvalues to see that X is positive definite.

```
eig(X)
```

The command returns the following result:

```
ans =

    0.4359
    8.7308
```

Example 2

Solve Sylvester Equation

Solve the Sylvester equation

$$AX + XB + C = 0$$

where

$$A = 5 \qquad B = \begin{bmatrix} 4 & 3 \\ 4 & 3 \end{bmatrix} \qquad C = \begin{bmatrix} 2 & 1 \end{bmatrix}$$

```
A = 5;
B = [4 3; 4 3];
C = [2 1];
X = lyap(A,B,C)
```

These commands return the following X matrix:

```
X =

   -0.2000   -0.0500
```

More About

Algorithms

`lyap` uses SLICOT routines SB03MD and SG03AD for Lyapunov equations and SB04MD (SLICOT) and ZTRSYL (LAPACK) for Sylvester equations.

References

[1] Bartels, R.H. and G.W. Stewart, "Solution of the Matrix Equation AX + XB = C," *Comm. of the ACM*, Vol. 15, No. 9, 1972.

[2] Barraud, A.Y., “A numerical algorithm to solve A XA - X = Q,” *IEEE Trans. Auto. Contr.*, AC-22, pp. 883–885, 1977.

[3] Hammarling, S.J., “Numerical solution of the stable, non-negative definite Lyapunov equation,” *IMA J. Num. Anal.*, Vol. 2, pp. 303–325, 1982.

[4] Penzl, T., ”Numerical solution of generalized Lyapunov equations,” *Advances in Comp. Math.*, Vol. 8, pp. 33–48, 1998.

[5] Golub, G.H., Nash, S. and Van Loan, C.F., “A Hessenberg-Schur method for the problem AX + XB = C,” *IEEE Trans. Auto. Contr.*, AC-24, pp. 909–913, 1979.

See Also

`covar` | `dlyap`

lyapchol

Square-root solver for continuous-time Lyapunov equation

Syntax

```
R = lyapchol(A,B)
X = lyapchol(A,B,E)
```

Description

`R = lyapchol(A,B)` computes a Cholesky factorization `X = R'*R` of the solution `X` to the Lyapunov matrix equation:

```
A*X + X*A' + B*B' = 0
```

All eigenvalues of matrix `A` must lie in the open left half-plane for `R` to exist.

`X = lyapchol(A,B,E)` computes a Cholesky factorization `X = R'*R` of `X` solving the generalized Lyapunov equation:

```
A*X*E' + E*X*A' + B*B' = 0
```

All generalized eigenvalues of (A,E) must lie in the open left half-plane for `R` to exist.

More About

Algorithms

`lyapchol` uses SLICOT routines SB03OD and SG03BD.

References

[1] Bartels, R.H. and G.W. Stewart, "Solution of the Matrix Equation AX + XB = C," *Comm. of the ACM*, Vol. 15, No. 9, 1972.

[2] Hammarling, S.J., “Numerical solution of the stable, non-negative definite Lyapunov equation,” *IMA J. Num. Anal.*, Vol. 2, pp. 303-325, 1982.

[3] Penzl, T., ”Numerical solution of generalized Lyapunov equations,” *Advances in Comp. Math.*, Vol. 8, pp. 33-48, 1998.

See Also

`lyap` | `dlyapchol`

mag2db

Convert magnitude to decibels (dB)

Syntax

```
ydb = mag2db(y)
```

Description

`ydb = mag2db(y)` returns the corresponding decibel (dB) value *ydb* for a given magnitude *y*. The relationship between magnitude and decibels is $ydb = 20 \log_{10}(y)$.

See Also

`db2mag`

margin

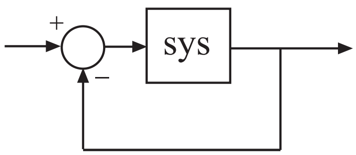
Gain margin, phase margin, and crossover frequencies

Syntax

```
[Gm,Pm,Wgm,Wpm] = margin(sys)
[Gm,Pm,Wgm,Wpm] = margin(mag,phase,w)
margin(sys)
```

Description

`margin` calculates the minimum gain margin, `Gm`, phase margin, `Pm`, and associated frequencies `Wgm` and `Wpm` of SISO open-loop models. The gain and phase margin of a system `sys` indicates the relative stability of the closed-loop system formed by applying unit negative feedback to `sys`, as in the following illustration.



The gain margin is the amount of gain increase or decrease required to make the loop gain unity at the frequency `Wgm` where the phase angle is –180° (modulo 360°). In other words, the gain margin is $1/g$ if g is the gain at the –180° phase frequency. Similarly, the phase margin is the difference between the phase of the response and –180° when the loop gain is 1.0. The frequency `Wpm` at which the magnitude is 1.0 is called the *unity-gain frequency* or *gain crossover frequency*. It is generally found that gain margins of three or more combined with phase margins between 30 and 60 degrees result in reasonable trade-offs between bandwidth and stability.

`[Gm,Pm,Wgm,Wpm] = margin(sys)` computes the gain margin `Gm`, the phase margin `Pm`, and the corresponding frequencies `Wgm` and `Wpm`, given the SISO open-loop dynamic system model `sys`. `Wgm` is the frequency where the gain margin is measured, which is a –180 degree phase crossing frequency. `Wpm` is the frequency where the phase margin is measured, which is a 0dB gain crossing frequency. These frequencies are expressed in radians/`TimeUnit`, where `TimeUnit` is the unit specified in the `TimeUnit` property of `sys`. When `sys` has several crossovers, `margin` returns the smallest gain and phase margins and corresponding frequencies.

The phase margin `Pm` is in degrees. The gain margin `Gm` is an absolute magnitude. You can compute the gain margin in dB by

```
Gm_dB = 20*log10(Gm)
```

`[Gm,Pm,Wgm,Wpm] = margin(mag,phase,w)` derives the gain and phase margins from Bode frequency response data (magnitude, phase, and frequency vector). `margin` interpolates between the frequency points to estimate the margin values. Provide the gain data `mag` in absolute units, and phase data `phase` in degrees. You can provide the frequency vector `w` in any units; `margin` returns `Wgm` and `Wpm` in the same units.

Note: When you use `margin(mag,phase,w)`, `margin` relies on interpolation to approximate the margins, which generally produces less accurate results. For example, if there is no 0 dB crossing within the `w` range, `margin` returns a phase margin of `Inf`. Therefore, if you have an analytical model `sys`, using `[Gm,Pm,Wgm,Wpm] = margin(sys)` is the most robust way to obtain the margins.

`margin(sys)`, without output arguments, plots the Bode response of `sys` on the screen and indicates the gain and phase margins on the plot. By default, gain margins are expressed in dB on the plot.

Examples

Gain and Phase Margins of Open-Loop Transfer Function

Create an open-loop discrete-time transfer function.

```
hd = tf([0.04798 0.0464],[1 -1.81 0.9048],0.1)
```

```
hd =

   0.04798 z + 0.0464
```

```
  ---------------------
  z^2 - 1.81 z + 0.9048

Sample time: 0.1 seconds
Discrete-time transfer function.
```

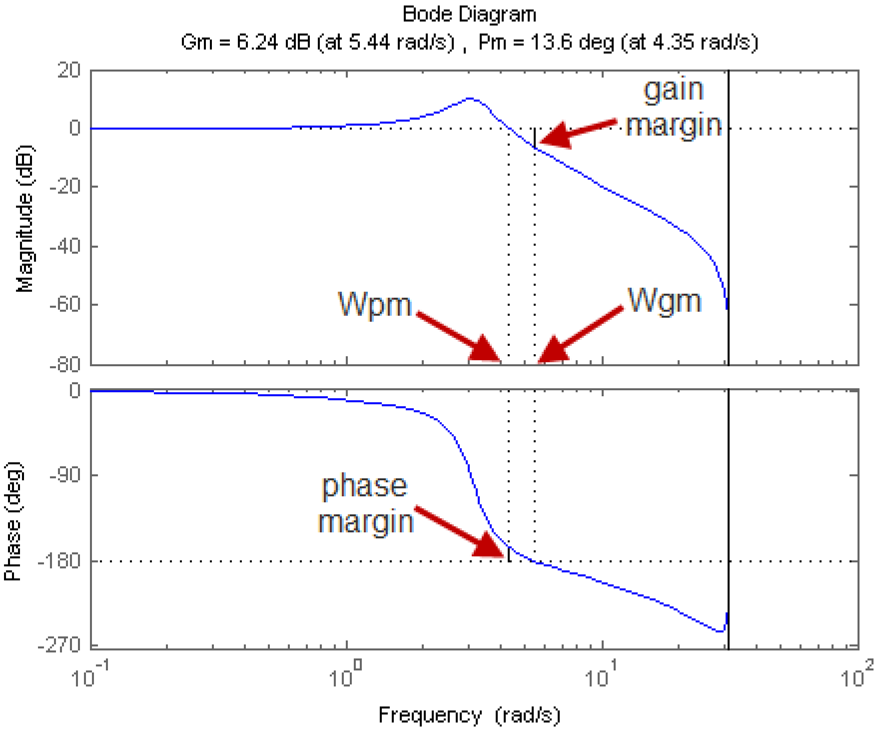
Compute the gain and phase margins.

```
[Gm,Pm,Wgm,Wpm] = margin(hd)
```

```
Gm =

    2.0517


Pm =

   13.5711


Wgm =

    5.4374


Wpm =

    4.3544
```

Display the gain and phase margins graphically.

```
margin(hd)
```



Solid vertical lines mark the gain margin and phase margin. The dashed vertical lines indicate the locations of `Wpm`, the frequency where the phase margin is measured, and `Wgm`, the frequency where the gain margin is measured.

More About

Algorithms

The phase margin is computed using H_∞ theory, and the gain margin by solving $H(j\omega) = \overline{H(j\omega)}$ for the frequency ω.

See Also

`bode` | `linearSystemAnalyzer`

minreal

Minimal realization or pole-zero cancelation

Syntax

```
sysr = minreal(sys)
sysr = minreal(sys,tol)
[sysr,u] = minreal(sys,tol)
... = minreal(sys,tol,false)
... = minreal(sys,[],false)
```

Description

`sysr = minreal(sys)` eliminates uncontrollable or unobservable state in state-space models, or cancels pole-zero pairs in transfer functions or zero-pole-gain models. The output `sysr` has minimal order and the same response characteristics as the original model `sys`.

`sysr = minreal(sys,tol)` specifies the tolerance used for state elimination or pole-zero cancellation. The default value is `tol = sqrt(eps)` and increasing this tolerance forces additional cancellations.

`[sysr,u] = minreal(sys,tol)` returns, for state-space model `sys`, an orthogonal matrix `U` such that `(U*A*U',U*B,C*U')` is a Kalman decomposition of (A,B,C)

`... = minreal(sys,tol,false)` and `... = minreal(sys,[],false)` disable the verbose output of the function. By default, `minreal` displays a message indicating the number of states removed from a state-space model `sys`.

Examples

The commands

```
g = zpk([],1,1);
h = tf([2 1],[1 0]);
```

```
cloop = inv(1+g*h) * g
```

produce the nonminimal zero-pole-gain model `cloop`.

```
cloop =

       s (s-1)
  -------------------
  (s-1) (s^2 + s + 1)

Continuous-time zero/pole/gain model.
```

To cancel the pole-zero pair at $s = 1$, type

```
cloopmin = minreal(cloop)
```

This command produces the following result.

```
cloopmin =

       s
  -------------
  (s^2 + s + 1)

Continuous-time zero/pole/gain model.
```

More About

Algorithms

Pole-zero cancellation is a straightforward search through the poles and zeros looking for matches that are within tolerance. Transfer functions are first converted to zero-pole-gain form.

See Also

`balreal` | `modred` | `sminreal`

modred

Model order reduction

Syntax

```
rsys = modred(sys,elim)
rsys = modred(sys,elim,'method')
```

Description

`rsys = modred(sys,elim)` reduces the order of a continuous or discrete state-space model `sys` by eliminating the states found in the vector `elim`. The full state vector *X* is partitioned as *X* = [*X1*;*X2*] where *X1* is the reduced state vector and *X2* is discarded.

`elim` can be a vector of indices or a logical vector commensurate with *X* where true values mark states to be discarded. This function is usually used in conjunction with `balreal`. Use `balreal` to first isolate states with negligible contribution to the I/O response. If `sys` has been balanced with `balreal` and the vector `g` of Hankel singular values has M small entries, you can use `modred` to eliminate the corresponding M states. For example:

```
[sys,g] = balreal(sys)  % Compute balanced realization
elim = (g<1e-8)         % Small entries of g are negligible states
rsys = modred(sys,elim) % Remove negligible states
```

`rsys = modred(sys,elim,'method')` also specifies the state elimination method. Choices for `'method'` include

- `'MatchDC'` (default): Enforce matching DC gains. The state-space matrices are recomputed as described in “Algorithms” on page 1-472.
- `'Truncate'`: Simply delete *X2*.

The `'Truncate'` option tends to produces a better approximation in the frequency domain, but the DC gains are not guaranteed to match.

If the state-space model `sys` has been balanced with `balreal` and the grammians have *m* small diagonal entries, you can reduce the model order by eliminating the last *m* states with `modred`.

Examples

Order Reduction by Matched-DC-Gain and Direct-Deletion Methods

Consider the following continuous fourth-order model.

$$h(s) = \frac{s^3 + 11s^2 + 36s + 26}{s^4 + 14.6s^3 + 74.96s^2 + 153.7s + 99.65}.$$

To reduce its order, first compute a balanced state-space realization with `balreal`.

```
h = tf([1 11 36 26],[1 14.6 74.96 153.7 99.65]);
[hb,g] = balreal(h);
```

Examine the gramians.

```
g'
```

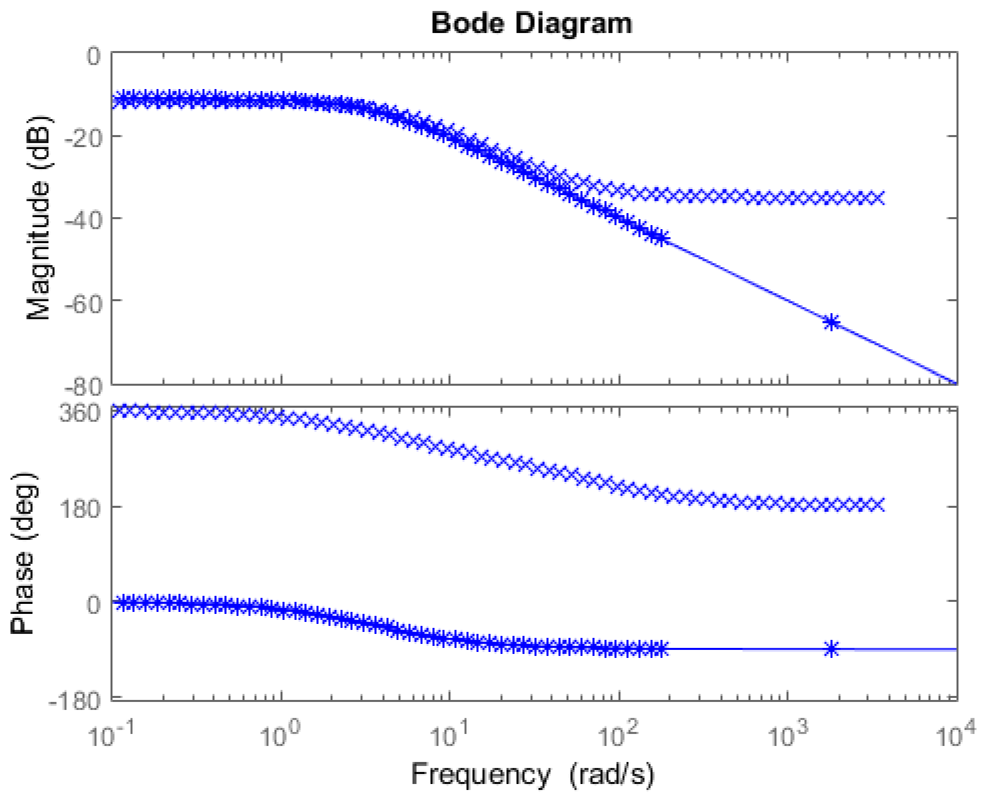
```
ans =

    0.1394    0.0095    0.0006    0.0000
```

The last three diagonal entries of the balanced gramians are relatively small. Eliminate these three least-contributing states with `modred`, using both matched-DC-gain and direct-deletion methods.

```
hmdc = modred(hb,2:4,'MatchDC');
hdel = modred(hb,2:4,'Truncate');
```

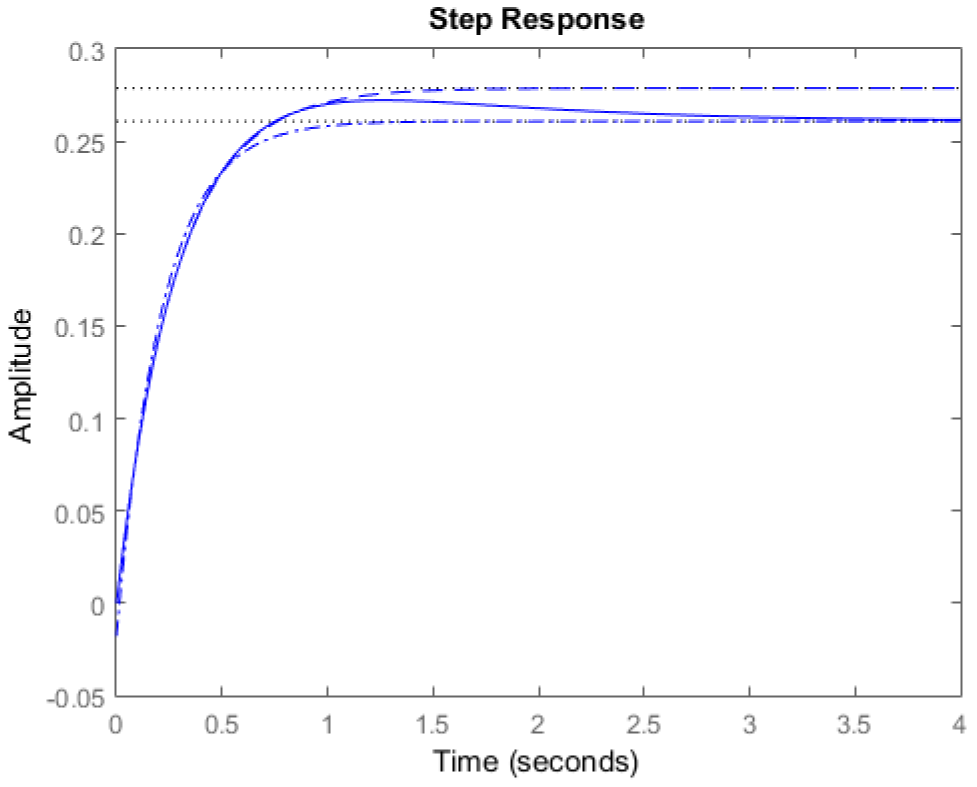
Both `hmdc` and `hdel` are first-order models. Compare their Bode responses against that of the original model.

```
bodeplot(h,'-',hmdc,'x',hdel,'*')
```



The reduced-order model `hdel` is clearly a better frequency-domain approximation of `h`. Now compare the step responses.

```
stepplot(h,'-',hmdc,'-.',hdel,'--')
```



While `hdel` accurately reflects the transient behavior, only `hmdc` gives the true steady-state response.

Limitations

With the matched DC gain method, A_{22} must be invertible in continuous time, and $I - A_{22}$ must be invertible in discrete time.

More About

Algorithms

The algorithm for the matched DC gain method is as follows. For continuous-time models

$$\dot{x} = Ax + By$$
$$y = Cx + Du$$

the state vector is partitioned into x_1, to be kept, and x_2, to be eliminated.

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} B_1 \\ B_2 \end{bmatrix} u$$
$$y = \begin{bmatrix} C_1 & C_2 \end{bmatrix} x + Du$$

Next, the derivative of x_2 is set to zero and the resulting equation is solved for x_1. The reduced-order model is given by

$$\dot{x}_1 = \left[A_{11} - A_{12} A_{22}{}^{-1} A_{21} \right] x_1 + \left[B_1 - A_{12} A_{22}{}^{-1} B_2 \right] u$$
$$y = \left[C_1 - C_2 A_{22}{}^{-1} A_{21} \right] x + \left[D - C_2 A_{22}{}^{-1} B_2 \right] u$$

The discrete-time case is treated similarly by setting

$$x_2[n+1] = x_2[n]$$

See Also

`balreal` | `minreal`

modsep

Region-based modal decomposition

Syntax

```
[H,H0] = modsep(G,N,REGIONFCN)
MODSEP(G,N,REGIONFCN,PARAM1,...)
```

Description

`[H,H0] = modsep(G,N,REGIONFCN)` decomposes the LTI model `G` into a sum of `n` simpler models `Hj` with their poles in disjoint regions `Rj` of the complex plane:

$$G(s) = H0 + \sum_{j=1}^{N} Hj(s)$$

`G` can be any LTI model created with `ss`, `tf`, or `zpk`, and `N` is the number of regions used in the decomposition. `modsep` packs the submodels `Hj` into an LTI array `H` and returns the static gain `H0` separately. Use `H(:,:,j)` to retrieve the submodel `Hj(s)`.

To specify the regions of interest, use a function of the form

```
IR = REGIONFCN(p)
```

that assigns a region index `IR` between 1 and `N` to a given pole `p`. You can specify this function as a string or a function handle, and use the syntax `MODSEP(G,N,REGIONFCN,PARAM1,...)` to pass extra input arguments:

```
IR = REGIONFCN(p,PARAM1,...)
```

Examples

To decompose `G` into `G(z) = H0 + H1(z) + H2(z)` where `H1` and `H2` have their poles inside and outside the unit disk respectively, use

```
[H,H0]  = modsep(G,2,@udsep)
```

where the function `udsep` is defined by

```
function r = udsep(p)
if abs(p)<1, r = 1;  % assign r=1 to poles inside unit disk
else         r = 2;  % assign r=2 to poles outside unit disk
end
```

To extract `H1(z)` and `H2(z)` from the LTI array `H`, use

```
H1 = H(:,:,1);  H2 = H(:,:,2);
```

See Also

`stabsep`

nblocks

Number of blocks in Generalized matrix or Generalized LTI model

Syntax

```
N = nblocks(M)
```

Description

`N = nblocks(M)` returns the number of "Control Design Blocks" in the Generalized LTI model or Generalized matrix M.

Input Arguments

`M`

AGeneralized LTI model (`genss` or `genfrd` model), a Generalized matrix (`genmat`), or an array of such models.

Output Arguments

`N`

The number of "Control Design Blocks" in M. If a block appears multiple times in M, N reflects the total number of occurrences.

If M is a model array, N is an array with the same dimensions as M. Each entry of N is the number of Control Design Blocks in the corresponding entry of M.

Examples

Number of Control Design Blocks in a Second-Order Filter Model

This example shows how to use `nblocks` to examine two different ways of parametrizing a model of a second-order filter.

1 Create a tunable (parametric) model of the second-order filter:

$$F(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n + \omega_n^2},$$

where the damping ζ and the natural frequency ω_n are tunable parameters.

```
wn = realp('wn',3);
zeta = realp('zeta',0.8);
F = tf(wn^2,[1 2*zeta*wn wn^2]);
```

`F` is a `genss` model with two tunable Control Design Blocks, the `realp` blocks `wn` and `zeta`. The blocks `wn` and `zeta` have initial values of 3 and 0.8, respectively.

2 Examine the number of tunable blocks in the model using `nblocks`.

```
nblocks(F)
```

This command returns the result:

```
ans =

     6
```

`F` has two tunable parameters, but the parameter `wn` appears five times—twice in the numerator and three times in the denominator.

3 Rewrite `F` for fewer occurrences of `wn`.

The second-order filter transfer function can be expressed as follows:

$$F(s) = \frac{1}{\left(\frac{s}{\omega_n}\right)^2 + 2\zeta\left(\frac{s}{\omega_n}\right) + 1}.$$

Use this expression to create the tunable filter:

```
F = tf(1,[(1/wn)^2 2*zeta*(1/wn) 1])
```

4 Examine the number of tunable blocks in the new filter model.

```
nblocks(F)
```

This command returns the result:

```
ans =

     4
```

In the new formulation, there are only three occurrences of the tunable parameter `wn`. Reducing the number of occurrences of a block in a model can improve performance time of calculations involving the model. However, the number of occurrences does not affect the results of tuning the model or sampling the model for parameter studies.

More About

- "Control Design Blocks"
- "Generalized Matrices"
- "Generalized and Uncertain LTI Models"

See Also

`genss` | `genfrd` | `genmat` | `getValue`

ndims

Query number of dimensions of dynamic system model or model array

Syntax

```
n = ndims(sys)
```

Description

`n = ndims(sys)` is the number of dimensions of a dynamic system model or a model array `sys`. A single model has two dimensions (one for outputs, and one for inputs). A model array has $2 + p$ dimensions, where $p \geq 2$ is the number of array dimensions. For example, a 2-by-3-by-4 array of models has $2 + 3 = 5$ dimensions.

```
ndims(sys) = length(size(sys))
```

Examples

```
sys = rss(3,1,1,3);
ndims(sys)
ans =
     4
```

`ndims` returns `4` for this 3-by-1 array of SISO models.

See Also

`size`

ngrid

Superimpose Nichols chart on Nichols plot

Syntax

```
ngrid
```

Description

`ngrid` superimposes Nichols chart grid lines over the Nichols frequency response of a SISO LTI system. The range of the Nichols grid lines is set to encompass the entire Nichols frequency response.

The chart relates the complex number $H/(1 + H)$ to H, where H is any complex number. For SISO systems, when H is a point on the open-loop frequency response, then

$$\frac{H}{1+H}$$

is the corresponding value of the closed-loop frequency response assuming unit negative feedback.

If the current axis is empty, `ngrid` generates a new Nichols chart grid in the region –40 dB to 40 dB in magnitude and –360 degrees to 0 degrees in phase. If the current axis does not contain a SISO Nichols frequency response, `ngrid` returns a warning.

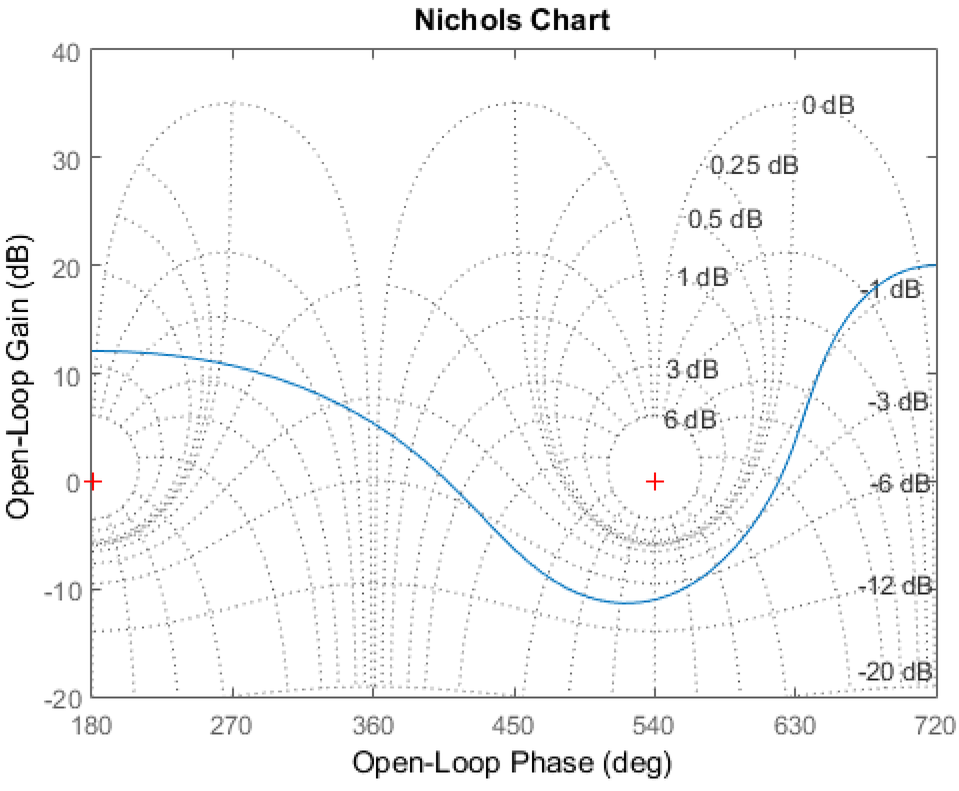
Examples

Nichols Response with Nichols Grid Lines

Plot the Nichols response with Nichols grid lines for the following system:

$$H(s) = \frac{-4s^4 + 48s^3 - 18s^2 + 250s + 600}{s^4 + 30s^3 + 282s^2 + 525s + 60}.$$

```
H = tf([-4 48 -18 250 600],[1 30 282 525 60]);
nichols(H)
ngrid
```



The right-click menu for Nichols charts includes the **Tight** option under **Zoom**. You can use this to clip unbounded branches of the Nichols chart.

See Also

`nichols`

nichols

Nichols chart of frequency response

Syntax

```
nichols(sys)
nichols(sys,w)
nichols(sys1,sys2,...,sysN)
nichols(sys1,sys2,...,sysN,w)
nichols(sys1,'PlotStyle1',...,sysN,'PlotStyleN')
[mag,phase,w] = nichols(sys)
[mag,phase] = nichols(sys,w)
```

Description

`nichols` creates a Nichols chart of the frequency response. A Nichols chart displays the magnitude (in dB) plotted against the phase (in degrees) of the system response. Nichols charts are useful to analyze open- and closed-loop properties of SISO systems, but offer little insight into MIMO control loops. Use `ngrid` to superimpose a Nichols chart on an existing SISO Nichols chart.

`nichols(sys)` creates a Nichols chart of the dynamic system `sys`. This model can be continuous or discrete, SISO or MIMO. In the MIMO case, `nichols` produces an array of Nichols charts, each plot showing the response of one particular I/O channel. The frequency range and gridding are determined automatically based on the system poles and zeros.

`nichols(sys,w)` specifies the frequency range or frequency points to be used for the chart. To focus on a particular frequency interval `[wmin,wmax]`, set `w = {wmin,wmax}`. To use particular frequency points, set `w` to the vector of desired frequencies. Use `logspace` to generate logarithmically spaced frequency vectors. Frequencies must be in `rad/TimeUnit`, where `TimeUnit` is the time units of the input dynamic system, specified in the TimeUnit property of sys.

`nichols(sys1,sys2,...,sysN)` or `nichols(sys1,sys2,...,sysN,w)` superimposes the Nichols charts of several models on a single figure. All systems must have the same number of inputs and outputs, but may otherwise be a mix of continuous- and discrete-time systems. You can also specify a distinctive color, linestyle, and/or marker for each system plot with the syntax `nichols(sys1,'PlotStyle1',...,sysN,'PlotStyleN')`.

See `bode` for an example.

`[mag,phase,w] = nichols(sys)` or `[mag,phase] = nichols(sys,w)` returns the magnitude and phase (in degrees) of the frequency response at the frequencies `w` (in `rad/TimeUnit`). The outputs `mag` and `phase` are 3-D arrays similar to those produced by `bode` (see the `bode` reference page). They have dimensions
(number of outputs) × (number of inputs) × (length of w)

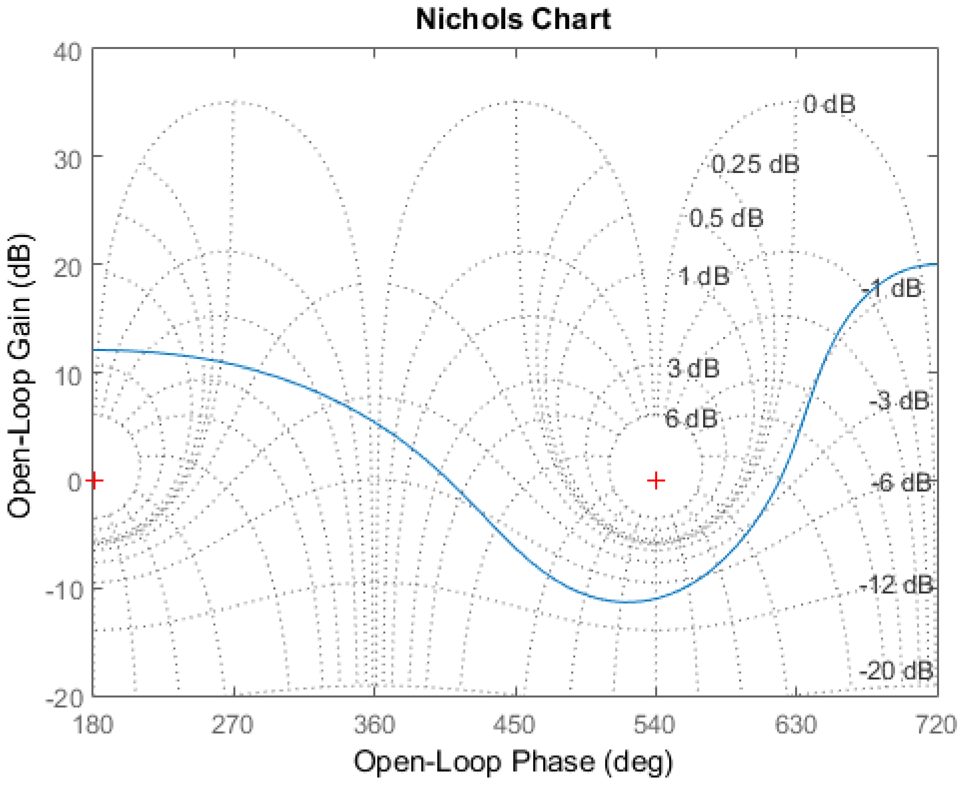
Examples

Nichols Response with Nichols Grid Lines

Plot the Nichols response with Nichols grid lines for the following system:

$$H(s) = \frac{-4s^4 + 48s^3 - 18s^2 + 250s + 600}{s^4 + 30s^3 + 282s^2 + 525s + 60}.$$

```
H = tf([-4 48 -18 250 600],[1 30 282 525 60]);
nichols(H)
ngrid
```



The right-click menu for Nichols charts includes the **Tight** option under **Zoom**. You can use this to clip unbounded branches of the Nichols chart.

More About

Tips

You can change the properties of your plot, for example the units. For information on the ways to change properties of your plots, see “Ways to Customize Plots”.

Algorithms

See `bode`.

See Also

`bode` | `evalfr` | `freqresp` | `linearSystemAnalyzer` | `ngrid` | `nyquist` | `sigma`

nicholsoptions

Create list of Nichols plot options

Syntax

```
P = nicholsoptions
P = nicholsoptions('cstprefs')
```

Description

`P = nicholsoptions` returns a list of available options for Nichols plots with default values set. You can use these options to customize the Nichols plot appearance from the command line.

`P = nicholsoptions('cstprefs')` initializes the plot options with the options you selected in the Control System Toolbox Preferences Editor. For more information about the editor, see "Toolbox Preferences Editor" in the User's Guide documentation.

This table summarizes the Nichols plot options.

Option	Description
Title, XLabel, YLabel	Label text and style
TickLabel	Tick label style
Grid	Show or hide the grid Specified as one of the following strings: `'off' | 'on'` **Default**: `'off'`
XlimMode, YlimMode	Limit modes
Xlim, Ylim	Axes limits
IOGrouping	Grouping of input-output pairs Specified as one of the following strings: `'none' |'inputs'|'outputs'|'all'` **Default**: `'none'`
InputLabels, OutputLabels	Input and output label styles.

Option	Description
InputVisible, OutputVisible	Visibility of input and output channels

Option	Description
FreqUnits	Frequency units, specified as one of the following strings: • `'Hz'` • `'rad/second'` • `'rpm'` • `'kHz'` • `'MHz'` • `'GHz'` • `'rad/nanosecond'` • `'rad/microsecond'` • `'rad/millisecond'` • `'rad/minute'` • `'rad/hour'` • `'rad/day'` • `'rad/week'` • `'rad/month'` • `'rad/year'` • `'cycles/nanosecond'` • `'cycles/microsecond'` • `'cycles/millisecond'` • `'cycles/hour'` • `'cycles/day'` • `'cycles/week'` • `'cycles/month'` • `'cycles/year'` **Default**: `'rad/s'` You can also specify `'auto'` which uses frequency units `rad/TimeUnit` relative

Option	Description
	to system time units specified in the `TimeUnit` property. For multiple systems with different time units, the units of the first system are used.
MagLowerLimMode	Enables a lower magnitude limit Specified as one of the following strings: `'auto' | 'manual'` **Default**: `'auto'`
MagLowerLim	Specifies the lower magnitude limit
PhaseUnits	Phase units Specified as one of the following strings: `'deg' | 'rad'` **Default**: `'deg'`
PhaseWrapping	Enables phase wrapping Specified as one of the following strings: `'on' | 'off'` **Default**: `'off'`
PhaseMatching	Enables phase matching Specified as one of the following strings: `'on' | 'off'` **Default**: `'off'`
PhaseMatchingFreq	Frequency for matching phase
PhaseMatchingValue	The value to make the phase responses close to

Examples

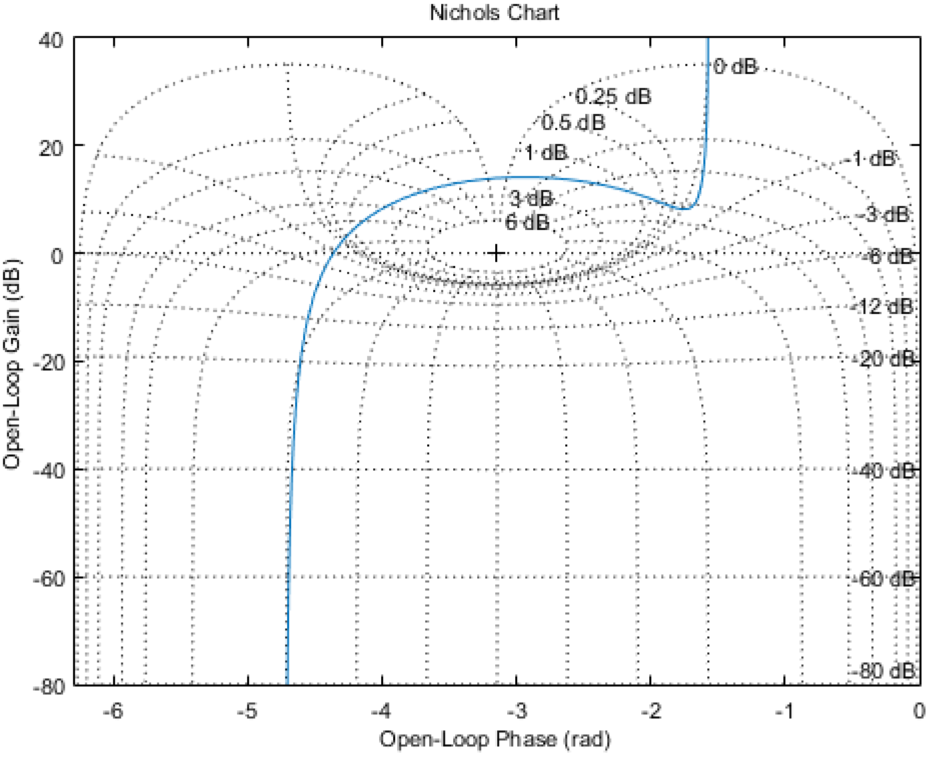
Set Options for Nichols Plot

Create an options set, and set the phase units and grid option.

```
P = nicholsoptions;
P.PhaseUnits = 'rad';
P.Grid = 'on';
```

Use the options set to generate a Nichols plot. Not the phase units and grid in the plot.

```
h = nicholsplot(tf(1,[1,.2,1,0]),P);
```



See Also

`getoptions` | `nicholsplot` | `setoptions`

nicholsplot

Plot Nichols frequency responses and return plot handle

Syntax

```
h = nicholsplot(sys)
nicholsplot(sys,{wmin,wmax})
nicholsplot(sys,w)
nicholsplot(sys1,sys2,...,w)
nicholsplot(AX,...)
nicholsplot(..., plotoptions)
```

Description

`h = nicholsplot(sys)` draws the Nichols plot of the dynamic system `sys`. It also returns the plot handle `h`. You can use this handle to customize the plot with the `getoptions` and `setoptions` commands. Type

```
help nicholsoptions
```

for a list of available plot options.

The frequency range and number of points are chosen automatically. See `bode` for details on the notion of frequency in discrete time.

`nicholsplot(sys,{wmin,wmax})` draws the Nichols plot for frequencies between `wmin` and `wmax` (in `rad/TimeUnit`, where `TimeUnit` is the time units of the input dynamic system, specified in the TimeUnit property of sys).

`nicholsplot(sys,w)` uses the user-supplied vector `w` of frequencies, in `rad/TimeUnit`, at which the Nichols response is to be evaluated. See `logspace` to generate logarithmically spaced frequency vectors.

`nicholsplot(sys1,sys2,...,w)` draws the Nichols plots of multiple models `sys1`,`sys2`,... on a single plot. The frequency vector `w` is optional. You can also specify a color, line style, and marker for each system, as in

```
nicholsplot(sys1,'r',sys2,'y--',sys3,'gx').
```

`nicholsplot(AX,...)` plots into the axes with handle `AX`.

`nicholsplot(..., plotoptions)` plots the Nichols plot with the options specified in `plotoptions`. Type

```
help nicholsoptions
```

for more details.

Examples

Generate Nichols plot and use plot handle to change frequency units to Hz

```
sys = rss(5);
h = nicholsplot(sys);
% Change units to Hz
setoptions(h,'FreqUnits','Hz');
```

More About

Tips

You can change the properties of your plot, for example the units. For information on the ways to change properties of your plots, see “Ways to Customize Plots”.

See Also

`getoptions` | `nichols` | `nicholsoptions` | `setoptions`

nmodels

Number of models in model array

Syntax

```
N = nmodels(sysarray)
```

Description

`N = nmodels(sysarray)` returns the number of models in an array of dynamic system models or static models.

Examples

Number of Models in Array

Create a 2-by-3-by-5 array of state-space models and confirm the number of models in the array.

```
sysarr = rss(2,2,2,2,3,4);
N = nmodels(sysarr)
```

```
N =

    24
```

Input Arguments

`sysarray` — Input model array

model array

Input model array, specified as an array of input-output models such as numeric LTI models, generalized models, or identified LTI models.

Output Arguments

`N` — Number of models in array

positive integer

Number of models in the input model array, returned as a positive integer.

See Also

`ndims` | `size`

norm

Norm of linear model

Syntax

```
n = norm(sys)
n = norm(sys,2)
n = norm(sys,inf)
[n,fpeak] = norm(sys,inf)
[...] = norm(sys,inf,tol)
```

Description

`n = norm(sys)` or `n = norm(sys,2)` return the H_2 norm of the linear dynamic system model sys.

`n = norm(sys,inf)` returns the H_∞ norm of sys.

`[n,fpeak] = norm(sys,inf)` also returns the frequency fpeak at which the gain reaches its peak value.

`[...] = norm(sys,inf,tol)` sets the relative accuracy of the H_∞ norm to tol.

Input Arguments

`sys`

Continuous- or discrete-time linear dynamic system model. sys can also be an array of linear models.

`tol`

Positive real value setting the relative accuracy of the H_∞ norm.

Default: 0.01

Output Arguments

n

H_2 norm or H_∞ norm of the linear model sys.

If sys is an array of linear models, n is an array of the same size as sys. In that case each entry of n is the norm of each entry of sys.

fpeak

Frequency at which the peak gain of sys occurs.

Examples

This example uses `norm` to compute the H_2 and H_∞ norms of a discrete-time linear system.

Consider the discrete-time transfer function

$$H(z) = \frac{z^3 - 2.841z^2 + 2.875z - 1.004}{z^3 - 2.417z^2 + 2.003z - 0.5488}$$

with sample time 0.1 second.

To compute the H_2 norm of this transfer function, enter:

```
H = tf([1 -2.841 2.875 -1.004],[1 -2.417 2.003 -0.5488],0.1)
norm(H)
```

These commands return the result:

```
ans =
    1.2438
```

To compute the H_∞ infinity norm, enter:

```
[ninf,fpeak] = norm(H,inf)
```

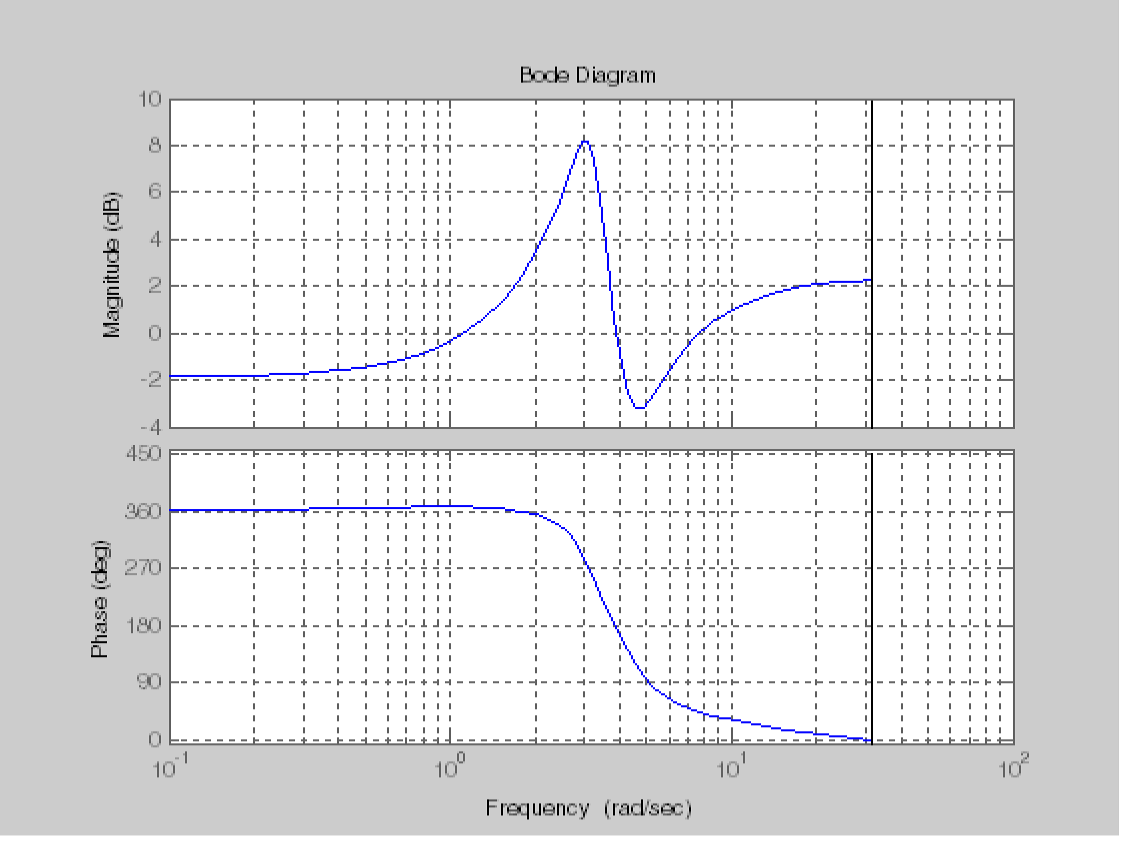
This command returns the result:

```
ninf =
```

```
    2.5488

fpeak =
    3.0844
```

You can use a Bode plot of $H(z)$ to confirm these values.

```
bode(H)
grid on;
```



The gain indeed peaks at approximately 3 rad/sec. To find the peak gain in dB, enter:

```
20*log10(ninf)
```

This command produces the following result:

```
ans =
    8.1268
```

More About

H2 norm

The H_2 norm of a stable continuous-time system with transfer function $H(s)$, is given by:

$$\|H\|_2 = \sqrt{\frac{1}{2\pi}\int_{-\infty}^{\infty}\mathrm{Trace}\left[H(j\omega)^H H(j\omega)\right]d\omega}.$$

For a discrete-time system with transfer function $H(z)$, the H_2 norm is given by:

$$\|H\|_2 = \sqrt{\frac{1}{2\pi}\int_{-\pi}^{\pi}\mathrm{Trace}\left[H(e^{j\omega})^H H(e^{j\omega})\right]d\omega}.$$

The H_2 norm is equal to the root-mean-square of the impulse response of the system. The H_2 norm measures the steady-state covariance (or power) of the output response $y = Hw$ to unit white noise inputs w:

$$\|H\|_2^2 = \lim_{t\to\infty} E\left\{y(t)^T y(t)\right\}, \qquad E\left(w(t)w(\tau)^T\right) = \delta(t-\tau)I.$$

The H_2 norm is infinite in the following cases:

- sys is unstable.
- sys is continuous and has a nonzero feedthrough (that is, nonzero gain at the frequency $\omega = \infty$).

`norm(sys)` produces the same result as

```
sqrt(trace(covar(sys,1)))
```

H-infinity norm

The H_∞ norm (also called the L_∞ norm) of a SISO linear system is the peak gain of the frequency response. For a MIMO system, the H_∞ norm is the peak gain across all input/output channels. Thus, for a continuous-time system $H(s)$, the H_∞ norm is given by:

$$\left\|H(s)\right\|_\infty = \max_\omega \left|H(j\omega)\right| \qquad \text{(SISO)}$$

$$\left\|H(s)\right\|_\infty = \max_\omega \sigma_{\max}\left(H(j\omega)\right) \qquad \text{(MIMO)}$$

where $\sigma_{\max}(\cdot)$ denotes the largest singular value of a matrix.

For a discrete-time system $H(z)$:

$$\left\|H(z)\right\|_\infty = \max_{\theta\in[0,\pi]} \left|H\left(e^{j\theta}\right)\right| \qquad \text{(SISO)}$$

$$\left\|H(z)\right\|_\infty = \max_{\theta\in[0,\pi]} \sigma_{\max}\left(H\left(e^{j\theta}\right)\right) \qquad \text{(MIMO)}$$

The H_∞ norm is infinite if sys has poles on the imaginary axis (in continuous time), or on the unit circle (in discrete time).

Algorithms

`norm` first converts sys to a state space model.

`norm` uses the same algorithm as `covar` for the H_2 norm. For the H_∞ norm, `norm` uses the algorithm of [1]. `norm` computes the H_∞ norm (peak gain) using the SLICOT library. For more information about the SLICOT library, see http://slicot.org.

References

[1] Bruisma, N.A. and M. Steinbuch, "A Fast Algorithm to Compute the H_∞-Norm of a Transfer Function Matrix," *System Control Letters*, 14 (1990), pp. 287-293.

See Also

`freqresp` | `sigma`

nyquist

Nyquist plot of frequency response

Syntax

```
nyquist(sys)
nyquist(sys,w)
nyquist(sys1,sys2,...,sysN)
nyquist(sys1,sys2,...,sysN,w)
nyquist(sys1,'PlotStyle1',...,sysN,'PlotStyleN')
[re,im,w] = nyquist(sys)
[re,im] = nyquist(sys,w)
[re,im,w,sdre,sdim] = nyquist(sys)
```

Description

`nyquist` creates a Nyquist plot of the frequency response of a dynamic system model. When invoked without left-hand arguments, `nyquist` produces a Nyquist plot on the screen. Nyquist plots are used to analyze system properties including gain margin, phase margin, and stability.

`nyquist(sys)` creates a Nyquist plot of a dynamic system `sys`. This model can be continuous or discrete, and SISO or MIMO. In the MIMO case, `nyquist` produces an array of Nyquist plots, each plot showing the response of one particular I/O channel. The frequency points are chosen automatically based on the system poles and zeros.

`nyquist(sys,w)` explicitly specifies the frequency range or frequency points to be used for the plot. To focus on a particular frequency interval, set `w = {wmin,wmax}`. To use particular frequency points, set `w` to the vector of desired frequencies. Use `logspace` to generate logarithmically spaced frequency vectors. Frequencies must be in `rad/TimeUnit`, where `TimeUnit` is the time units of the input dynamic system, specified in the TimeUnit property of sys.

`nyquist(sys1,sys2,...,sysN)` or `nyquist(sys1,sys2,...,sysN,w)` superimposes the Nyquist plots of several LTI models on a single figure. All systems must have the same number of inputs and outputs, but may otherwise be a mix of continuous- and discrete-time systems. You can also specify a distinctive color, linestyle, and/or marker for each system plot with the syntax `nyquist(sys1,'PlotStyle1',...,sysN,'PlotStyleN')`.

`[re,im,w] = nyquist(sys)` and `[re,im] = nyquist(sys,w)` return the real and imaginary parts of the frequency response at the frequencies `w` (in `rad/TimeUnit`). `re` and `im` are 3-D arrays (see "Arguments" below for details).

`[re,im,w,sdre,sdim] = nyquist(sys)` also returns the standard deviations of `re` and `im` for the identified system `sys`.

Arguments

The output arguments `re` and `im` are 3-D arrays with dimensions

$$(\text{number of outputs}) \times (\text{number of inputs}) \times (\text{length of w})$$

For SISO systems, the scalars `re(1,1,k)` and `im(1,1,k)` are the real and imaginary parts of the response at the frequency ω_k = w(k).

$$\text{re}(1,1,k) = \text{Re}\left(h(j\omega_k)\right)$$
$$\text{im}(1,1,k) = \text{Im}\left(h(jw_k)\right)$$

For MIMO systems with transfer function $H(s)$, `re(:,:,k)` and `im(:,:,k)` give the real and imaginary parts of $H(j\omega_k)$ (both arrays with as many rows as outputs and as many columns as inputs). Thus,

$$\text{re}(\text{i},\text{j},\text{k}) = \text{Re}\left(h_{ij}(j\omega_k)\right)$$
$$\text{im}(\text{i},\text{j},\text{k}) = \text{Im}\left(h_{ij}(j\omega_k)\right)$$

where h_{ij} is the transfer function from input j to output i.

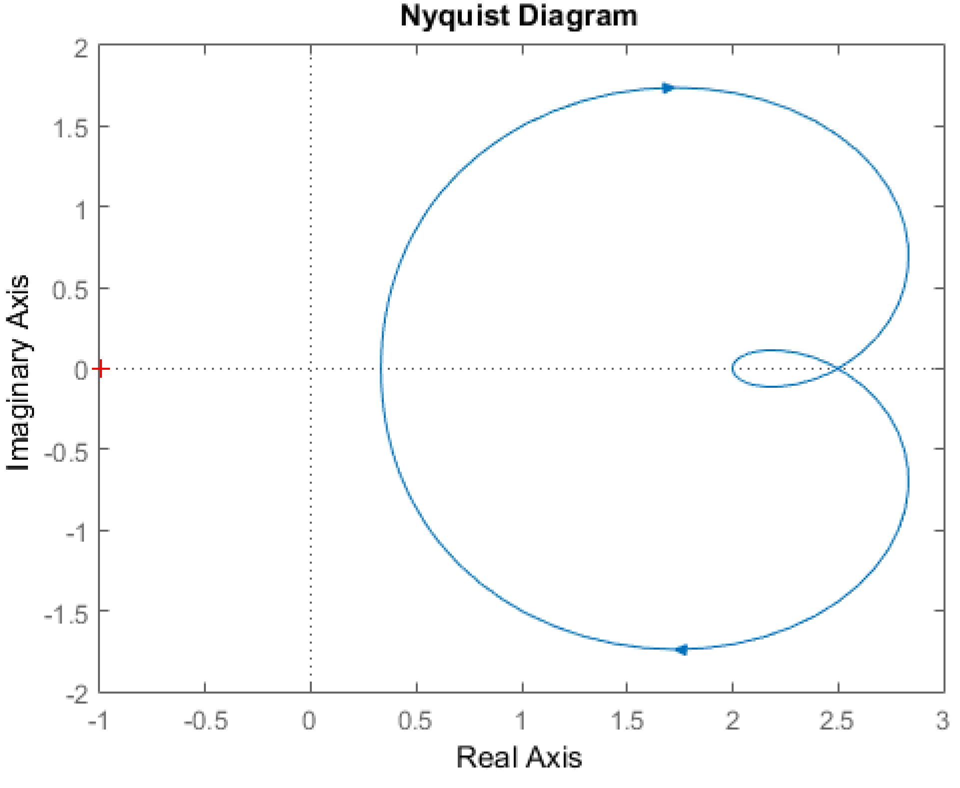
Examples

Nyquist Plot of Dynamic System

Plot the Nyquist response of the system

$$H(s) = \frac{2s^2 + 5s + 1}{s^2 + 2s + 3}$$

```
H = tf([2 5 1],[1 2 3]);
nyquist(H)
```



The nyquist function has support for M-circles, which are the contours of the constant closed-loop magnitude. M-circles are defined as the locus of complex numbers where

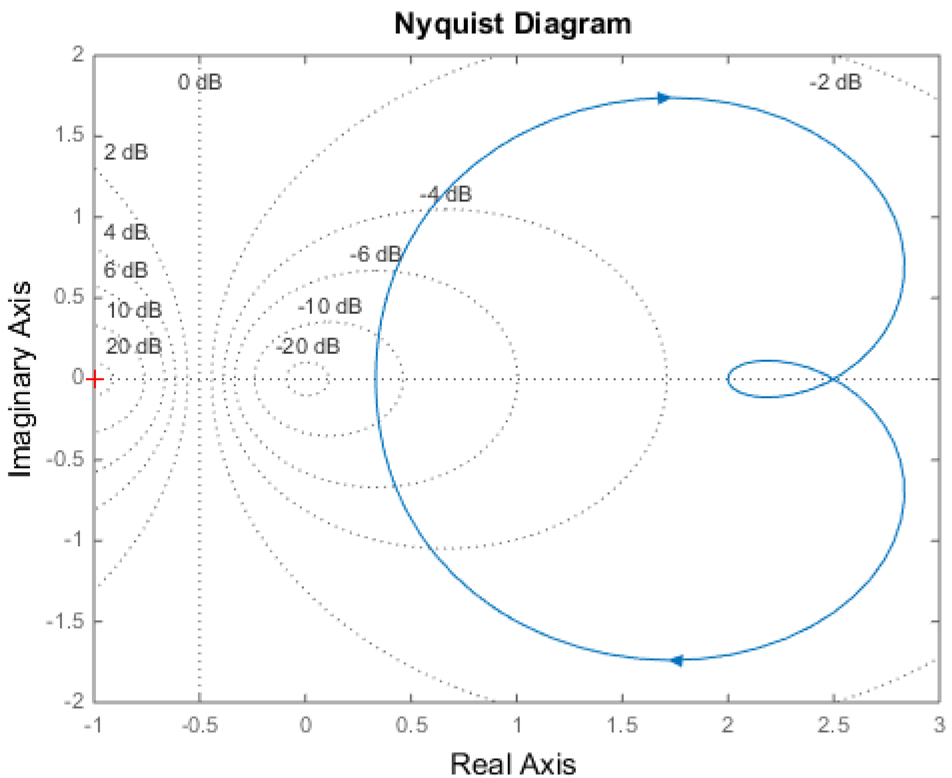
$$T(j\omega) = \left| \frac{G(j\omega)}{1 + G(j\omega)} \right|$$

is a constant value. In this equation, ω is the frequency in radians/TimeUnit, where `TimeUnit` is the system time units, and *G* is the collection of complex numbers that satisfy the constant magnitude requirement.

To activate the grid, select **Grid** from the right-click menu or type

```
grid
```

at the MATLAB prompt. This figure shows the M circles for transfer function *H*.

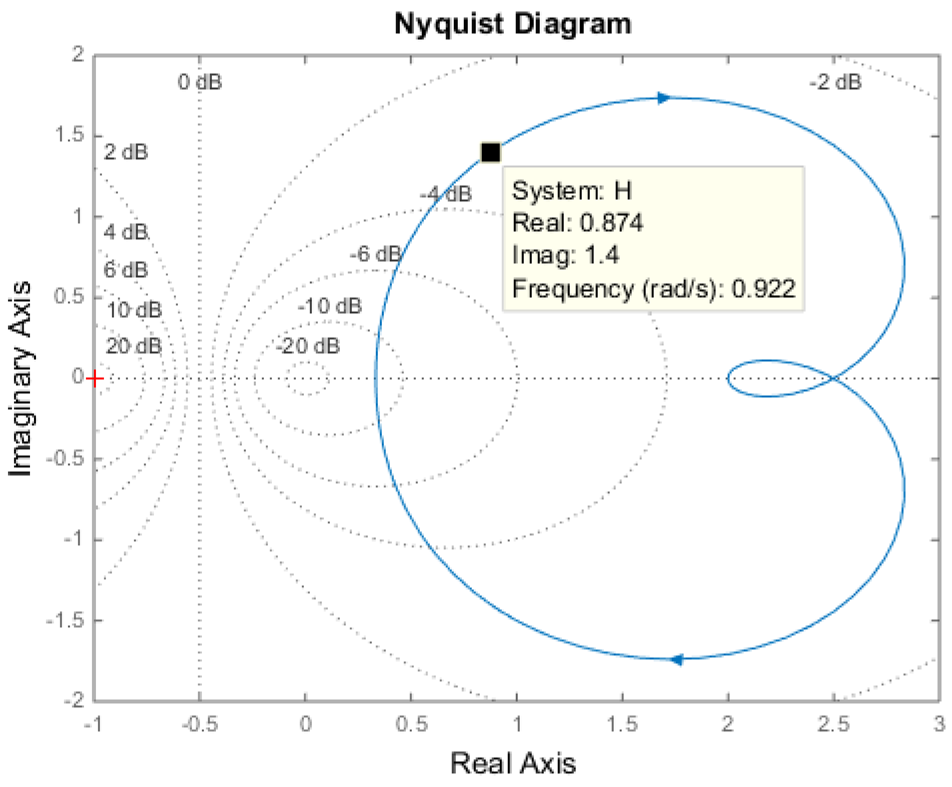


You have two zoom options available from the right-click menu that apply specifically to Nyquist plots:

- **Tight** —Clips unbounded branches of the Nyquist plot, but still includes the critical point (-1, 0)

- **On (-1,0)** — Zooms around the critical point (-1,0)

Also, click anywhere on the curve to activate data markers that display the real and imaginary values at a given frequency. This figure shows the nyquist plot with a data marker.



Nyquist Plot of Identified Model with Response Uncertainty

Compute the standard deviation of the real and imaginary parts of frequency response of an identified model. Use this data to create a 3σ plot of the response uncertainty. (Identified models require System Identification Toolbox.)

Identify a transfer function model based on data. Obtain the standard deviation data for the real and imaginary parts of the frequency response.

```
load iddata2 z2;
sys_p = tfest(z2,2);
w = linspace(-10*pi,10*pi,512);
[re, im, ~, sdre, sdim] = nyquist(sys_p,w);
```

`sys_p` is an identified transfer function model. `sdre` and `sdim` contain `1-std` standard deviation uncertainty values in `re` and `im` respectively.

Create a `Nyquist` plot showing the response and its 3σ uncertainty:

```
re = squeeze(re);
im = squeeze(im);
sdre = squeeze(sdre);
sdim = squeeze(sdim);
plot(re,im,'b', re+3*sdre, im+3*sdim, 'k:', re-3*sdre, im-3*sdim, 'k:')
```

More About

Tips

You can change the properties of your plot, for example the units. For information on the ways to change properties of your plots, see “Ways to Customize Plots”.

Algorithms

See `bode`.

See Also

`evalfr` | `freqresp` | `bode` | `linearSystemAnalyzer` | `nichols` | `sigma`

nyquistoptions

List of Nyquist plot options

Syntax

```
P = nyquistoptions
P = nyquistoptions('cstprefs')
```

Description

`P = nyquistoptions` returns the default options for Nyquist plots. You can use these options to customize the Nyquist plot appearance using the command line.

`P = nyquistoptions('cstprefs')` initializes the plot options with the options you selected in the Control System and System Identification Toolbox Preferences Editor. For more information about the editor, see "Toolbox Preferences Editor" in the User's Guide documentation.

The following table summarizes the Nyquist plot options.

Option	Description
Title, XLabel, YLabel	Label text and style
TickLabel	Tick label style
Grid	Show or hide the grid Specified as one of the following strings: `'off' | 'on'` **Default**: `'off'`
XlimMode, YlimMode	Limit modes
Xlim, Ylim	Axes limits
IOGrouping	Grouping of input-output pairs Specified as one of the following strings: `'none' |'inputs'|'outputs'|'all'` **Default**: `'none'`
InputLabels, OutputLabels	Input and output label styles

Option	Description
InputVisible, OutputVisible	Visibility of input and output channels

Option	Description
FreqUnits	Frequency units, specified as one of the following strings: • `'Hz'` • `'rad/second'` • `'rpm'` • `'kHz'` • `'MHz'` • `'GHz'` • `'rad/nanosecond'` • `'rad/microsecond'` • `'rad/millisecond'` • `'rad/minute'` • `'rad/hour'` • `'rad/day'` • `'rad/week'` • `'rad/month'` • `'rad/year'` • `'cycles/nanosecond'` • `'cycles/microsecond'` • `'cycles/millisecond'` • `'cycles/hour'` • `'cycles/day'` • `'cycles/week'` • `'cycles/month'` • `'cycles/year'` **Default**: `'rad/s'` You can also specify `'auto'` which uses frequency units `rad/TimeUnit` relative to system time units specified in the `TimeUnit` property. For

Option	Description
	multiple systems with different time units, the units of the first system are used.
MagUnits	Magnitude units Specified as one of the following strings: `'dB'` | `'abs'` **Default**: `'dB'`
PhaseUnits	Phase units Specified as one of the following strings: `'deg'` | `'rad'` **Default**: `'deg'`
ShowFullContour	Show response for negative frequencies Specified as one of the following strings: `'on'` | `'off'` **Default**: `'on'`
ConfidenceRegionNumbe	Number of standard deviations to use to plotting the response confidence region (identified models only). **Default**: `1`.
ConfidenceRegionDisplay	The frequency spacing of confidence ellipses. For identified models only. **Default**: `5`, which means the confidence ellipses are shown at every 5th frequency sample.

Examples

This example shows how to create a Nyquist plot displaying the full contour (the response for both positive and negative frequencies).

```
P = nyquistoptions;
P.ShowFullContour = 'on';
h = nyquistplot(tf(1,[1,.2,1]),P);
```

See Also

`nyquist` | `nyquistplot` | `getoptions` | `setoptions`

nyquistplot

Nyquist plot with additional plot customization options

Syntax

```
h = nyquistplot(sys)
nyquistplot(sys,{wmin,wmax})
nyquistplot(sys,w)
nyquistplot(sys1,sys2,...,w)
nyquistplot(AX,...)
nyquistplot(..., plotoptions)
```

Description

`h = nyquistplot(sys)` draws the Nyquist plot of the dynamic system model `sys`. It also returns the plot handle `h`. You can use this handle to customize the plot with the `getoptions` and `setoptions` commands. Type

```
help nyquistoptions
```

for a list of available plot options.

The frequency range and number of points are chosen automatically. See `bode` for details on the notion of frequency in discrete time.

`nyquistplot(sys,{wmin,wmax})` draws the Nyquist plot for frequencies between `wmin` and `wmax` (in `rad/TimeUnit`, where `TimeUnit` is the time units of the input dynamic system, specified in the TimeUnit property of sys).

`nyquistplot(sys,w)` uses the user-supplied vector `w` of frequencies (in `rad/TimeUnit`, where `TimeUnit` is the time units of the input dynamic system, specified in the TimeUnit property of sys) at which the Nyquist response is to be evaluated. See `logspace` to generate logarithmically spaced frequency vectors.

`nyquistplot(sys1,sys2,...,w)` draws the Nyquist plots of multiple models `sys1`,`sys2`,... on a single plot. The frequency vector `w` is optional. You can also specify a color, line style, and marker for each system, as in

```
nyquistplot(sys1,'r',sys2,'y--',sys3,'gx')
```

`nyquistplot(AX,...)` plots into the axes with handle `AX`.

`nyquistplot(..., plotoptions)` plots the Nyquist response with the options specified in `plotoptions`. Type

```
help nyquistoptions
```

for more details.

Examples

Example 1

Customize Nyquist Plot Frequency Units

Plot the Nyquist frequency response and change the units to rad/s.

```
sys = rss(5);
h = nyquistplot(sys);
% Change units to radians per second.
setoptions(h,'FreqUnits','rad/s');
```

Example 2

Compare the frequency responses of identified state-space models of order 2 and 6 along with their `1-std` confidence regions rendered at every 50th frequency sample.

```
load iddata1
sys1 = n4sid(z1, 2) % discrete-time IDSS model of order 2
sys2 = n4sid(z1, 6) % discrete-time IDSS model of order 6
```

Both models produce about 76% fit to data. However, `sys2` shows higher uncertainty in its frequency response, especially close to `Nyquist` frequency as shown by the plot:

```
w = linspace(10,10*pi,256);
h = nyquistplot(sys1,sys2,w);
setoptions(h,'ConfidenceRegionDisplaySpacing',50,'ShowFullContour','off');
```

Right-click to turn on the confidence region characteristic by using the **Characteristics-> Confidence Region**.

More About

Tips

You can change the properties of your plot, for example the units. For information on the ways to change properties of your plots, see “Ways to Customize Plots”.

See Also

`nyquist` | `setoptions` | `getoptions`

obsv

Observability matrix

Syntax

```
obsv(A,C)
Ob = obsv(sys)
```

Description

`obsv` computes the observability matrix for state-space systems. For an n-by-n matrix `A` and a p-by-n matrix `C`, `obsv(A,C)` returns the observability matrix

$$Ob = \begin{bmatrix} C \\ CA \\ CA^2 \\ \vdots \\ CA^{n-1} \end{bmatrix}$$

with n columns and np rows.

`Ob = obsv(sys)` calculates the observability matrix of the state-space model `sys`. This syntax is equivalent to executing

```
Ob = obsv(sys.A,sys.C)
```

The model is observable if `Ob` has full rank n.

Examples

Determine if the pair

```
A =
       1         1
```

```
     4    -2

C =
     1     0
     0     1
```

is observable. Type

```
Ob = obsv(A,C);

% Number of unobservable states
unob = length(A)-rank(Ob)
```

These commands produce the following result.

```
unob =
     0
```

More About

Tips

`obsv` is here for educational purposes and is not recommended for serious control design. Computing the rank of the observability matrix is not recommended for observability testing. `Ob` will be numerically singular for most systems with more than a handful of states. This fact is well documented in the control literature. For example, see section III in http://lawww.epfl.ch/webdav/site/la/users/105941/public/NumCompCtrl.pdf

See Also

`obsvf`

obsvf

Compute observability staircase form

Syntax

```
[Abar,Bbar,Cbar,T,k] = obsvf(A,B,C)
obsvf(A,B,C,tol)
```

Description

If the observability matrix of `(A,C)` has rank $r \le n$, where n is the size of `A`, then there exists a similarity transformation such that

$$\bar{A} = TAT^T, \quad \bar{B} = TB, \quad \bar{C} = CT^T$$

where T is unitary and the transformed system has a *staircase* form with the unobservable modes, if any, in the upper left corner.

$$\bar{A} = \begin{bmatrix} A_{no} & A_{12} \\ 0 & A_o \end{bmatrix}, \ \bar{B} = \begin{bmatrix} B_{no} \\ B_o \end{bmatrix}, \ \bar{C} = [0 \ C_o]$$

where (C_o, A_o) is observable, and the eigenvalues of A_{no} are the unobservable modes.

`[Abar,Bbar,Cbar,T,k] = obsvf(A,B,C)` decomposes the state-space system with matrices `A`, `B`, and `C` into the observability staircase form `Abar`, `Bbar`, and `Cbar`, as described above. `T` is the similarity transformation matrix and `k` is a vector of length n, where n is the number of states in `A`. Each entry of `k` represents the number of observable states factored out during each step of the transformation matrix calculation [1]. The number of nonzero elements in `k` indicates how many iterations were necessary to calculate `T`, and `sum(k)` is the number of states in A_o, the observable portion of `Abar`.

`obsvf(A,B,C,tol)` uses the tolerance `tol` when calculating the observable/unobservable subspaces. When the tolerance is not specified, it defaults to `10*n*norm(a,1)*eps`.

Examples

Form the observability staircase form of

```
A =
     1     1
     4    -2

B =
     1    -1
     1    -1

C =
     1     0
     0     1
```

by typing

```
[Abar,Bbar,Cbar,T,k] = obsvf(A,B,C)
Abar =
     1     1
     4    -2
Bbar =
     1     1
     1    -1
Cbar =
     1     0
     0     1
T =
     1     0
     0     1
k =
     2     0
```

More About

Algorithms

`obsvf` implements the Staircase Algorithm of [1] by calling `ctrbf` and using duality.

References

[1] Rosenbrock, M.M., *State-Space and Multivariable Theory*, John Wiley, 1970.

See Also

`ctrbf` | `obsv`

ord2

Generate continuous second-order systems

Syntax

```
[A,B,C,D] = ord2(wn,z)
[num,den] = ord2(wn,z)
```

Description

`[A,B,C,D] = ord2(wn,z)` generates the state-space description `(A,B,C,D)` of the second-order system

$$h(s) = \frac{1}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

given the natural frequency `wn` (ω_n) and damping factor z (ζ). Use `ss` to turn this description into a state-space object.

`[num,den] = ord2(wn,z)` returns the numerator and denominator of the second-order transfer function. Use `tf` to form the corresponding transfer function object.

Examples

To generate an LTI model of the second-order transfer function with damping factor ζ = 0.4 and natural frequency ω_n = 2.4 rad/sec., type

```
[num,den] = ord2(2.4,0.4)
num =
     1
den =
    1.0000    1.9200    5.7600
sys = tf(num,den)
Transfer function:
         1
```

```
-------------------
s^2 + 1.92 s + 5.76
```

See Also

rss | ss | tf

order

Query model order

Syntax

```
NS = order(sys)
```

Description

`NS = order(sys)` returns the model order `NS`. The order of a dynamic system model is the number of poles (for proper transfer functions) or the number of states (for state-space models). For improper transfer functions, the order is defined as the minimum number of states needed to build an equivalent state-space model (ignoring pole/zero cancellations).

`order(sys)` is an overloaded method that accepts SS, TF, and ZPK models. For LTI arrays, `NS` is an array of the same size listing the orders of each model in `sys`.

Caveat

`order` does not attempt to find minimal realizations of MIMO systems. For example, consider this 2-by-2 MIMO system:

```
s=tf('s');
h = [1, 1/(s*(s+1)); 1/(s+2), 1/(s*(s+1)*(s+2))];
order(h)
ans =

     6
```

Although `h` has a 3rd order realization, `order` returns 6. Use

```
order(ss(h,'min'))
```

to find the minimal realization order.

See Also

pole | balred

pade

Padé approximation of model with time delays

Syntax

```
[num,den] = pade(T,N)
pade(T,N)
sysx = pade(sys,N)
sysx = pade(sys,NU,NY,NINT)
```

Description

`pade` approximates time delays by rational models. Such approximations are useful to model time delay effects such as transport and computation delays within the context of continuous-time systems. The Laplace transform of a time delay of T seconds is exp($-sT$). This exponential transfer function is approximated by a rational transfer function using Padé approximation formulas [1].

`[num,den] = pade(T,N)` returns the Padé approximation of order `N` of the continuous-time I/O delay exp($-sT$) in transfer function form. The row vectors `num` and `den` contain the numerator and denominator coefficients in descending powers of s. Both are `N`th-order polynomials.

When invoked without output arguments, `pade(T,N)` plots the step and phase responses of the `N`th-order Padé approximation and compares them with the exact responses of the model with I/O delay `T`. Note that the Padé approximation has unit gain at all frequencies.

`sysx = pade(sys,N)` produces a delay-free approximation `sysx` of the continuous delay system `sys`. All delays are replaced by their `N`th-order Padé approximation. See "Models with Time Delays" for more information about models with time delays.

`sysx = pade(sys,NU,NY,NINT)` specifies independent approximation orders for each input, output, and I/O or internal delay. Here `NU`, `NY`, and `NINT` are integer arrays such that

- `NU` is the vector of approximation orders for the input channel
- `NY` is the vector of approximation orders for the output channel
- `NINT` is the approximation order for I/O delays (TF or ZPK models) or internal delays (state-space models)

You can use scalar values for `NU`, `NY`, or `NINT` to specify a uniform approximation order. You can also set some entries of `NU`, `NY`, or `NINT` to `Inf` to prevent approximation of the corresponding delays.

Examples

Third-Order Padé Approximation

Compute a third-order Padé approximation of a 0.1-second I/O delay.

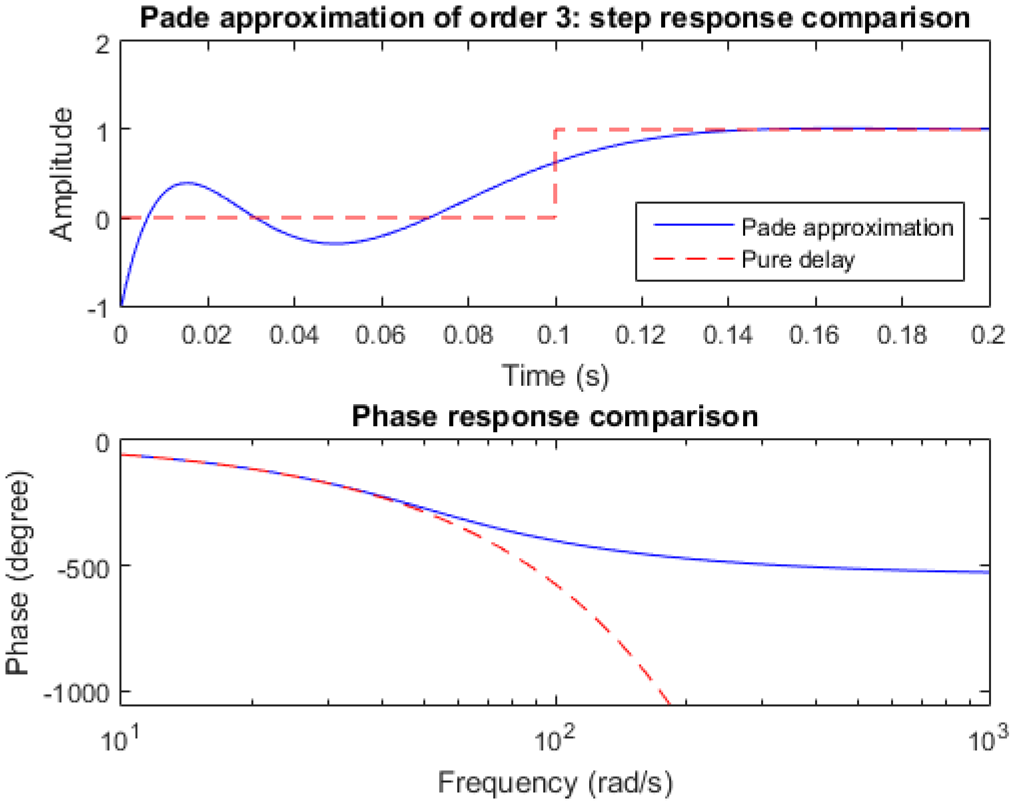
```
s = tf('s');
sys = exp(-0.1*s);
sysx = pade(sys,3)
```

```
sysx =

  -s^3 + 120 s^2 - 6000 s + 1.2e05
  --------------------------------
  s^3 + 120 s^2 + 6000 s + 1.2e05

Continuous-time transfer function.
```

Here, `sys` is a dynamic system representation of the exact time delay of 0.1 s. `sysx` is a transfer function that approximates that delay.

Compare the time and frequency responses of the true delay and its approximation. Calling the `pade` command without output arguments generates the comparison plots. In this case the first argument to `pade` is just the magnitude of the exact time delay, rather than a dynamic system representing the time delay.

```
pade(0.1,3)
```



Limitations

High-order Padé approximations produce transfer functions with clustered poles. Because such pole configurations tend to be very sensitive to perturbations, Padé approximations with order `N>10` should be avoided.

More About

- "Time-Delay Approximation"

References

[1] Golub, G. H. and C. F. Van Loan, *Matrix Computations*, Johns Hopkins University Press, Baltimore, 1989, pp. 557-558.

See Also

`c2d` | `absorbDelay` | `thiran`

parallel

Parallel connection of two models

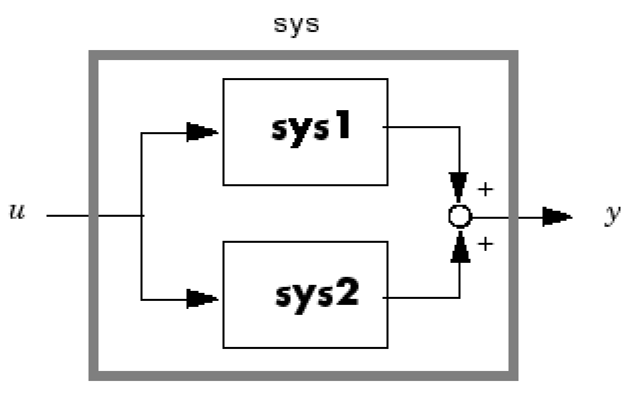
Syntax

```
parallel
sys = parallel(sys1,sys2)
sys = parallel(sys1,sys2,inp1,inp2,out1,out2)
sys = parallel(sys1,sys2,'name')
```

Description

`parallel` connects two model objects in parallel. This function accepts any type of model. The two systems must be either both continuous or both discrete with identical sample time. Static gains are neutral and can be specified as regular matrices.

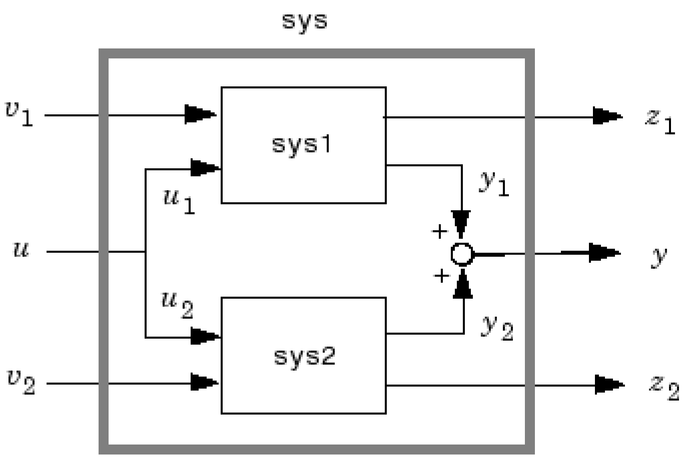
`sys = parallel(sys1,sys2)` forms the basic parallel connection shown in the following figure.



This command equals the direct addition

```
sys = sys1 + sys2
```

`sys = parallel(sys1,sys2,inp1,inp2,out1,out2)` forms the more general parallel connection shown in the following figure.



The vectors `inp1` and `inp2` contain indexes into the input channels of `sys1` and `sys2`, respectively, and define the input channels u_1 and u_2 in the diagram. Similarly, the vectors `out1` and `out2` contain indexes into the outputs of these two systems and define the output channels y_1 and y_2 in the diagram. The resulting model `sys` has $[v_1 ; u ; v_2]$ as inputs and $[z_1 ; y ; z_2]$ as outputs.

`sys = parallel(sys1,sys2,'name')` connects `sys1` and `sys2` by matching I/O names. You must specify all I/O names of `sys1` and `sys2`. The matching names appear in `sys` in the same order as in `sys1`. For example, the following specification:

```
sys1 = ss(eye(3),'InputName',{'C','B','A'},'OutputName',{'Z','Y','X'});
sys2 = ss(eye(3),'InputName',{'A','C','B'},'OutputName',{'X','Y','Z'});
parallel(sys1,sys2,'name')
```

returns this result:

```
d =
       C  B  A
    Z  1  1  0
    Y  1  1  0
    X  0  0  2

Static gain.
```

Note: If `sys1` and `sys2` are model arrays, parallel returns model array `sys` of the same size, where `sys(:,:,k)=parallel(sys1(:,:,k),sys2(:,:,k),inp1,...)`.

Examples

See Kalman Filtering for an example.

See Also

`append` | `feedback` | `series`

permute

Permute array dimensions in model arrays

Syntax

```
newarray = permute(sysarray,order)
```

Description

`newarray = permute(sysarray,order)` rearranges the array dimensions of a model array so that the dimensions are in the specified order. The input and output dimensions of the model array are not counted as array dimensions for this operation.

Examples

Permute Model Array Dimensions

Create a 1-by-2-by-3 array of state-space models and rearrange it so that its dimensions are 3-by-2-by-1.

```
sysarr = rss(2,2,2,1,2,3);
newarr = permute(sysarr,[3 2 1]);
size(newarr)
```

```
3x2 array of state-space models.
Each model has 2 outputs, 2 inputs, and 2 states.
```

The input and output dimensions of the model array remain unchanged.

Input Arguments

`sysarray` — Model array to rearrange

model array

Model array to rearrange, specified as an array of input-output models such as numeric LTI models, generalized models, or identified LTI models.

`order` — Dimensions of rearranged model array

vector

Dimensions of rearranged model array, specified as a vector of positive integers. For example, to rearrange a model array into a 3-by-2 array, order is `[3 2]`.

Data Types: `double`

Output Arguments

`newarray` — Rearranged model array

model array

Rearranged model array, returned as an array of input-output models with the new dimensions as specified in order.

See Also

`ndims` | `reshape` | `size`

pid

Create PID controller in parallel form, convert to parallel-form PID controller

Syntax

```
C = pid(Kp,Ki,Kd,Tf)
C = pid(Kp,Ki,Kd,Tf,Ts)
C = pid(sys)
C = pid(Kp)
C = pid(Kp,Ki)
C = pid(Kp,Ki,Kd)
C = pid(...,Name,Value)
C = pid
```

Description

`C = pid(Kp,Ki,Kd,Tf)` creates a continuous-time PID controller with proportional, integral, and derivative gains Kp, Ki, and Kd and first-order derivative filter time constant Tf:

$$C = K_p + \frac{K_i}{s} + \frac{K_d s}{T_f s + 1}.$$

This representation is in *parallel form*. If all of Kp, Ki, Kd, and Tf are real, then the resulting `C` is a `pid` controller object. If one or more of these coefficients is tunable (`realp` or `genmat`), then `C` is a tunable generalized state-space (`genss`) model object.

`C = pid(Kp,Ki,Kd,Tf,Ts)` creates a discrete-time PID controller with sample time Ts. The controller is:

$$C = K_p + K_i IF(z) + \frac{K_d}{T_f + DF(z)}.$$

IF(*z*) and *DF*(*z*) are the *discrete integrator formulas* for the integrator and derivative filter. By default, $IF(z) = DF(z) = T_s z/(z-1)$. To choose different discrete integrator formulas, use the `IFormula` and `DFormula` properties. (See "Properties" on page 1-534 for more information about `IFormula` and `DFormula`). If `DFormula` = `'ForwardEuler'` (the default value) and Tf ≠ 0, then Ts and Tf must satisfy `Tf > Ts/2`. This requirement ensures a stable derivative filter pole.

`C = pid(sys)` converts the dynamic system sys to a parallel form `pid` controller object.

`C = pid(Kp)` creates a continuous-time proportional (P) controller with Ki = 0, Kd = 0, and Tf = 0.

`C = pid(Kp,Ki)` creates a proportional and integral (PI) controller with Kd = 0 and Tf = 0.

`C = pid(Kp,Ki,Kd)` creates a proportional, integral, and derivative (PID) controller with Tf = 0.

`C = pid(...,Name,Value)` creates a controller or converts a dynamic system to a `pid` controller object with additional options specified by one or more Name,Value pair arguments.

`C = pid` creates a P controller with Kp = 1.

Input Arguments

Kp

Proportional gain.

Kp can be:

- A real and finite value.
- An array of real and finite values.
- A tunable parameter (`realp`).
- A tunable generalized matrix (`genmat`), such as a gain surface for gain-scheduled tuning, created using `gainsurf` (requires Robust Control Toolbox software).

When Kp = 0, the controller has no proportional action.

Default: 1

`Ki`

Integral gain.

Ki can be:

- A real and finite value.
- An array of real and finite values.
- A tunable parameter (`realp`).
- A tunable generalized matrix (`genmat`), such as a gain surface for gain-scheduled tuning, created using `gainsurf` (requires Robust Control Toolbox software).

When Ki = 0, the controller has no integral action.

Default: 0

`Kd`

Derivative gain.

Kd can be:

- A real and finite value.
- An array of real and finite values.
- A tunable parameter (`realp`).
- A tunable generalized matrix (`genmat`), such as a gain surface for gain-scheduled tuning, created using `gainsurf` (requires Robust Control Toolbox software).

When Kd = 0, the controller has no derivative action.

Default: 0

`Tf`

Time constant of the first-order derivative filter.

Tf can be:

- A real, finite, and nonnegative value.

- An array of real, finite, and nonnegative values.
- A tunable parameter (`realp`).
- A tunable generalized matrix (`genmat`), such as a gain surface for gain-scheduled tuning, created using `gainsurf` (requires Robust Control Toolbox software).

When Tf = 0, the controller has no filter on the derivative action.

Default: 0

`Ts`

Sample time.

To create a discrete-time `pid` controller, provide a positive real value (`Ts > 0`). `pid` does not support discrete-time controller with undetermined sample time (`Ts = -1`).

Ts must be a scalar value. In an array of `pid` controllers, each controller must have the same Ts.

`sys`

SISO dynamic system to convert to parallel `pid` form.

sys must represent a valid PID controller that can be written in parallel form with `Tf` ≥ 0.

sys can also be an array of SISO dynamic systems.

Name-Value Pair Arguments

Specify optional comma-separated pairs of Name,Value arguments. `Name` is the argument name and `Value` is the corresponding value. `Name` must appear inside single quotes (`' '`). You can specify several name and value pair arguments in any order as `Name1,Value1,...,NameN,ValueN`.

Use Name,Value syntax to set the numerical integration formulas `IFormula` and `DFormula` of a discrete-time `pid` controller, or to set other object properties such as `InputName` and `OutputName`. For information about available properties of `pid` controller objects, see “Properties” on page 1-534.

Output Arguments

C

PID controller, represented as a `pid` controller object, an array of `pid` controller objects, a `genss` object, or a `genss` array.

- If all the gains Kp, Ki, Kd, and Tf have numeric values, then C is a `pid` controller object. When the gains are numeric arrays, C is an array of `pid` controller objects. The controller type (P, I, PI, PD, PDF, PID, PIDF) depends upon the values of the gains. For example, when Kd = 0, but Kp and Ki are nonzero, C is a PI controller.
- If one or more gains is a tunable parameter (`realp`) or generalized matrix (`genmat`), then C is a generalized state-space model (`genss`).

Properties

Kp, Ki, Kd

PID controller gains.

The `Kp`, `Ki`, and `Kd` properties store the proportional, integral, and derivative gains, respectively. `Kp`, `Ki`, and `Kd` values are real and finite.

Tf

Derivative filter time constant.

The `Tf` property stores the derivative filter time constant of the `pid` controller object. `Tf` are real, finite, and greater than or equal to zero.

IFormula

Discrete integrator formula $IF(z)$ for the integrator of the discrete-time `pid` controller C:

$$C = K_p + K_i IF(z) + \frac{K_d}{T_f + DF(z)}.$$

`IFormula` can take the following values:

- `'ForwardEuler'` — $IF(z) = \dfrac{T_s}{z-1}$.

  This formula is best for small sample time, where the Nyquist limit is large compared to the bandwidth of the controller. For larger sample time, the `ForwardEuler` formula can result in instability, even when discretizing a system that is stable in continuous time.

- `'BackwardEuler'` — $IF(z) = \dfrac{T_s z}{z-1}$.

  An advantage of the `BackwardEuler` formula is that discretizing a stable continuous-time system using this formula always yields a stable discrete-time result.

- `'Trapezoidal'` — $IF(z) = \dfrac{T_s}{2}\dfrac{z+1}{z-1}$.

  An advantage of the `Trapezoidal` formula is that discretizing a stable continuous-time system using this formula always yields a stable discrete-time result. Of all available integration formulas, the `Trapezoidal` formula yields the closest match between frequency-domain properties of the discretized system and the corresponding continuous-time system.

When C is a continuous-time controller, `IFormula` is `''`.

Default: `'ForwardEuler'`

`DFormula`

Discrete integrator formula $DF(z)$ for the derivative filter of the discrete-time `pid` controller C:

$$C = K_p + K_i IF(z) + \frac{K_d}{T_f + DF(z)}.$$

`DFormula` can take the following values:

- `'ForwardEuler'` — $DF(z) = \dfrac{T_s}{z-1}$.

This formula is best for small sample time, where the Nyquist limit is large compared to the bandwidth of the controller. For larger sample time, the `ForwardEuler` formula can result in instability, even when discretizing a system that is stable in continuous time.

- `'BackwardEuler'` — $DF(z) = \frac{T_s z}{z-1}$.

  An advantage of the `BackwardEuler` formula is that discretizing a stable continuous-time system using this formula always yields a stable discrete-time result.

- `'Trapezoidal'` — $DF(z) = \frac{T_s}{2}\frac{z+1}{z-1}$.

  An advantage of the `Trapezoidal` formula is that discretizing a stable continuous-time system using this formula always yields a stable discrete-time result. Of all available integration formulas, the `Trapezoidal` formula yields the closest match between frequency-domain properties of the discretized system and the corresponding continuous-time system.

  The `Trapezoidal` value for `DFormula` is not available for a `pid` controller with no derivative filter (`Tf = 0`).

When C is a continuous-time controller, `DFormula` is `''`.

Default: `'ForwardEuler'`

`InputDelay`

Time delay on the system input. `InputDelay` is always 0 for a `pid` controller object.

`OutputDelay`

Time delay on the system Output. `OutputDelay` is always 0 for a `pid` controller object.

`Ts`

Sample time. For continuous-time models, `Ts = 0`. For discrete-time models, `Ts` is a positive scalar representing the sampling period. This value is expressed in the unit specified by the `TimeUnit` property of the model. To denote a discrete-time model with unspecified sample time, set `Ts = -1`.

Changing this property does not discretize or resample the model. Use `c2d` and `d2c` to convert between continuous- and discrete-time representations. Use `d2d` to change the sample time of a discrete-time system.

Default: `0` (continuous time)

`TimeUnit`

String representing the unit of the time variable. This property specifies the units for the time variable, the sample time `Ts`, and any time delays in the model. Use any of the following values:

- `'nanoseconds'`
- `'microseconds'`
- `'milliseconds'`
- `'seconds'`
- `'minutes'`
- `'hours'`
- `'days'`
- `'weeks'`
- `'months'`
- `'years'`

Changing this property has no effect on other properties, and therefore changes the overall system behavior. Use `chgTimeUnit` to convert between time units without modifying system behavior.

Default: `'seconds'`

`InputName`

Input channel names. Set `InputName` to a string for single-input model. For a multi-input model, set `InputName` to a cell array of strings.

Alternatively, use automatic vector expansion to assign input names for multi-input models. For example, if `sys` is a two-input model, enter:

```
sys.InputName = 'controls';
```

The input names automatically expand to `{'controls(1)';'controls(2)'}`.

You can use the shorthand notation `u` to refer to the `InputName` property. For example, `sys.u` is equivalent to `sys.InputName`.

Input channel names have several uses, including:

- Identifying channels on model display and plots
- Extracting subsystems of MIMO systems
- Specifying connection points when interconnecting models

Default: Empty string `''` for all input channels

InputUnit

Input channel units. Use `InputUnit` to keep track of input signal units. For a single-input model, set `InputUnit` to a string. For a multi-input model, set `InputUnit` to a cell array of strings. `InputUnit` has no effect on system behavior.

Default: Empty string `''` for all input channels

InputGroup

Input channel groups. The `InputGroup` property lets you assign the input channels of MIMO systems into groups and refer to each group by name. Specify input groups as a structure. In this structure, field names are the group names, and field values are the input channels belonging to each group. For example:

```
sys.InputGroup.controls = [1 2];
sys.InputGroup.noise = [3 5];
```

creates input groups named `controls` and `noise` that include input channels 1, 2 and 3, 5, respectively. You can then extract the subsystem from the `controls` inputs to all outputs using:

```
sys(:,'controls')
```

Default: Struct with no fields

OutputName

Output channel names. Set `OutputName` to a string for single-output model. For a multi-output model, set `OutputName` to a cell array of strings.

Alternatively, use automatic vector expansion to assign output names for multi-output models. For example, if `sys` is a two-output model, enter:

```
sys.OutputName = 'measurements';
```

The output names automatically expand to `{'measurements(1)';'measurements(2)'}`.

You can use the shorthand notation `y` to refer to the `OutputName` property. For example, `sys.y` is equivalent to `sys.OutputName`.

Output channel names have several uses, including:

- Identifying channels on model display and plots
- Extracting subsystems of MIMO systems
- Specifying connection points when interconnecting models

Default: Empty string `''` for all output channels

OutputUnit

Output channel units. Use `OutputUnit` to keep track of output signal units. For a single-output model, set `OutputUnit` to a string. For a multi-output model, set `OutputUnit` to a cell array of strings. `OutputUnit` has no effect on system behavior.

Default: Empty string `''` for all output channels

OutputGroup

Output channel groups. The `OutputGroup` property lets you assign the output channels of MIMO systems into groups and refer to each group by name. Specify output groups as a structure. In this structure, field names are the group names, and field values are the output channels belonging to each group. For example:

```
sys.OutputGroup.temperature = [1];
sys.InputGroup.measurement = [3 5];
```

creates output groups named `temperature` and `measurement` that include output channels 1, and 3, 5, respectively. You can then extract the subsystem from all inputs to the `measurement` outputs using:

```
sys('measurement',:)
```

Default: Struct with no fields

Name

System name. Set `Name` to a string to label the system.

Default: `''`

Notes

Any text that you want to associate with the system. Set `Notes` to a string or a cell array of strings.

Default: `{}`

UserData

Any type of data you wish to associate with system. Set `UserData` to any MATLAB data type.

Default: `[]`

SamplingGrid

Sampling grid for model arrays, specified as a data structure.

For model arrays that are derived by sampling one or more independent variables, this property tracks the variable values associated with each model in the array. This information appears when you display or plot the model array. Use this information to trace results back to the independent variables.

Set the field names of the data structure to the names of the sampling variables. Set the field values to the sampled variable values associated with each model in the array. All sampling variables should be numeric and scalar valued, and all arrays of sampled values should match the dimensions of the model array.

For example, suppose you create a 11-by-1 array of linear models, `sysarr`, by taking snapshots of a linear time-varying system at times `t = 0:10`. The following code stores the time samples with the linear models.

```
 sysarr.SamplingGrid = struct('time',0:10)
```

Similarly, suppose you create a 6-by-9 model array, `M`, by independently sampling two variables, `zeta` and `w`. The following code attaches the `(zeta,w)` values to `M`.

```
[zeta,w] = ndgrid(<6 values of zeta>,<9 values of w>)
M.SamplingGrid = struct('zeta',zeta,'w',w)
```

When you display M, each entry in the array includes the corresponding zeta and w values.

```
M
```

```
M(:,:,1,1) [zeta=0.3, w=5] =

        25
  --------------
  s^2 + 3 s + 25


M(:,:,2,1) [zeta=0.35, w=5] =

         25
  ----------------
  s^2 + 3.5 s + 25

...
```

For model arrays generated by linearizing a Simulink model at multiple parameter values or operating points, the software populates SamplingGrid automatically with the variable values that correspond to each entry in the array. For example, the Simulink Control Design commands linearize and slLinearizer populate SamplingGrid in this way.

Default: []

Examples

PID Controller with Proportional and Derivative Gains, and Filter Time Constant (PDF Controller)

Create a continuous-time controller with proportional and derivative gains, and filter time constant (PDF controller).

```
Kp=1;
Ki=0;
Kd=3;
Tf=0.5;
C = pid(Kp,Ki,Kd,Tf)
```

```
C =

                s
  Kp + Kd * --------
             Tf*s+1

  with Kp = 1, Kd = 3, Tf = 0.5

Continuous-time PDF controller in parallel form.
```

The display shows the controller type, formula, and parameter values.

Discrete-Time PI Controller

Create a discrete-time PI controller with trapezoidal discretization formula.

To create a discrete-time controller, set the value of `Ts` using Name,Value syntax.

```
C = pid(5,2.4,'Ts',0.1,'IFormula','Trapezoidal') % Ts = 0.1s
```

This command produces the result:

```
Discrete-time PI controller in parallel form:

          Ts*(z+1)
Kp + Ki * --------
          2*(z-1)

with Kp = 5, Ki = 2.4, Ts = 0.1
```

Alternatively, you can create the same discrete-time controller by supplying `Ts` as the fifth argument after all four PID parameters `Kp`, `Ki`, `Kd`, and `Tf`.

```
C = pid(5,2.4,0,0,0.1,'IFormula','Trapezoidal');
```

PID Controller with Custom Input and Output Names

Create a PID controller, and set dynamic system properties `InputName` and `OutputName`.

```
C = pid(1,2,3,'InputName','e','OutputName','u');
```

Array of PID Controllers

Create a 2-by-3 grid of PI controllers with proportional gain ranging from 1–2 and integral gain ranging from 5–9.

Create a grid of PI controllers with proportional gain varying row to row and integral gain varying column to column. To do so, start with arrays representing the gains.

```
Kp = [1 1 1;2 2 2];
Ki = [5:2:9;5:2:9];
pi_array = pid(Kp,Ki,'Ts',0.1,'IFormula','BackwardEuler');
```

These commands produce a 2-by-3 array of discrete-time `pid` objects. All `pid` objects in an array must have the same sample time, discrete integrator formulas, and dynamic system properties (such as `InputName` and `OutputName`).

Alternatively, you can use `stack` to build arrays of `pid` objects.

```
C = pid(1,5,0.1)           % PID controller
Cf = pid(1,5,0.1,0.5)      % PID controller with filter
pid_array = stack(2,C,Cf); % stack along 2nd array dimension
```

These commands produce a 1-by-2 array of controllers. Enter the command:

```
size(pid_array)
```

to see the result

```
1x2 array of PID controller.
Each PID has 1 output and 1 input.
```

Convert PID Controller from Standard to Parallel Form

Convert a standard form `pidstd` controller to parallel form.

Standard PID form expresses the controller actions in terms of an overall proportional gain K_p, integral and derivative times T_i and T_d, and filter divisor N. You can convert any standard form controller to parallel form using `pid`.

```
stdsys = pidstd(2,3,4,5);  % Standard-form controller
parsys = pid(stdsys)
```

These commands produce a parallel-form controller:

```
Continuous-time PIDF controller in parallel form:

           1            s
Kp + Ki * --- + Kd * --------
           s          Tf*s+1
```

```
with Kp = 2, Ki = 0.66667, Kd = 8, Tf = 0.8
```

Convert Dynamic System to Parallel-Form PID Controller

Convert a continuous-time dynamic system that represents a PID controller to parallel `pid` form.

The dynamic system

$$H(s) = \frac{3(s+1)(s+2)}{s}$$

represents a PID controller. Use `pid` to obtain $H(s)$ to in terms of the PID gains K_p, K_i, and K_d.

```
H = zpk([-1,-2],0,3);
C = pid(H)
```

These commands produce the result:

```
Continuous-time PID controller in parallel form:

             1
Kp + Ki * --- + Kd * s
             s

with Kp = 9, Ki = 6, Kd = 3
```

Convert Discrete-Time Zero-Pole-Gain Model to Parallel-Form PID Controller

Convert a discrete-time dynamic system that represents a PID controller with derivative filter to parallel `pid` form.

```
% PIDF controller expressed in zpk form
sys = zpk([-0.5,-0.6],[1 -0.2],3,'Ts',0.1)
```

The resulting `pid` object depends upon the discrete integrator formula you specify for `IFormula` and `DFormula`. For example, if you use the default `ForwardEuler` for both formulas:

```
C = pid(sys)
```

returns the result

```
Discrete-time PIDF controller in parallel form:

            Ts               1
Kp + Ki * ------ + Kd * -----------
           z-1         Tf+Ts/(z-1)

with Kp = 2.75, Ki = 60, Kd = 0.020833, Tf = 0.083333, Ts = 0.1
```

Converting using the `Trapezoidal` formula returns different parameter values:

```
C = pid(sys,'IFormula','Trapezoidal','DFormula','Trapezoidal')
```

This command returns the result:

```
Discrete-time PIDF controller in parallel form:

          Ts*(z+1)                  1
Kp + Ki * -------- + Kd * -------------------
          2*(z-1)         Tf+Ts/2*(z+1)/(z-1)

with Kp = -0.25, Ki = 60, Kd = 0.020833, Tf = 0.033333, Ts = 0.1
```

For this particular `sys`, you cannot write `sys` in parallel PID form using the `BackwardEuler` formula for `DFormula`. Doing so would result in `Tf` < 0, which is not permitted. In that case, `pid` returns an error.

Discretize a Continuous-time PID Controller

First, discretize the controller using the `'zoh'` method of `c2d`.

```
Cc = pid(1,2,3,4)  % continuous-time pidf controller
Cd1 = c2d(Cc,0.1,'zoh')
```

`c2d` computes new parameters for the discrete-time controller:

```
Discrete-time PIDF controller in parallel form:

            Ts               1
Kp + Ki * ------ + Kd * -----------
           z-1         Tf+Ts/(z-1)

with Kp = 1, Ki = 2, Kd = 3.0377, Tf = 4.0502, Ts = 0.1
```

The resulting discrete-time controller uses `ForwardEuler` ($T_s/(z-1)$) for both `IFormula` and `DFormula`.

The discrete integrator formulas of the discretized controller depend upon the `c2d` discretization method, as described in "Tips" on page 1-546. To use a different `IFormula` and `DFormula`, directly set `Ts`, `IFormula`, and `DFormula` to the desired values:

```
Cd2 = Cc;
Cd2.Ts = 0.1;
Cd2.IFormula = 'BackwardEuler';
Cd2.DFormula = 'BackwardEuler';
```

These commands do not compute new parameter values for the discretized controller. To see this, enter:

```
Cd2
```

to obtain the result:

```
Discrete-time PIDF controller in parallel form:

           Ts*z                1
Kp + Ki * ------ + Kd * -------------
            z-1         Tf+Ts*z/(z-1)

with Kp = 1, Ki = 2, Kd = 3, Tf = 4, Ts = 0.1
```

More About

Tips

- Use `pid` either to create a `pid` controller object from known PID gains and filter time constant, or to convert a dynamic system model to a `pid` object.
- To deisgn a PID controller for a particular plant, use `pidtune` or `pidTuner`.
- Create arrays of `pid` controller objects by:
  - Specifying array values for Kp,Ki,Kd, and Tf
  - Specifying an array of dynamic systems sys to convert to `pid` controller objects
  - Using `stack` to build arrays from individual controllers or smaller arrays

  In an array of `pid` controllers, each controller must have the same sample time Ts and discrete integrator formulas `IFormula` and `DFormula`.

- To create or convert to a standard-form controller, use `pidstd`. Standard form expresses the controller actions in terms of an overall proportional gain K_p, integral and derivative times T_i and T_d, and filter divisor N:

$$C = K_p \left(1 + \frac{1}{T_i}\frac{1}{s} + \frac{T_d s}{\frac{T_d}{N}s + 1} \right).$$

- There are two ways to discretize a continuous-time `pid` controller:
  - Use the `c2d` command. `c2d` computes new parameter values for the discretized controller. The discrete integrator formulas of the discretized controller depend upon the `c2d` discretization method you use, as shown in the following table.

c2d Discretization Method	IFormula	DFormula
'zoh'	ForwardEuler	ForwardEuler
'foh'	Trapezoidal	Trapezoidal
'tustin'	Trapezoidal	Trapezoidal
'impulse'	ForwardEuler	ForwardEuler
'matched'	ForwardEuler	ForwardEuler

    For more information about `c2d` discretization methods, See the `c2d` reference page. For more information about `IFormula` and `DFormula`, see "Properties" on page 1-534 .

  - If you require different discrete integrator formulas, you can discretize the controller by directly setting `Ts`, `IFormula`, and `DFormula` to the desired values. (See this example.) However, this method does not compute new gain and filter-constant values for the discretized controller. Therefore, this method might yield a poorer match between the continuous- and discrete-time `pid` controllers than using `c2d`.

- "What Are Model Objects?"
- "PID Controllers"

See Also

`pidstd` | `piddata` | `pidtune` | `pidTuner` | `ltiblock.pid` | `genss` | `realp`

Introduced in R2010b

piddata

Access PID data

Syntax

```
[Kp,Ki,Kd,Tf] = piddata(sys)
[Kp,Ki,Kd,Tf,Ts] = piddata(sys)
[Kp,Ki,Kd,Tf,Ts] = piddata(sys, J1,...,JN)
```

Description

`[Kp,Ki,Kd,Tf] = piddata(sys)` returns the PID gains Kp,Ki, Kd and the filter time constant Tf of the parallel-form controller represented by the dynamic system sys.

`[Kp,Ki,Kd,Tf,Ts] = piddata(sys)` also returns the sample time Ts.

`[Kp,Ki,Kd,Tf,Ts] = piddata(sys, J1,...,JN)` extracts the data for a subset of entries in the array of sys dynamic systems. The indices J specify the array entries to extract.

Input Arguments

sys

SISO dynamic system or array of SISO dynamic systems. If sys is not a `pid` object, it must represent a valid PID controller that can be written in parallel PID form.

J

Integer indices of *N* entries in the array sys of dynamic systems.

Output Arguments

Kp

Proportional gain of the parallel-form PID controller represented by dynamic system sys.

If sys is a `pid` controller object, the output Kp is equal to the `Kp` value of sys.

If sys is not a pid object, Kp is the proportional gain of a parallel PID controller equivalent to sys.

If sys is an array of dynamic systems, Kp is an array of the same dimensions as sys.

Ki

Integral gain of the parallel-form PID controller represented by dynamic system sys.

If sys is a `pid` controller object, the output Ki is equal to the `Ki` value of sys.

If sys is not a pid object, Ki is the integral gain of a parallel PID controller equivalent to sys.

If sys is an array of dynamic systems, Ki is an array of the same dimensions as sys.

Kd

Derivative gain of the parallel-form PID controller represented by dynamic system sys.

If sys is a `pid` controller object, the output Kd is equal to the `Kd` value of sys.

If sys is not a pid object, Kd is the derivative gain of a parallel PID controller equivalent to sys.

If sys is an array of dynamic systems, Kd is an array of the same dimensions as sys.

Tf

Filter time constant of the parallel-form PID controller represented by dynamic system sys.

If sys is a `pid` controller object, the output Tf is equal to the `Tf` value of sys.

If sys is not a pid object, Tf is the filter time constant of a parallel PID controller equivalent to sys.

If sys is an array of dynamic systems, Tf is an array of the same dimensions as sys.

Ts

Sample time of the dynamic system sys. Ts is always a scalar value.

Examples

Extract the proportional, integral, and derivative gains and the filter time constant from a parallel-form `pid` controller.

For the following `pid` object:

```
sys = pid(1,4,0.3,10);
```

you can extract the parameter values from `sys` by entering:

```
[Kp Ki Kd Tf] = piddata(sys);
```

Extract the parallel form proportional and integral gains from an equivalent standard-form PI controller.

For a standard-form PI controller, such as:

```
sys = pidstd(2,3);
```

you can extract the gains of an equivalent parallel-form PI controller by entering:

```
[Kp Ki] = piddata(sys)
```

These commands return the result:

```
Kp =

     2


Ki =

    0.6667
```

Extract parameters from a dynamic system that represents a PID controller.

The dynamic system

$$H(z) = \frac{(z-0.5)(z-0.6)}{(z-1)(z+0.8)}$$

represents a discrete-time PID controller with a derivative filter. Use `piddata` to extract the parallel-form PID parameters.

```
H = zpk([0.5 0.6],[1,-0.8],1,0.1);  % sample time Ts = 0.1s
[Kp Ki Kd Tf Ts] = piddata(H);
```

the `piddata` function uses the default `ForwardEuler` discrete integrator formula for `Iformula` and `Dformula` to compute the parameter values.

Extract the gains from an array of PI controllers.

```
sys = pid(rand(2,3),rand(2,3)); % 2-by-3 array of PI controllers
[Kp Ki Kd Tf] = piddata(sys);
```

The parameters `Kp`, `Ki`, `Kd`, and `Tf` are also 2-by-3 arrays.

Use the index input J to extract the parameters of a subset of `sys`.

```
[Kp Ki Kd Tf] = piddata(sys,5);
```

More About

Tips

If sys is not a `pid` controller object, `piddata` returns the PID gains Kp, Ki, Kd and the filter time constant Tf of a parallel-form controller equivalent to sys.

For discrete-time sys, `piddata` returns the parameters of an equivalent parallel-form controller. This controller has discrete integrator formulas `Iformula` and `Dformula` set to `ForwardEuler`. See the `pid` reference page for more information about discrete integrator formulas.

See Also

`pid` | `pidstd` | `get`

pidstd

Create a PID controller in standard form, convert to standard-form PID controller

Syntax

```
C = pidstd(Kp,Ti,Td,N)
C = pidstd(Kp,Ti,Td,N,Ts)
C = pidstd(sys)
C = pidstd(Kp)
C = pidstd(Kp,Ti)
C = pidstd(Kp,Ti,Td)
C = pidstd(...,Name,Value)
C = pidstd
```

Description

`C = pidstd(Kp,Ti,Td,N)` creates a continuous-time PIDF (PID with first-order derivative filter) controller object in standard form. The controller has proportional gain Kp, integral and derivative times Ti and Td, and first-order derivative filter divisor N:

$$C = K_p \left(1 + \frac{1}{T_i}\frac{1}{s} + \frac{T_d s}{\frac{T_d}{N}s + 1} \right).$$

`C = pidstd(Kp,Ti,Td,N,Ts)` creates a discrete-time controller with sample time Ts. The discrete-time controller is:

$$C = K_p \left(1 + \frac{1}{T_i} IF(z) + \frac{T_d}{\frac{T_d}{N} + DF(z)} \right).$$

$IF(z)$ and $DF(z)$ are the *discrete integrator formulas* for the integrator and derivative filter. By default, $IF(z) = DF(z) = T_s z/(z - 1)$. To choose different discrete integrator formulas, use the `IFormula` and `DFormula` inputs. (See “Properties” on page 1-556 for more information about `IFormula` and `DFormula`). If `DFormula` = `'ForwardEuler'` (the default value) and N ≠ `Inf`, then Ts, Td, and N must satisfy `Td/N > Ts/2`. This requirement ensures a stable derivative filter pole.

`C = pidstd(sys)` converts the dynamic system sys to a standard form `pidstd` controller object.

`C = pidstd(Kp)` creates a continuous-time proportional (P) controller with Ti = `Inf`, Td = 0, and N = `Inf`.

`C = pidstd(Kp,Ti)` creates a proportional and integral (PI) controller with Td = 0 and N = `Inf`.

`C = pidstd(Kp,Ti,Td)` creates a proportional, integral, and derivative (PID) controller with N = `Inf`.

`C = pidstd(...,Name,Value)` creates a controller or converts a dynamic system to a `pidstd` controller object with additional options specified by one or more Name,Value pair arguments.

`C = pidstd` creates a P controller with Kp = 1.

Input Arguments

Kp

Proportional gain.

Kp must be a real and finite value.

For an array of `pidstd` controllers, Kp must be an array of real and finite values.

Default: 1

Ti

Integral time.

Ti must be a real and positive value. When Ti = `Inf`, the controller has no integral action.

For an array of `pidstd` controllers, Ti must be an array of real and positive values.

Default: `Inf`

`Td`

Derivative time.

Td must be a real, finite, and nonnegative value. When Td = 0, the controller has no derivative action.

For an array of `pidstd` controllers, Td must be an array of real, finite, and nonnegative values.

Default: 0

`N`

Time constant of the first-order derivative filter.

N must be a real and positive value. When N = `Inf`, the controller has no derivative filter.

For an array of `pidstd` controllers, N must be an array of real and positive values.

Default: `Inf`

`Ts`

Sample time.

To create a discrete-time `pidstd` controller, provide a positive real value (`Ts > 0`).`pidstd` does not support discrete-time controller with undetermined sample time (`Ts = -1`).

Ts must be a scalar value. In an array of `pidstd` controllers, each controller must have the same Ts.

`sys`

SISO dynamic system to convert to standard `pidstd` form.

sys must represent a valid controller that can be written in standard form with $Ti > 0$, $Td \geq 0$, and $N > 0$.

sys can also be an array of SISO dynamic systems.

Name-Value Pair Arguments

Specify optional comma-separated pairs of Name,Value arguments. `Name` is the argument name and `Value` is the corresponding value. `Name` must appear inside single quotes (`' '`). You can specify several name and value pair arguments in any order as `Name1,Value1,...,NameN,ValueN`.

Use Name,Value syntax to set the numerical integration formulas `IFormula` and `DFormula` of a discrete-time `pidstd` controller, or to set other object properties such as `InputName` and `OutputName`. For information about available properties of `pidstd` controller objects, see “Properties” on page 1-556.

Output Arguments

C

`pidstd` object representing a single-input, single-output PID controller in standard form.

The controller type (P, PI, PD, PDF, PID, PIDF) depends upon the values of Kp, Ti, Td, and N. For example, when Td = `Inf` and Kp and Ti are finite and nonzero, C is a PI controller. Enter `getType(C)` to obtain the controller type.

When the inputs Kp,Ti, Td, and N or the input sys are arrays, C is an array of `pidstd` objects.

Properties

Kp

Proportional gain. `Kp` must be real and finite.

Ti

Integral time. `Ti` must be real, finite, and greater than or equal to zero.

Td

Derivative time. `Td` must be real, finite, and greater than or equal to zero.

N

Derivative time. `N` must be real, and greater than or equal to zero.

IFormula

Discrete integrator formula $IF(z)$ for the integrator of the discrete-time `pidstd` controller C:

$$C = K_p \left(1 + \frac{1}{T_i} IF(z) + \frac{T_d}{\frac{T_d}{N} + DF(z)} \right).$$

`IFormula` can take the following values:

- `'ForwardEuler'` — $IF(z) = \frac{T_s}{z-1}$.

  This formula is best for small sample time, where the Nyquist limit is large compared to the bandwidth of the controller. For larger sample time, the `ForwardEuler` formula can result in instability, even when discretizing a system that is stable in continuous time.

- `'BackwardEuler'` — $IF(z) = \frac{T_s z}{z-1}$.

  An advantage of the `BackwardEuler` formula is that discretizing a stable continuous-time system using this formula always yields a stable discrete-time result.

- `'Trapezoidal'` — $IF(z) = \frac{T_s}{2} \frac{z+1}{z-1}$.

  An advantage of the `Trapezoidal` formula is that discretizing a stable continuous-time system using this formula always yields a stable discrete-time result. Of all available integration formulas, the `Trapezoidal` formula yields the closest match between frequency-domain properties of the discretized system and the corresponding continuous-time system.

When C is a continuous-time controller, `IFormula` is `''`.

Default: `'ForwardEuler'`

`DFormula`

Discrete integrator formula $DF(z)$ for the derivative filter of the discrete-time `pidstd` controller C:

$$C = K_p\left(1+\frac{1}{T_i}IF(z)+\frac{T_d}{\frac{T_d}{N}+DF(z)}\right).$$

`DFormula` can take the following values:

- `'ForwardEuler'` — $DF(z) = \dfrac{T_s}{z-1}$.

  This formula is best for small sample time, where the Nyquist limit is large compared to the bandwidth of the controller. For larger sample time, the `ForwardEuler` formula can result in instability, even when discretizing a system that is stable in continuous time.

- `'BackwardEuler'` — $DF(z) = \dfrac{T_s z}{z-1}$.

  An advantage of the `BackwardEuler` formula is that discretizing a stable continuous-time system using this formula always yields a stable discrete-time result.

- `'Trapezoidal'` — $DF(z) = \dfrac{T_s}{2}\dfrac{z+1}{z-1}$.

  An advantage of the `Trapezoidal` formula is that discretizing a stable continuous-time system using this formula always yields a stable discrete-time result. Of all available integration formulas, the `Trapezoidal` formula yields the closest match between frequency-domain properties of the discretized system and the corresponding continuous-time system.

  The `Trapezoidal` value for `DFormula` is not available for a `pidstd` controller with no derivative filter (`N = Inf`).

When C is a continuous-time controller, `DFormula` is `''`.

Default: `'ForwardEuler'`

`InputDelay`

Time delay on the system input. `InputDelay` is always 0 for a `pidstd` controller object.

`OutputDelay`

Time delay on the system Output. `OutputDelay` is always 0 for a `pidstd` controller object.

`Ts`

Sample time. For continuous-time models, `Ts = 0`. For discrete-time models, `Ts` is a positive scalar representing the sampling period. This value is expressed in the unit specified by the `TimeUnit` property of the model. To denote a discrete-time model with unspecified sample time, set `Ts = -1`.

Changing this property does not discretize or resample the model. Use `c2d` and `d2c` to convert between continuous- and discrete-time representations. Use `d2d` to change the sample time of a discrete-time system.

Default: `0` (continuous time)

`TimeUnit`

String representing the unit of the time variable. This property specifies the units for the time variable, the sample time `Ts`, and any time delays in the model. Use any of the following values:

- `'nanoseconds'`
- `'microseconds'`
- `'milliseconds'`
- `'seconds'`
- `'minutes'`
- `'hours'`
- `'days'`
- `'weeks'`
- `'months'`
- `'years'`

Changing this property has no effect on other properties, and therefore changes the overall system behavior. Use `chgTimeUnit` to convert between time units without modifying system behavior.

Default: `'seconds'`

`InputName`

Input channel names. Set `InputName` to a string for single-input model. For a multi-input model, set `InputName` to a cell array of strings.

Alternatively, use automatic vector expansion to assign input names for multi-input models. For example, if `sys` is a two-input model, enter:

```
sys.InputName = 'controls';
```

The input names automatically expand to `{'controls(1)';'controls(2)'}`.

You can use the shorthand notation `u` to refer to the `InputName` property. For example, `sys.u` is equivalent to `sys.InputName`.

Input channel names have several uses, including:

- Identifying channels on model display and plots
- Extracting subsystems of MIMO systems
- Specifying connection points when interconnecting models

Default: Empty string `''` for all input channels

`InputUnit`

Input channel units. Use `InputUnit` to keep track of input signal units. For a single-input model, set `InputUnit` to a string. For a multi-input model, set `InputUnit` to a cell array of strings. `InputUnit` has no effect on system behavior.

Default: Empty string `''` for all input channels

`InputGroup`

Input channel groups. The `InputGroup` property lets you assign the input channels of MIMO systems into groups and refer to each group by name. Specify input groups as a structure. In this structure, field names are the group names, and field values are the input channels belonging to each group. For example:

```
sys.InputGroup.controls = [1 2];
sys.InputGroup.noise = [3 5];
```

creates input groups named `controls` and `noise` that include input channels 1, 2 and 3, 5, respectively. You can then extract the subsystem from the `controls` inputs to all outputs using:

```
sys(:,'controls')
```

Default: Struct with no fields

`OutputName`

Output channel names. Set `OutputName` to a string for single-output model. For a multi-output model, set `OutputName` to a cell array of strings.

Alternatively, use automatic vector expansion to assign output names for multi-output models. For example, if `sys` is a two-output model, enter:

```
sys.OutputName = 'measurements';
```

The output names automatically expand to `{'measurements(1)';'measurements(2)'}`.

You can use the shorthand notation `y` to refer to the `OutputName` property. For example, `sys.y` is equivalent to `sys.OutputName`.

Output channel names have several uses, including:

- Identifying channels on model display and plots
- Extracting subsystems of MIMO systems
- Specifying connection points when interconnecting models

Default: Empty string `''` for all output channels

`OutputUnit`

Output channel units. Use `OutputUnit` to keep track of output signal units. For a single-output model, set `OutputUnit` to a string. For a multi-output model, set `OutputUnit` to a cell array of strings. `OutputUnit` has no effect on system behavior.

Default: Empty string `''` for all output channels

OutputGroup

Output channel groups. The `OutputGroup` property lets you assign the output channels of MIMO systems into groups and refer to each group by name. Specify output groups as a structure. In this structure, field names are the group names, and field values are the output channels belonging to each group. For example:

```
sys.OutputGroup.temperature = [1];
sys.InputGroup.measurement = [3 5];
```

creates output groups named `temperature` and `measurement` that include output channels 1, and 3, 5, respectively. You can then extract the subsystem from all inputs to the `measurement` outputs using:

```
sys('measurement',:)
```

Default: Struct with no fields

Name

System name. Set `Name` to a string to label the system.

Default: `''`

Notes

Any text that you want to associate with the system. Set `Notes` to a string or a cell array of strings.

Default: `{}`

UserData

Any type of data you wish to associate with system. Set `UserData` to any MATLAB data type.

Default: `[]`

SamplingGrid

Sampling grid for model arrays, specified as a data structure.

For model arrays that are derived by sampling one or more independent variables, this property tracks the variable values associated with each model in the array. This information appears when you display or plot the model array. Use this information to trace results back to the independent variables.

Set the field names of the data structure to the names of the sampling variables. Set the field values to the sampled variable values associated with each model in the array. All sampling variables should be numeric and scalar valued, and all arrays of sampled values should match the dimensions of the model array.

For example, suppose you create a 11-by-1 array of linear models, `sysarr`, by taking snapshots of a linear time-varying system at times `t = 0:10`. The following code stores the time samples with the linear models.

```
 sysarr.SamplingGrid = struct('time',0:10)
```

Similarly, suppose you create a 6-by-9 model array, `M`, by independently sampling two variables, `zeta` and `w`. The following code attaches the `(zeta,w)` values to `M`.

```
[zeta,w] = ndgrid(<6 values of zeta>,<9 values of w>)
M.SamplingGrid = struct('zeta',zeta,'w',w)
```

When you display `M`, each entry in the array includes the corresponding `zeta` and `w` values.

```
M

M(:,:,1,1) [zeta=0.3, w=5] =

        25
  --------------
  s^2 + 3 s + 25


M(:,:,2,1) [zeta=0.35, w=5] =

         25
  ----------------
  s^2 + 3.5 s + 25

...
```

For model arrays generated by linearizing a Simulink model at multiple parameter values or operating points, the software populates `SamplingGrid` automatically with the variable values that correspond to each entry in the array. For example, the Simulink

Control Design commands `linearize` and `slLinearizer` populate `SamplingGrid` in this way.

Default: `[]`

Examples

Create a continuous-time standard-form PDF controller with proportional gain 1, derivative time 3, and a filter divisor of 6.

```
C = pidstd(1,Inf,3,6);
```

```
C =

                      s
  Kp * (1 + Td * ------------)
                  (Td/N)*s+1

  with Kp = 1, Td = 3, N = 6

Continuous-time PDF controller in standard form
```

The display shows the controller type, formula, and coefficient values.

Create a discrete-time PI controller with trapezoidal discretization formula.

To create a discrete-time controller, set the value of `Ts` using Name,Value syntax.

```
C = pidstd(1,0.5,'Ts',0.1,'IFormula','Trapezoidal') % Ts = 0.1s
```

This command produces the result:

```
Discrete-time PI controller in standard form:

           1     Ts*(z+1)
Kp * (1 + ---- * --------)
           Ti    2*(z-1)

with Kp = 1, Ti = 0.5, Ts = 0.1
```

Alternatively, you can create the same discrete-time controller by supplying `Ts` as the fifth argument after all four PID parameters `Kp`, `Ti`, `Td`, and `N`.

```
C = pidstd(5,2.4,0,Inf,0.1,'IFormula','Trapezoidal');
```

Create a PID controller and set dynamic system properties `InputName` and `OutputName`.

```
C = pidstd(1,0.5,3,'InputName','e','OutputName','u')
```

Create a 2-by-3 grid of PI controllers with proportional gain ranging from 1–2 and integral time ranging from 5–9.

Create a grid of PI controllers with proportional gain varying row to row and integral time varying column to column. To do so, start with arrays representing the gains.

```
Kp = [1 1 1;2 2 2];
Ti = [5:2:9;5:2:9];
pi_array = pidstd(Kp,Ti,'Ts',0.1,'IFormula','BackwardEuler');
```

These commands produce a 2-by-3 array of discrete-time `pidstd` objects. All `pidstd` objects in an array must have the same sample time, discrete integrator formulas, and dynamic system properties (such as `InputName` and `OutputName`).

Alternatively, you can use the `stack` command to build arrays of `pidstd` objects.

```
C = pidstd(1,5,0.1)        % PID controller
Cf = pidstd(1,5,0.1,0.5)   % PID controller with filter
pid_array = stack(2,C,Cf); % stack along 2nd array dimension
```

These commands produce a 1-by-2 array of controllers. Enter the command:

```
size(pid_array)
```

to see the result

```
1x2 array of PID controller.
Each PID has 1 output and 1 input.
```

Convert a standard form `pid` controller to parallel form.

Parallel PID form expresses the controller actions in terms of an proportional, integral, and derivative gains K_p, K_i, and K_d, and a filter time constant T_f. You can convert a parallel form controller `parsys` to standard form using `pidstd`, provided that:

- `parsys` is not a pure integrator (I) controller.

- The gains Kp, Ki, and Kd of parsys all have the same sign.

```
parsys = pid(2,3,4,5);  % Standard-form controller
stdsys = pidstd(parsys)
```

These commands produce a parallel-form controller:

```
Continuous-time PIDF controller in standard form:

             1      1              s
Kp * (1 + ---- * --- + Td * ------------)
            Ti      s          (Td/N)*s+1

with Kp = 2, Ti = 0.66667, Td = 2, N = 0.4
```

Convert a continuous-time dynamic system that represents a PID controller to parallel pid form.

The dynamic system

$$H(s) = \frac{3(s+1)(s+2)}{s}$$

represents a PID controller. Use pidstd to obtain $H(s)$ to in terms of the standard-form PID parameters K_p, T_i, and T_d.

```
H = zpk([-1,-2],0,3);
C = pidstd(H)
```

These commands produce the result:

```
Continuous-time PID controller in standard form:

             1      1
Kp * (1 + ---- * --- + Td * s)
            Ti      s

with Kp = 9, Ti = 1.5, Td = 0.33333
```

Convert a discrete-time dynamic system that represents a PID controller with derivative filter to standard pidstd form.

```
% PIDF controller expressed in zpk form
sys = zpk([-0.5,-0.6],[1 -0.2],3,'Ts',0.1)
```

The resulting `pidstd` object depends upon the discrete integrator formula you specify for `IFormula` and `DFormula`.

For example, if you use the default `ForwardEuler` for both formulas:

```
C = pidstd(sys)
```

you obtain the result:

```
Discrete-time PIDF controller in standard form:

            1       Ts                  1
Kp * (1 + ---- * ------ + Td * ---------------)
           Ti      z-1          (Td/N)+Ts/(z-1)

with Kp = 2.75, Ti = 0.045833, Td = 0.0075758, N = 0.090909, Ts = 0.1
```

For this particular `sys`, you cannot write `sys` in standard PID form using the `BackwardEuler` formula for the `DFormula`. Doing so would result in `N` < 0, which is not permitted. In that case, `pidstd` returns an error.

Similarly, you cannot write `sys` in standard form using the `Trapezoidal` formula for both integrators. Doing so would result in negative `Ti` and `Td`, which also returns an error.

Discretize a continuous-time `pidstd` controller.

First, discretize the controller using the `'zoh'` method of `c2d`.

```
Cc = pidstd(1,2,3,4)  % continuous-time pidf controller
Cd1 = c2d(Cc,0.1,'zoh')
```

`c2d` computes new parameters for the discrete-time controller:

```
Discrete-time PIDF controller in standard form:

            1       Ts                  1
Kp * (1 + ---- * ------ + Td * ---------------)
           Ti      z-1          (Td/N)+Ts/(z-1)

with Kp = 1, Ti = 2, Td = 3.2044, N = 4, Ts = 0.1
```

The resulting discrete-time controller uses `ForwardEuler` ($T_s/(z-1)$) for both `IFormula` and `DFormula`.

The discrete integrator formulas of the discretized controller depend upon the `c2d` discretization method, as described in "Tips" on page 1-568. To use a different `IFormula` and `DFormula`, directly set `Ts`, `IFormula`, and `DFormula` to the desired values:

```
Cd2 = Cc;
Cd2.Ts = 0.1;
Cd2.IFormula = 'BackwardEuler';
Cd2.DFormula = 'BackwardEuler';
```

These commands do not compute new parameter values for the discretized controller. To see this, enter:

```
Cd2
```

to obtain the result:

```
Discrete-time PIDF controller in standard form:

           1      Ts*z                 1
Kp * (1 + ---- * ------ + Td * -----------------)
           Ti      z-1         (Td/N)+Ts*z/(z-1)

with Kp = 1, Ti = 2, Td = 3, N = 4, Ts = 0.1
```

More About

Tips

- Use `pidstd` either to create a `pidstd` controller object from known PID gain, integral and derivative times, and filter divisor, or to convert a dynamic system model to a `pidstd` object.
- To tune a PID controller for a particular plant, use `pidtune` or `pidTuner`.
- Create arrays of `pidstd` controllers by:
  - Specifying array values for Kp,Ti,Td, and N
  - Specifying an array of dynamic systems sys to convert to standard PID form
  - Using `stack` to build arrays from individual controllers or smaller arrays

  In an array of `pidstd` controllers, each controller must have the same sample time Ts and discrete integrator formulas `IFormula` and `DFormula`.

- To create or convert to a parallel-form controller, use `pid`. Parallel form expresses the controller actions in terms of proportional, integral, and derivative gains K_p, K_i and K_d, and a filter time constant T_f:

$$C = K_p + \frac{K_i}{s} + \frac{K_d s}{T_f s + 1}.$$

- There are two ways to discretize a continuous-time `pidstd` controller:
  - Use the `c2d` command. `c2d` computes new parameter values for the discretized controller. The discrete integrator formulas of the discretized controller depend upon the `c2d` discretization method you use, as shown in the following table.

c2d Discretization Method	IFormula	DFormula
'zoh'	ForwardEuler	ForwardEuler
'foh'	Trapezoidal	Trapezoidal
'tustin'	Trapezoidal	Trapezoidal
'impulse'	ForwardEuler	ForwardEuler
'matched'	ForwardEuler	ForwardEuler

    For more information about `c2d` discretization methods, See the `c2d` reference page. For more information about `IFormula` and `DFormula`, see “Properties” on page 1-556 .
  - If you require different discrete integrator formulas, you can discretize the controller by directly setting `Ts`, `IFormula`, and `DFormula` to the desired values. (See this example.) However, this method does not compute new gain and filter-constant values for the discretized controller. Therefore, this method might yield a poorer match between the continuous- and discrete-time `pidstd` controllers than using `c2d`.

- “What Are Model Objects?”
- “PID Controllers”

See Also

`pid` | `piddata` | `pidtune` | `pidTuner`

pidstddata

Access PIDSTD data

Syntax

```
[Kp,Ti,Td,N] = pidstddata(sys)
[Kp,Ti,Td,N,Ts] = pidstddata(sys)
[Kp,Ti,Td,N,Ts] = pidstddata(sys, J1,...,JN)
```

Description

`[Kp,Ti,Td,N] = pidstddata(sys)` returns the proportional gain Kp, integral time Ti, derivative time Td, and filter divisor N of the standard-form controller represented by the dynamic system sys.

`[Kp,Ti,Td,N,Ts] = pidstddata(sys)` also returns the sample time Ts.

`[Kp,Ti,Td,N,Ts] = pidstddata(sys, J1,...,JN)` extracts the data for a subset of entries in the array of sys dynamic systems. The indices J specify the array entries to extract.

Input Arguments

sys

SISO dynamic system or array of SISO dynamic systems. If sys is not a `pidstd` object, it must represent a valid PID controller that can be written in standard PID form.

J

Integer indices of N entries in the array sys of dynamic systems.

Output Arguments

`Kp`

Proportional gain of the standard-form PID controller represented by dynamic system sys.

If sys is a `pidstd` controller object, the output Kp is equal to the `Kp` value of sys.

If sys is not a pidstd object, Kp is the proportional gain of a standard-form PID controller equivalent to sys.

If sys is an array of dynamic systems, Kp is an array of the same dimensions as sys.

`Ti`

Integral time constant of the standard-form PID controller represented by dynamic system sys.

If sys is a `pidstd` controller object, the output Ti is equal to the `Ti` value of sys.

If sys is not a pidstd object, Ti is the integral time constant of a standard-form PID controller equivalent to sys.

If sys is an array of dynamic systems, Ti is an array of the same dimensions as sys.

`Td`

Derivative time constant of the standard-form PID controller represented by dynamic system sys.

If sys is a `pidstd` controller object, the output Td is equal to the `Td` value of sys.

If sys is not a pidstd object, Td is the derivative time constant of a standard-form PID controller equivalent to sys.

If sys is an array of dynamic systems, Td is an array of the same dimensions as sys.

`N`

Filter divisor of the standard-form PID controller represented by dynamic system sys.

If sys is a `pidstd` controller object, the output N is equal to the `N` value of sys.

If sys is not a pidstd object, N is the filter time constant of a standard-form PID controller equivalent to sys.

If sys is an array of dynamic systems, N is an array of the same dimensions as sys.

Ts

Sample time of the dynamic system sys. Ts is always a scalar value.

Examples

Extract the proportional, integral, and derivative gains and the filter time constant from a standard-form `pidstd` controller.

For the following `pidstd` object:

```
sys = pidstd(1,4,0.3,10);
```

you can extract the parameter values from `sys` by entering:

```
[Kp Ti Td N] = pidstddata(sys);
```

Extract the standard-form proportional and integral gains from an equivalent parallel-form PI controller.

For a standard-form PI controller, such as:

```
sys = pid(2,3);
```

you can extract the gains of an equivalent parallel-form PI controller by entering:

```
[Kp Ti] = pidstddata(sys)
```

These commands return the result:

```
Kp =

     2


Ti =
```

```
0.6667
```

Extract parameters from a dynamic system that represents a PID controller.

The dynamic system

$$H(z) = \frac{(z-0.5)(z-0.6)}{(z-1)(z+0.8)}$$

represents a discrete-time PID controller with a derivative filter. Use `pidstddata` to extract the standard-form PID parameters.

```
H = zpk([0.5 0.6],[1,-0.8],1,0.1);  % sample time Ts = 0.1s
[Kp Ti Td N Ts] = pidstddata(H);
```

the `pidstddata` function uses the default `ForwardEuler` discrete integrator formula for `Iformula` and `Dformula` to compute the parameter values.

Extract the gains from an array of PI controllers.

```
sys = pidstd(rand(2,3),rand(2,3)); % 2-by-3 array of PI controllers
[Kp Ti Td N] = pidstddata(sys);
```

The parameters `Kp`, `Ti`, `Td`, and `N` are also 2-by-3 arrays.

Use the index input J to extract the parameters of a subset of `sys`.

```
[Kp Ti Td N] = pidstddata(sys,5);
```

More About

Tips

If sys is not a `pidstd` controller object, `pidstddata` returns Kp, Ti, Td and N values of a standard-form controller equivalent to sys.

For discrete-time sys, `piddata` returns parameters of an equivalent `pidstd` controller. This controller has discrete integrator formulas `Iformula` and `Dformula` set to `ForwardEuler`. See the `pidstd` reference page for more information about discrete integrator formulas.

See Also

`pidstd` | `pid` | `get`

pidtool

Open PID Tuner for PID tuning

Note: `pidtool` has been removed. Use `pidTuner` instead.

---

pidtune

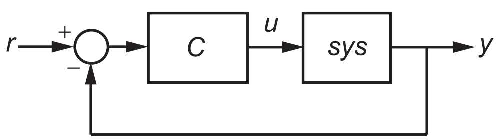
PID tuning algorithm for linear plant model

Syntax

```
C = pidtune(sys,type)
C = pidtune(sys,C0)
C = pidtune(sys,type,wc)
C = pidtune(sys,C0,wc)
C = pidtune(sys,...,opts)
[C,info] = pidtune(...)
```

Description

`C = pidtune(sys,type)` designs a PID controller of type type for the plant sys in the unit feedback loop



`pidtune` tunes the parameters of the PID controller C to balance performance (response time) and robustness (stability margins).

`C = pidtune(sys,C0)` designs a controller of the same type and form as the controller C0. If sys and C0 are discrete-time models, C has the same discrete integrator formulas as C0.

`C = pidtune(sys,type,wc)` and `C = pidtune(sys,C0,wc)` specify a target value wc for the first 0 dB gain crossover frequency of the open-loop response `L = sys*C`.

`C = pidtune(sys,...,opts)` uses additional tuning options, such as the target phase margin. Use `pidtuneOptions` to specify the option set opts.

`[C,info] = pidtune(...)` returns the data structure info, which contains information about closed-loop stability, the selected open-loop gain crossover frequency, and the actual phase margin.

Input Arguments

`sys`

Single-input, single-output dynamic system model of the plant for controller design. sys can be:

- Any type of SISO dynamic system model, including Numeric LTI models and identified models. If `sys` is a tunable or uncertain model, `pidtune` designs a controller for the current or nominal value of `sys`.
- A continuous- or discrete-time model.
- Stable, unstable, or integrating. A plant with unstable poles, however, might not be stabilizable under PID control.
- A model that includes any type of time delay. A plant with long time delays, however, might not achieve adequate performance under PID control.
- An array of plant models. If sys is an array, `pidtune` designs a separate controller for each plant in the array.

If the plant has unstable poles, and sys is one of the following:

- A `frd` model
- A `ss` model with internal time delays that cannot be converted to I/O delays

you must use `pidtuneOptions` to specify the number of unstable poles in the plant, if any.

`type`

Controller type (actions) of the controller to design, specified as one of the following strings.

String	Type	Continuous-Time Controller Formula (parallel form)	Discrete-Time Controller Formula (parallel form, ForwardEuler integration method)
`'p'`	Proportional only	K_p	K_p
`'i'`	Integral only	$\frac{K_i}{s}$	$K_i \frac{T_s}{z-1}$

String	Type	Continuous-Time Controller Formula (parallel form)	Discrete-Time Controller Formula (parallel form, ForwardEuler integration method)
`'pi'`	Proportional and integral	$K_p + \frac{K_i}{s}$	$K_p + K_i \frac{T_s}{z-1}$
`'pd'`	Proportional and derivative	$K_p + K_d s$	$K_p + K_d \frac{z-1}{T_s}$
`'pdf'`	Proportional and derivative with first-order filter on derivative term	$K_p + \frac{K_d s}{T_f s+1}$	$K_p + K_d \frac{1}{T_f + \frac{T_s}{z-1}}$
`'pid'`	Proportional, integral, and derivative	$K_p + \frac{K_i}{s} + K_d s$	$K_p + K_i \frac{T_s}{z-1} + K_d \frac{z-1}{T_s}$
`'pidf'`	Proportional, integral, and derivative with first-order filter on derivative term	$K_p + \frac{K_i}{s} + \frac{K_d s}{T_f s+1}$	$K_p + K_i \frac{T_s}{z-1} + K_d \frac{1}{T_f + \frac{T_s}{z-1}}$

When you use the type input, `pidtune` designs a controller in parallel (`pid`) form. Use the input C0 instead of type if you want to design a controller in standard (`pidstd`) form.

If sys is a discrete-time model with sample time `Ts`, `pidtune` designs a discrete-time controller with the same `Ts`. The controller has the `ForwardEuler` discrete integrator formula for both integral and derivative actions. Use the input C0 instead of type if you want to design a controller having a different discrete integrator formula.

`C0`

`pid` or `pidstd` controller specifying properties of the designed controller. If you provide C0, `pidtune`:

- Designs a controller of the type represented by C0.
- Returns a `pid` controller, if C0 is a `pid` controller.
- Returns a `pidstd` controller, if C0 is a `pidstd` controller.

- Returns a controller with the same `Iformula` and `Dformula` values as C0, if sys is a discrete-time system. See the `pid` and `pidstd` reference pages for more information about `Iformula` and `Dformula`.

`wc`

Target value for the 0 dB gain crossover frequency of the tuned open-loop response `L = sys*C`. Specify wc in units of radians/`TimeUnit`, where `TimeUnit` is the time unit of sys. The crossover frequency wc roughly sets the control bandwidth. The closed-loop response time is approximately `1/wc`.

Increase wc to speed up the response. Decrease wc to improve stability. When you omit wc, `pidtune` automatically chooses a value, based on the plant dynamics, that achieves a balance between response and stability.

`opts`

Option set specifying additional tuning options for the `pidtune` design algorithm, such as target phase margin or design focus. Use `pidtuneOptions` to create opts.

Output Arguments

`C`

Controller designed for sys. If sys is an array of linear models, `pidtune` designs a controller for each linear model and returns an array of PID controllers.

Controller form:

- If the second argument to `pidtune` is type, C is a `pid` controller.
- If the second argument to `pidtune` is C0:
  - C is a `pid` controller, if C0 is a `pid` object.
  - C is a `pidstd` controller, if C0 is a `pidstd` object.

Controller type:

- If the second argument to `pidtune` is type, C generally has the specified type.
- If the second argument to `pidtune` is C0, C generally has the same type as C0.

In either case, however, where the algorithm can achieve adequate performance and robustness using a lower-order controller than specified with type or C0, `pidtune` returns a C having fewer actions than specified. For example, C can be a PI controller even though type is `'pidf'`.

Time domain:

- C has the same time domain as sys.
- If sys is a discrete-time model, C has the same sample time as sys.
- If you specify C0, C has the same `Iformula` and `Dformula` as C0. If no C0 is specified, both `Iformula` and `Dformula` are `Forward Euler`. See the `pid` and `pidstd` reference pages for more information about `Iformula` and `Dformula`.

If you specify C0, C also obtains model properties such as `InputName` and `OutputName` from C0. For more information about model properties, see the reference pages for each type of dynamic system model.

`info`

Data structure containing information about performance and robustness of the tuned PID loop. The fields of info are:

- `Stable` — Boolean value indicating closed-loop stability. `Stable` is 1 if the closed loop is stable, and 0 otherwise.
- `CrossoverFrequency` — First 0 dB crossover frequency of the open-loop system C*sys, in `rad/TimeUnit`, where `TimeUnit` is the time units specified in the TimeUnit property of sys.
- `PhaseMargin` — Phase margin of the tuned PID loop, in degrees.

If sys is an array of plant models, info is an array of data structures containing information about each tuned PID loop.

Examples

PID Controller Design at the Command Line

This example shows how to design a PID controller for the plant given by:

$$sys = \frac{1}{(s+1)^3}.$$

As a first pass, create a model of the plant and design a simple PI controller for it.

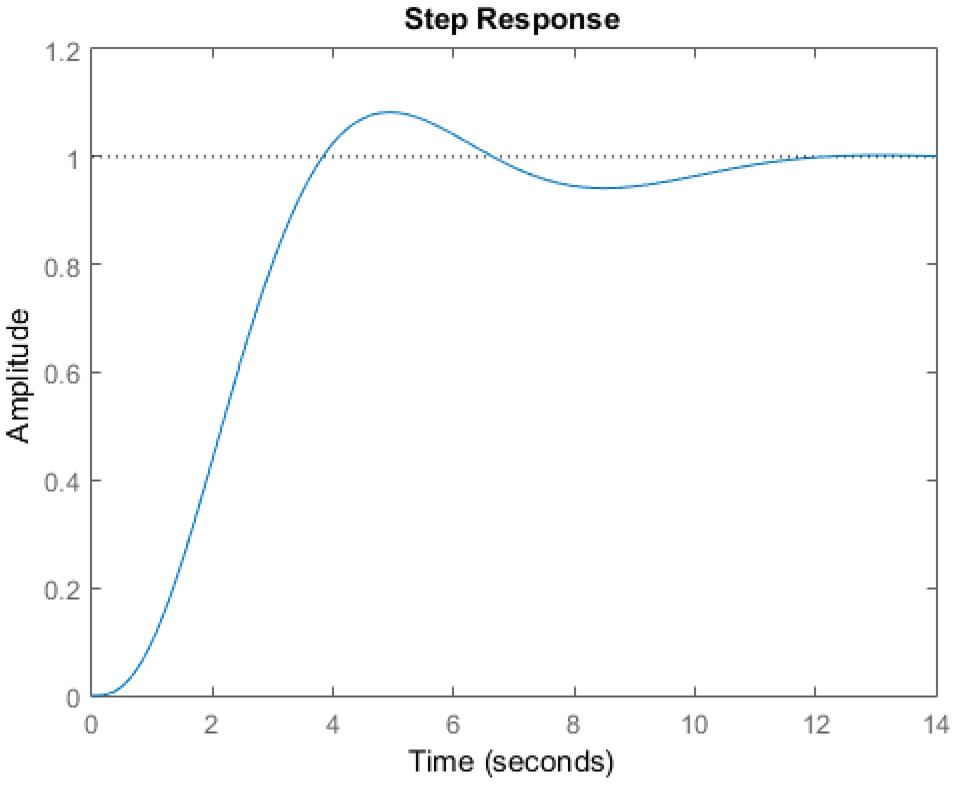
```
sys = zpk([],[-1 -1 -1],1);
[C_pi,info] = pidtune(sys,'pi')
```

```
C_pi =

             1
  Kp + Ki * ---
             s

  with Kp = 1.14, Ki = 0.454

Continuous-time PI controller in parallel form.


info =

                Stable: 1
    CrossoverFrequency: 0.5205
           PhaseMargin: 60.0000
```

`C_pi` is a `pid` controller object that represents a PI controller. The fields of `info` show that the tuning algorithm chooses an open-loop crossover frequency of about 0.52 rad/s.

Examine the closed-loop step response (reference tracking) of the controlled system.

```
T_pi = feedback(C_pi*sys, 1);
step(T_pi)
```



To improve the response time, you can set a higher target crossover frequency than the result that `pidtune` automatically selects, 0.52. Increase the crossover frequency to 1.0.

```
[C_pi_fast,info] = pidtune(sys,'pi',1.0)
```

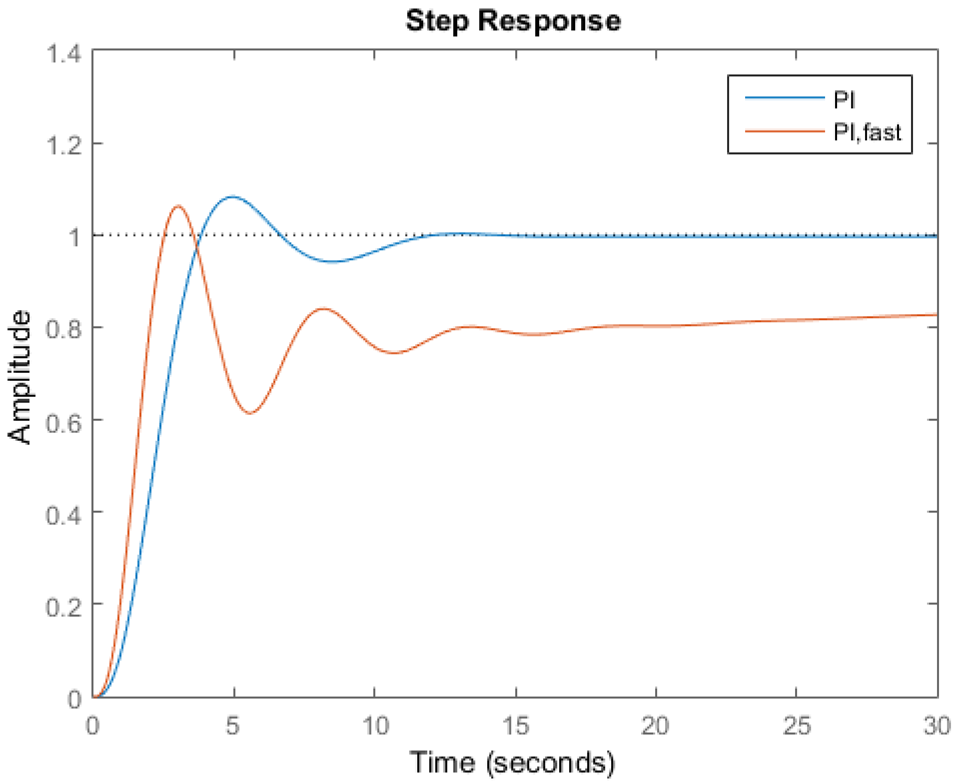
```
C_pi_fast =

             1
  Kp + Ki * ---
             s

  with Kp = 2.83, Ki = 0.0495
```

```
Continuous-time PI controller in parallel form.


info =

               Stable: 1
    CrossoverFrequency: 1
          PhaseMargin: 43.9973
```

The new controller achieves the higher crossover frequency, but at the cost of a reduced phase margin.

Compare the closed-loop step response with the two controllers.

```
T_pi_fast = feedback(C_pi_fast*sys,1);
step(T_pi,T_pi_fast)
axis([0 30 0 1.4])
legend('PI','PI,fast')
```



This reduction in performance results because the PI controller does not have enough degrees of freedom to achieve a good phase margin at a crossover frequency of 1.0 rad/s. Adding a derivative action improves the response.

Design a PIDF controller for `Gc` with the target crossover frequency of 1.0 rad/s.

```
[C_pidf_fast,info] = pidtune(sys,'pidf',1.0)
```

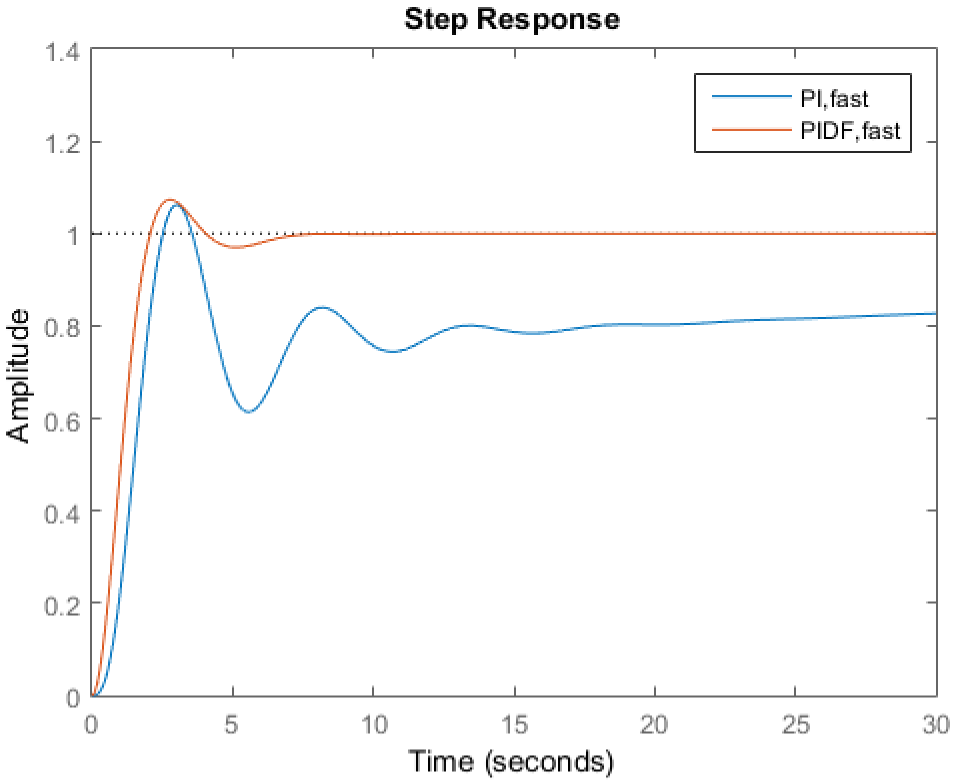
```
C_pidf_fast =

             1            s
  Kp + Ki * --- + Kd * --------
             s          Tf*s+1
```

```
  with Kp = 2.72, Ki = 0.985, Kd = 1.72, Tf = 0.00875

Continuous-time PIDF controller in parallel form.


info =

                Stable: 1
    CrossoverFrequency: 1
           PhaseMargin: 60.0000
```

The fields of info show that the derivative action in the controller allows the tuning algorithm to design a more aggressive controller that achieves the target crossover frequency with a good phase margin.

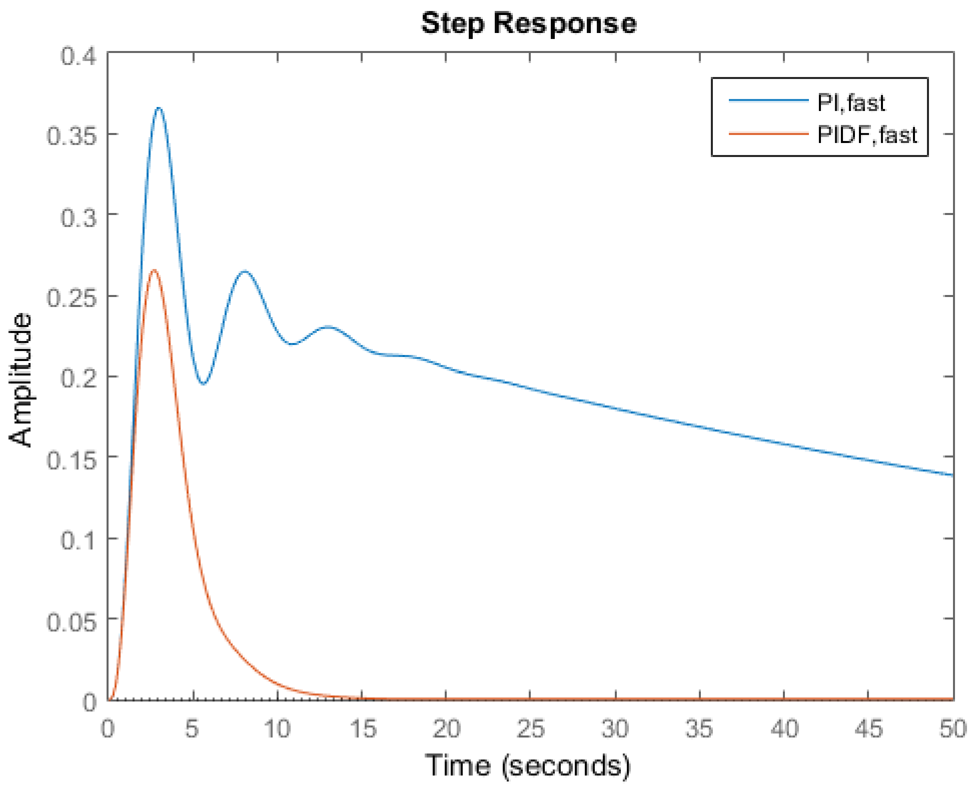
Compare the closed-loop step response and disturbance rejection for the fast PI and PIDF controllers.

```
T_pidf_fast =  feedback(C_pidf_fast*sys,1);
step(T_pi_fast, T_pidf_fast);
axis([0 30 0 1.4]);
legend('PI,fast','PIDF,fast');
```



You can compare the input (load) disturbance rejection of the controlled system with the fast PI and PIDF controllers. To do so, plot the response of the closed-loop transfer function from the plant input to the plant output.

```
S_pi_fast = feedback(sys,C_pi_fast);
S_pidf_fast = feedback(sys,C_pidf_fast);
step(S_pi_fast,S_pidf_fast);
axis([0 50 0 0.4]);
legend('PI,fast','PIDF,fast');
```



This plot shows that the PIDF controller also provides faster disturbance rejection.

Tune Standard-Form PID Controller

This example shows how to design a PID controller in standard form for the plant defined by

$$sys = \frac{1}{(s+1)^3}.$$

To design a controller in standard form, use a standard-form controller as the `C0` argument to `pidtune`.

```
sys = zpk([],[-1 -1 -1],1);
C0 = pidstd(1,1,1);
C = pidtune(sys,C0)
```

```
C =

             1      1
  Kp * (1 + ---- * --- + Td * s)
             Ti     s

  with Kp = 2.18, Ti = 2.36, Td = 0.591

Continuous-time PID controller in standard form
```

Specify Integrator Discretization Method

This example shows how to design a discrete-time PI controller using a specified method to discretize the integrator.

If your plant is in discrete time, `pidtune` automatically returns a discrete-time controller using the default Forward Euler integration method. To specify a different integration method, use `pid` or `pidstd` to create a discrete-time controller having the desired integration method.

```
sys = c2d(tf([1 1],[1 5 6]),0.1);
C0 = pid(1,1,'Ts',0.1,'IFormula','BackwardEuler');
C = pidtune(sys,C0)
```

```
C =

             Ts*z
  Kp + Ki * ------
              z-1

  with Kp = -0.518, Ki = 10.4, Ts = 0.1

Sample time: 0.1 seconds
Discrete-time PI controller in parallel form.
```

Using `C0` as an input causes `pidtune` to design a controller `C` of the same form, type, and discretization method as `C0`. The display shows that the integral term of `C` uses the Backward Euler integration method.

Specify a Trapezoidal integrator and compare the resulting controller.

```
C0_tr = pid(1,1,'Ts',0.1,'IFormula','Trapezoidal');
Ctr = pidtune(sys,C_tr)
```

```
Ctr =

       Ts*(z+1)
  Ki * --------
       2*(z-1)

  with Ki = 10.4, Ts = 0.1

Sample time: 0.1 seconds
Discrete-time I-only controller.
```

Alternatives

For interactive PID tuning, use the PID Tuner GUI (`pidTuner`). See “PID Controller Design for Fast Reference Tracking” for an example of designing a controller using the PID Tuner GUI.

The PID Tuner GUI cannot design controllers for multiple plants at once.

More About

Tips

By default, `pidtune` with the type input returns a `pid` controller in parallel form. To design a controller in standard form, use a `pidstd` controller as input argument C0. For more information about parallel and standard controller forms, see the `pid` and `pidstd` reference pages.

Algorithms

For information about the MathWorks® PID tuning algorithm, see “PID Tuning Algorithm”.

- “PID Tuning Algorithm”

References

Åström, K. J. and Hägglund, T. *Advanced PID Control*, Research Triangle Park, NC: Instrumentation, Systems, and Automation Society, 2006.

See Also

`pid` | `pidstd` | `pidtuneOptions` | `pidTuner`

Introduced in R2010b

pidtuneOptions

Define options for the `pidtune` command

Syntax

```
opt = pidtuneOptions
opt = pidtuneOptions(Name,Value)
```

Description

`opt = pidtuneOptions` returns the default option set for the `pidtune` command.

`opt = pidtuneOptions(Name,Value)` creates an option set with the options specified by one or more Name,Value pair arguments.

Input Arguments

Name-Value Pair Arguments

Specify optional comma-separated pairs of Name,Value arguments. `Name` is the argument name and `Value` is the corresponding value. `Name` must appear inside single quotes (`' '`). You can specify several name and value pair arguments in any order as `Name1,Value1,...,NameN,ValueN`.

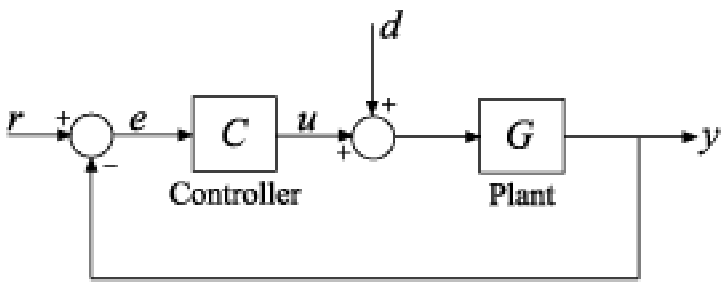
`'PhaseMargin'`

Target phase margin in degrees. `pidtune` attempts to design a controller such that the phase margin is at least the value specified for `PhaseMargin`. The selected crossover frequency could restrict the achievable phase margin. Typically, higher phase margin improves stability and overshoot, but limits bandwidth and response speed.

Default: 60

`'DesignFocus'`

Closed-loop performance objective to favor in the design. For a given target phase margin, `pidtune` chooses a controller design that balances the two measures of performance, reference tracking and disturbance rejection. When you change the `DesignFocus` option, the tuning algorithm attempts to adjust the PID gains to favor either reference tracking or disturbance rejection while achieving the same target phase margin. In the control architecture assumed by `pidtune`, shown in the following diagram, reference tracking is the response at *y* to signals at *r*, and disturbance rejection is the suppression at *y* of signals at *d*.



The `DesignFocus` option can take the following values:

- `'balanced'` (default) — For a given robustness, tune the controller to balance reference tracking and disturbance rejection.
- `'reference-tracking'` — Tune the controller to favor reference tracking, if possible.
- `'disturbance-rejection'` — Tune the controller to favor disturbance rejection, if possible.

The more tunable parameters there are in the system, the more likely it is that the PID algorithm can achieve the desired design focus without sacrificing robustness. For example, setting the design focus is more likely to be effective for PID controllers than for P or PI controllers. In all cases, how much you can fine-tune the performance of the system depends strongly on the properties of your plant.

For an example illustrating the effect of this option, see "Tune PID Controller to Favor Reference Tracking or Disturbance Rejection at Command Line".

Default: `'balanced'`

'NumUnstablePoles'

Number of unstable poles in the plant. When your plant is a `frd` model or a state-space model with internal delays, you must specify the number of open-loop unstable poles (if any). Incorrect values might result in PID controllers that fail to stabilize the real plant. (`pidtune` ignores this option for other model types.)

Unstable poles are poles located at:

- Re(s) > 0, for continuous-time plants
- $|z| > 1$, for discrete-time plants

A pure integrator in the plant ($s = 0$) or ($|z| > 1$) does not count as an unstable pole for `NumUnstablePoles`. If your plant is a `frd` model of a plant with a pure integrator, for best results, ensure that your frequency response data covers a low enough frequency to capture the integrator slope.

Default: 0

Output Arguments

opt

Object containing the specified options for `pidtune`.

Examples

Tune a PIDF controller with a target phase margin of 45 degrees, favoring the disturbance-rejection measure of performance.

```
sys = tf(1,[1 3 3 1]);
opts = pidtuneOptions('PhaseMargin',45,'DesignFocus','disturbance-rejection');
[C,info] = pidtune(sys,'pid',opts);
```

More About

Tips

- When using the `pidtune` command to design a PID controller for a plant with unstable poles, if your plant model is one of the following:

- A `frd` model
- A `ss` model with internal delays that cannot be converted to I/O delays

then use `pidtuneOptions` to specify the number of unstable poles in the plant.

- “PID Tuning Algorithm”

See Also

`pidtune`

Introduced in R2010b

pidTuner

Open PID Tuner for PID tuning

Syntax

```
pidTuner(sys,type)
pidTuner(sys,Cbase)
pidTuner(sys)
pidTuner
```

Description

`pidTuner(sys,type)` launches the PID Tuner GUI and designs a controller of type type for plant sys.

`pidTuner(sys,Cbase)` launches the GUI with a baseline controller Cbase so that you can compare performance between the designed controller and the baseline controller. If Cbase is a `pid` or `pidstd` controller object, the PID Tuner designs a controller of the same form, type, and discrete integrator formulas as Cbase.

`pidTuner(sys)` designs a parallel-form PI controller.

`pidTuner` launches the GUI with default plant of 1 and proportional (P) controller of 1.

Input Arguments

sys

Plant model for controller design. sys can be:

- Any SISO LTI system (such as `ss`, `tf`, `zpk`, or `frd`).
- Any System Identification Toolbox SISO linear model (`idtf`, `idfrd`, `idgrey`, `idpoly`, `idproc`, or `idss`.
- A continuous- or discrete-time model.

- Stable, unstable, or integrating. However, you might not be able to stabilize a plant with unstable poles under PID control.
- A model that includes any type of time delay. A plant with long time delays, however, might not achieve adequate performance under PID control.

If the plant has unstable poles, and sys is either:

- A `frd` model
- A `ss` model with internal time delays that cannot be converted to I/O delays

then you must specify the number of unstable poles in the plant. To do this, After launching the PID Tuner GUI, click the  button to open the **Import Linear System** dialog box. In that dialog box, you can reimport sys, specifying the number of unstable poles where prompted.

`type`

Controller type (actions) of the controller you are designing, specified as one of the following strings:

String	Type	Continuous-Time Controller Formula (parallel form)	Discrete-Time Controller Formula (parallel form, `ForwardEuler` integration method)
`'p'`	proportional only	K_p	K_p
`'i'`	integral only	$\frac{K_i}{s}$	$K_i \frac{T_s}{z-1}$
`'pi'`	proportional and integral	$K_p + \frac{K_i}{s}$	$K_p + K_i \frac{T_s}{z-1}$
`'pd'`	proportional and derivative	$K_p + K_d s$	$K_p + K_d \frac{z-1}{T_s}$
`'pdf'`	proportional and derivative with	$K_p + \frac{K_d s}{T_f s + 1}$	$K_p + K_d \frac{1}{T_f + \frac{T_s}{z-1}}$

String	Type	Continuous-Time Controller Formula (parallel form)	Discrete-Time Controller Formula (parallel form, `ForwardEuler` integration method)
	first-order filter on derivative term		
`'pid'`	proportional, integral, and derivative	$K_p + \frac{K_i}{s} + K_d s$	$K_p + K_i \frac{T_s}{z-1} + K_d \frac{z-1}{T_s}$
`'pidf'`	proportional, integral, and derivative with first-order filter on derivative term	$K_p + \frac{K_i}{s} + \frac{K_d s}{T_f s + 1}$	$K_p + K_i \frac{T_s}{z-1} + K_d \frac{1}{T_f + \frac{T_s}{z-1}}$

When you use the type input, the PID Tuner designs a controller in parallel form. If you want to design a controller in standard form, Use the input Cbase instead of type, or select `Standard` from the **Form** menu. For more information about parallel and standard forms, see the `pid` and `pidstd` reference pages.

If sys is a discrete-time model with sample time `Ts`, the PID Tuner designs a discrete-time `pid` controller using the `ForwardEuler` discrete integrator formula. If you want to design a controller having a different discrete integrator formula, use the input Cbase instead of type or the **Preferences** dialog box. For more information about discrete integrator formulas, see the `pid` and `pidstd` reference pages.

`Cbase`

A dynamic system representing a baseline controller, permitting comparison of the performance of the designed controller to the performance of Cbase.

If Cbase is a `pid` or `pidstd` object, the PID Tuner also uses it to configure the type, form, and discrete integrator formulas of the designed controller. The designed controller:

- Is the type represented by Cbase.
- Is a parallel-form controller, if Cbase is a `pid` controller object.
- Is a standard-form controller, if Cbase is a `pidstd` controller object.
- Has the same `Iformula` and `Dformula` values as Cbase. For more information about `Iformula` and `Dformula`, see the `pid` and `pidstd` reference pages .

If Cbase is any other dynamic system, the PID Tuner designs a parallel-form PI controller. You can change the controller form and type using the **Form** and **Type** menus after launching the PID Tuner.

Examples

Interactive PID Tuning of Parallel-Form Controller

Launch the PID Tuner to design a parallel-form PIDF controller for a discrete-time plant:

```
Gc = zpk([],[-1 -1 -1],1);
Gd = c2d(Gc,0.1);           % Create discrete-time plant

pidTuner(Gd,'pidf')          % Launch PID Tuner
```

Interactive PID Tuning of Standard-Form Controller Using Integrator Discretization Method

Design a standard-form PIDF controller using `BackwardEuler` discrete integrator formula:

```
Gc = zpk([],[-1 -1 -1],1);
Gd = c2d(Gc,0.1);           % Create discrete-time plant


% Create baseline controller.
Cbase = pidstd(1,2,3,4,'Ts',0.1,...
      'IFormula','BackwardEuler','DFormula','BackwardEuler')

pidTuner(Gd,Cbase)          % Launch PID Tuner
```

The PID Tuner designs a controller for `Gd` having the same form, type, and discrete integrator formulas as `Cbase`. For comparison, you can display the response plots of `Cbase` with the response plots of the designed controller by clicking the **Show baseline** checkbox on the PID Tuner GUI.

Alternatives

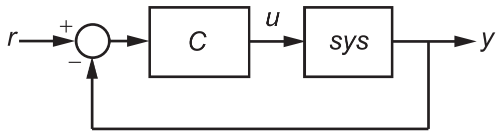
You can open PID Tuner from the MATLAB desktop, in the **Apps** tab. When you do so, use the **Plant** menu in PID Tuner to specify your plant model.

For PID tuning at the command line, use `pidtune`. The `pidtune` command can design a controller for multiple plants at once.

More About

Tips

- The PID Tuner designs a controller in the feedforward path of a single control loop with unit feedback:



- The PID Tuner has a default target phase margin of 60 degrees and automatically tunes the PID gains to balance performance (response time) and robustness (stability margins). Use the **Response time** or **Bandwidth** and **Phase Margin** sliders to tune the controller's performance to your requirements. Increasing performance typically decreases robustness, and vice versa.
- Select response plots from the **Response** menu to analyze the controller's performance.
- If you provide Cbase, check **Show baseline** to display the response of the baseline controller.
- For more detailed information about using the PID Tuner, see "Designing PID Controllers with the PID Tuner".

Algorithms

Typical PID tuning objectives include:

- Closed-loop stability — The closed-loop system output remains bounded for bounded input.
- Adequate performance — The closed-loop system tracks reference changes and suppresses disturbances as rapidly as possible. The larger the loop bandwidth (the first frequency at which the open-loop gain is unity), the faster the controller responds to changes in the reference or disturbances in the loop.
- Adequate robustness — The loop design has enough phase margin and gain margin to allow for modeling errors or variations in system dynamics.

The MathWorks algorithm for tuning PID controllers helps you meet these objectives by automatically tuning the PID gains to balance performance (response time) and robustness (stability margins).

By default, the algorithm chooses a crossover frequency (loop bandwidth) based upon the plant dynamics, and designs for a target phase margin of 60°. If you change the bandwidth or phase margin using the sliders in the PID Tuner GUI, the algorithm computes PID gains that best meet those targets.

- "Designing PID Controllers with the PID Tuner"

References

Åström, K. J. and Hägglund, T. *Advanced PID Control*, Research Triangle Park, NC: Instrumentation, Systems, and Automation Society, 2006.

See Also

`pid` | `pidstd` | `pidtune`

place

Pole placement design

Syntax

```
K = place(A,B,p)
[K,prec,message] = place(A,B,p)
```

Description

Given the single- or multi-input system

$$\dot{x} = Ax + Bu$$

and a vector `p` of desired self-conjugate closed-loop pole locations, `place` computes a gain matrix `K` such that the state feedback $u = -Kx$ places the closed-loop poles at the locations `p`. In other words, the eigenvalues of $A - BK$ match the entries of `p` (up to the ordering).

`K = place(A,B,p)` places the desired closed-loop poles `p` by computing a state-feedback gain matrix `K`. All the inputs of the plant are assumed to be control inputs. The length of `p` must match the row size of `A`. `place` works for multi-input systems and is based on the algorithm from [1]. This algorithm uses the extra degrees of freedom to find a solution that minimizes the sensitivity of the closed-loop poles to perturbations in A or B.

`[K,prec,message] = place(A,B,p)` returns `prec`, an estimate of how closely the eigenvalues of $A - BK$ match the specified locations `p` (`prec` measures the number of accurate decimal digits in the actual closed-loop poles). If some nonzero closed-loop pole is more than 10% off from the desired location, `message` contains a warning message.

You can also use `place` for estimator gain selection by transposing the `A` matrix and substituting `C'` for `B`.

```
l = place(A',C',p).'
```

Examples

Pole Placement Design

Consider a state-space system `(a,b,c,d)` with two inputs, three outputs, and three states. You can compute the feedback gain matrix needed to place the closed-loop poles at `p = [-1 -1.23 -5.0]` by

```
p = [-1 -1.23 -5.0];
K = place(a,b,p)
```

More About

Algorithms

`place` uses the algorithm of [1] which, for multi-input systems, optimizes the choice of eigenvectors for a robust solution.

In high-order problems, some choices of pole locations result in very large gains. The sensitivity problems attached with large gains suggest caution in the use of pole placement techniques. See [2] for results from numerical testing.

References

[1] Kautsky, J., N.K. Nichols, and P. Van Dooren, "Robust Pole Assignment in Linear State Feedback," *International Journal of Control,* 41 (1985), pp. 1129-1155.

[2] Laub, A.J. and M. Wette, *Algorithms and Software for Pole Assignment and Observers*, UCRL-15646 Rev. 1, EE Dept., Univ. of Calif., Santa Barbara, CA, Sept. 1984.

See Also

`lqr` | `rlocus`

pole

Compute poles of dynamic system

Syntax

```
pole(sys)
```

Description

`pole(sys)` computes the poles `p` of the SISO or MIMO dynamic system model `sys`.

If `sys` has internal delays, poles are obtained by first setting all internal delays to zero (creating a zero-order Padé approximation) so that the system has a finite number of zeros. For some systems, setting delays to 0 creates singular algebraic loops, which result in either improper or ill-defined, zero-delay approximations. For these systems, `pole` returns an error. This error does not imply a problem with the model `sys` itself.

Limitations

Multiple poles are numerically sensitive and cannot be computed to high accuracy. A pole λ with multiplicity m typically gives rise to a cluster of computed poles distributed on a circle with center λ and radius of order

$$\rho \approx \varepsilon^{1/m}$$

where ε is the relative machine precision (`eps`).

More About

Algorithms

For state-space models, the poles are the eigenvalues of the A matrix, or the generalized eigenvalues of $A - \lambda E$ in the descriptor case.

For SISO transfer functions or zero-pole-gain models, the poles are simply the denominator roots (see `roots`).

For MIMO transfer functions (or zero-pole-gain models), the poles are computed as the union of the poles for each SISO entry. If some columns or rows have a common denominator, the roots of this denominator are counted only once.

See Also

`pzmap` | `zero` | `damp` | `esort` | `dsort`

prescale

Optimal scaling of state-space models

Syntax

```
scaledsys = prescale(sys)
scaledsys = prescale(sys,focus)
[scaledsys,info] = prescale(...)
prescale(sys)
```

Description

`scaledsys = prescale(sys)` scales the entries of the state vector of a state-space model `sys` to maximize the accuracy of subsequent frequency-domain analysis. The scaled model `scaledsys` is equivalent to `sys`.

`scaledsys = prescale(sys,focus)` specifies a frequency interval `focus` = {`fmin`,`fmax`} (in `rad/TimeUnit`, where `TimeUnit` is the system's time units specified in the TimeUnit property of `sys`) over which to maximize accuracy. This is useful when `sys` has a combination of slow and fast dynamics and scaling cannot achieve high accuracy over the entire dynamic range. By default, `prescale` attempts to maximize accuracy in the frequency band with dominant dynamics.

`[scaledsys,info] = prescale(...)` also returns a structure `info` with the fields shown in the following table.

`SL`	Left scaling factors
`SR`	Right scaling factors
`Freqs`	Frequencies used to test accuracy
`RelAcc`	Guaranteed relative accuracy at these frequencies

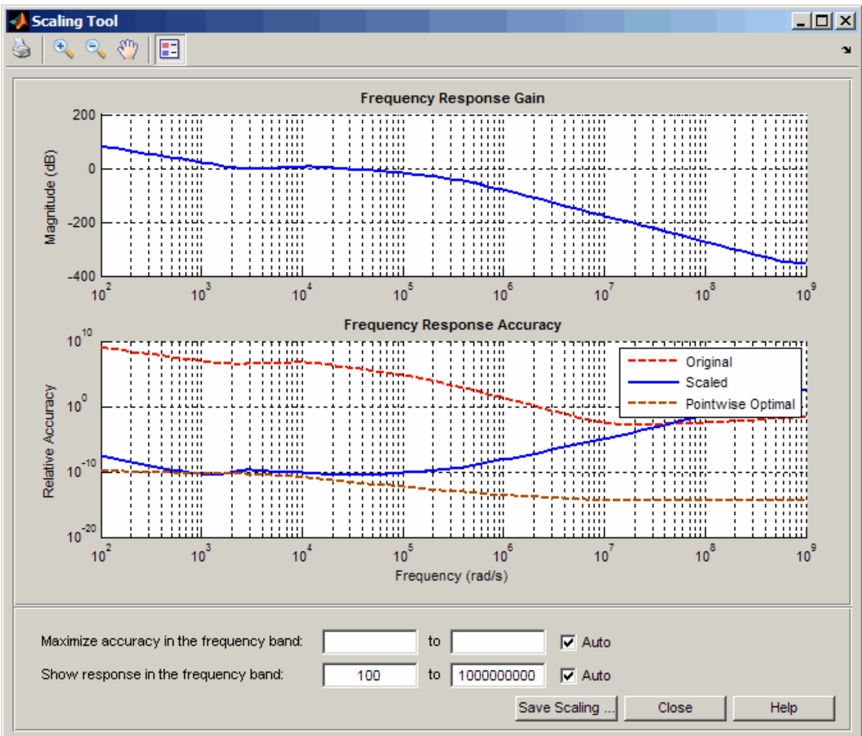
The test frequencies lie in the frequency interval `focus` when specified. The scaled state-space matrices are

$$A_s = T_L A T_R$$
$$B_s = T_L B$$
$$C_s = C T_R$$
$$E_s = T_L E T_R$$

where $T_L = diag(SL)$ and $T_R = diag(SR)$. T_L and T_R are inverse of each other for explicit models (E = [ ]).

`prescale(sys)` opens an interactive GUI for:

- Visualizing accuracy trade-offs for `sys`.
- Adjusting the frequency interval where the accuracy of `sys` is maximized.



For more information on scaling and using the Scaling Tool GUI, see “Scaling State-Space Models”.

More About

Tips

Most frequency-domain analysis commands perform automatic scaling equivalent to `scaledsys = prescale(sys)`.

You do not need to scale for time-domain simulations and doing so may invalidate the initial condition `x0` used in `initial` and `lsim` simulations.

See Also

`ss`

pzmap

Pole-zero plot of dynamic system

Syntax

```
pzmap(sys)
pzmap(sys1,sys2,...,sysN)
[p,z] = pzmap(sys)
```

Description

`pzmap(sys)` creates a pole-zero plot of the continuous- or discrete-time dynamic system model sys. For SISO systems, `pzmap` plots the transfer function poles and zeros. For MIMO systems, it plots the system poles and transmission zeros. The poles are plotted as `x`'s and the zeros are plotted as `o`'s.

`pzmap(sys1,sys2,...,sysN)` creates the pole-zero plot of multiple models on a single figure. The models can have different numbers of inputs and outputs and can be a mix of continuous and discrete systems.

`[p,z] = pzmap(sys)` returns the system poles and (transmission) zeros in the column vectors `p` and `z`. No plot is drawn on the screen.

You can use the functions `sgrid` or `zgrid` to plot lines of constant damping ratio and natural frequency in the *s*- or *z*-plane.

Examples

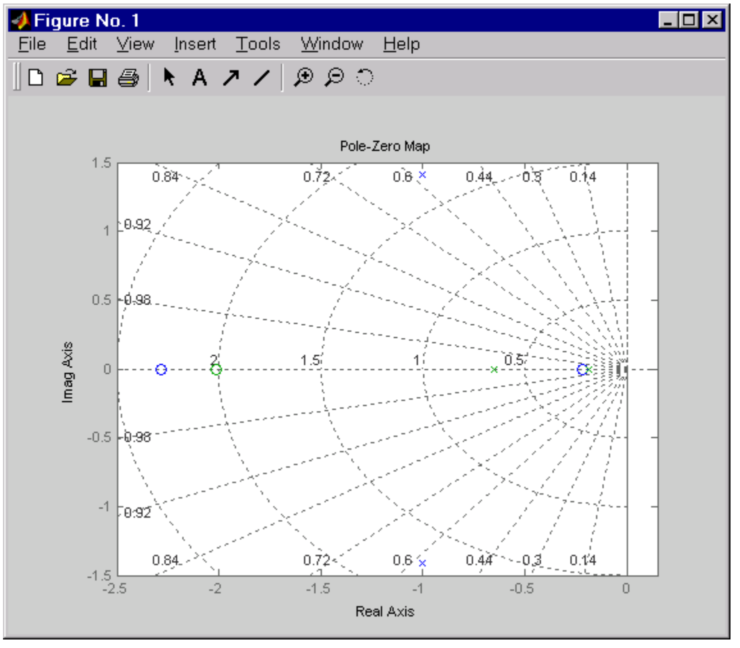
Example 1

Pole-Zero Plot of Dynamic System

Plot the poles and zeros of the continuous-time system

$$H(s) = \frac{2s^2 + 5s + 1}{s^2 + 2s + 3}$$

```
H = tf([2 5 1],[1 2 3]); sgrid
pzmap(H)
grid on
```



Example 2

Plot the `pzmap` for a 2-input-output discrete-time IDSS model.

```
A = [0.1 0; 0.2 0.9]; B = [.1 .2; 0.1 .02]; C = [10 20; 2 -5]; D = [1 2; 0 1];
sys = idss(A,B,C,D, 'Ts', 0.1);
```

More About

Tips

You can change the properties of your plot, for example the units. For information on the ways to change properties of your plots, see “Ways to Customize Plots”.

Algorithms

`pzmap` uses a combination of `pole` and `zero`.

See Also

`pole` | `sgrid` | `zgrid` | `zero` | `iopzmap` | `damp` | `esort` | `dsort` | `rlocus`

pzplot

Pole-zero map of dynamic system model with plot customization options

Syntax

```
h = pzplot(sys)
pzplot(sys1,sys2,...)
pzplot(AX,...)
pzplot(..., plotoptions)
```

Description

`h = pzplot(sys)` computes the poles and (transmission) zeros of the dynamic system model `sys` and plots them in the complex plane. The poles are plotted as x's and the zeros are plotted as o's. It also returns the plot handle `h`. You can use this handle to customize the plot with the `getoptions` and `setoptions` commands. Type

```
help pzoptions
```

for a list of available plot options.

`pzplot(sys1,sys2,...)` shows the poles and zeros of multiple models `sys1`,`sys2`,... on a single plot. You can specify distinctive colors for each model, as in

```
pzplot(sys1,'r',sys2,'y',sys3,'g')
```

`pzplot(AX,...)` plots into the axes with handle `AX`.

`pzplot(..., plotoptions)` plots the poles and zeros with the options specified in `plotoptions`. Type

```
help pzoptions
```

for more detail.

The function `sgrid` or `zgrid` can be used to plot lines of constant damping ratio and natural frequency in the *s*- or *z*-plane.

For arrays `sys` of dynamic system models, `pzmap` plots the poles and zeros of each model in the array on the same diagram.

Examples

Use the plot handle to change the color of the plot's title.

```
sys = rss(3,2,2);
h = pzplot(sys);
p = getoptions(h); % Get options for plot.
p.Title.Color = [1,0,0]; % Change title color in options.
setoptions(h,p); % Apply options to plot.
```

More About

Tips

You can change the properties of your plot, for example the units. For information on the ways to change properties of your plots, see “Ways to Customize Plots”.

See Also

`pzmap` | `setoptions` | `iopzplot` | `getoptions`

pzoptions

Create list of pole/zero plot options

Syntax

```
P = pzoptions
P = pzoption('cstprefs')
```

Description

`P = pzoptions` returns a list of available options for pole/zero plots (pole/zero, input-output pole/zero and root locus) with default values set.. You can use these options to customize the pole/zero plot appearance from the command line.

`P = pzoption('cstprefs')` initializes the plot options with the options you selected in the Control System and System Identification Toolbox Preferences Editor. For more information about the editor, see "Toolbox Preferences Editor" in the User's Guide documentation.

This table summarizes the available pole/zero plot options.

Option	Description
Title, XLabel, YLabel	Label text and style
TickLabel	Tick label style
Grid	Show or hide the grid Specified as one of the following strings: `'off' | 'on'` **Default**: `'off'`
XlimMode, YlimMode	Limit modes
Xlim, Ylim	Axes limits
IOGrouping	Grouping of input-output pairs Specified as one of the following strings: `'none' |'inputs'|'outputs'|'all'` **Default**: `'none'`
InputLabels, OutputLabels	Input and output label styles

Option	Description
InputVisible, OutputVisible	Visibility of input and output channels

Option	Description
FreqUnits	Frequency units, specified as one of the following strings: • `'Hz'` • `'rad/second'` • `'rpm'` • `'kHz'` • `'MHz'` • `'GHz'` • `'rad/nanosecond'` • `'rad/microsecond'` • `'rad/millisecond'` • `'rad/minute'` • `'rad/hour'` • `'rad/day'` • `'rad/week'` • `'rad/month'` • `'rad/year'` • `'cycles/nanosecond'` • `'cycles/microsecond'` • `'cycles/millisecond'` • `'cycles/hour'` • `'cycles/day'` • `'cycles/week'` • `'cycles/month'` • `'cycles/year'` **Default**: `'rad/s'` You can also specify `'auto'` which uses frequency units `rad/TimeUnit` relative

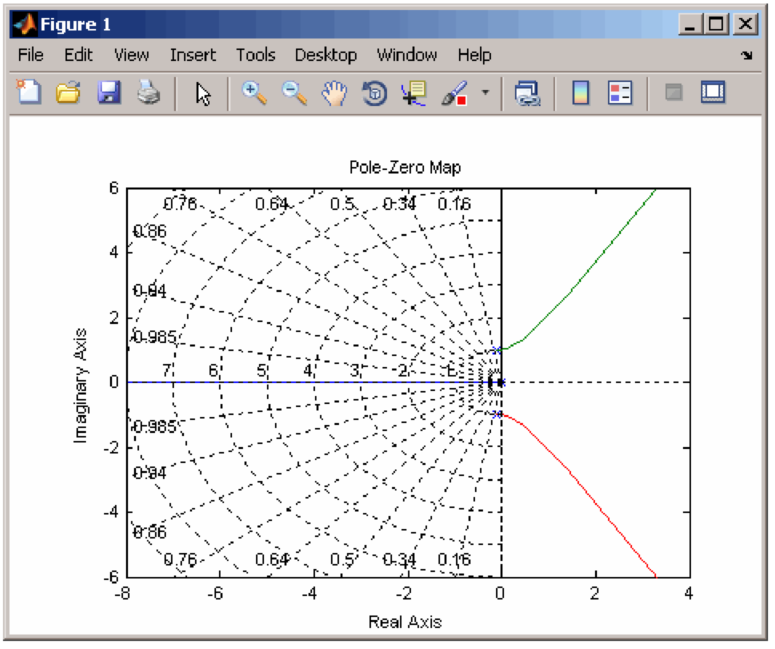
Option	Description
	to system time units specified in the `TimeUnit` property. For multiple systems with different time units, the units of the first system are used.
TimeUnits	Time units, specified as one of the following strings: • `'nanoseconds'` • `'microseconds'` • `'milliseconds'` • `'seconds'` • `'minutes'` • `'hours'` • `'days'` • `'weeks'` • `'months'` • `'years'` **Default**: `'seconds'` You can also specify `'auto'` which uses time units specified in the `TimeUnit` property of the input system. For multiple systems with different time units, the units of the first system is used.
ConfidenceRegionNumberSD	Number of standard deviations to use when displaying the confidence region characteristic for identified models (valid only `iopzplot`).

Examples

In this example, you enable the grid option before creating a plot.

```
P = pzoptions; % Create set of plot options P
P.Grid = 'on'; % Set the grid to on in options
h = rlocusplot(tf(1,[1,.2,1,0]),P);
```

The following root locus plot is created with the grid enabled.



See Also

iopzplot | pzplot | setoptions | getoptions

realp

Real tunable parameter

Syntax

```
p = realp(paramname,initvalue)
```

Description

`p = realp(paramname,initvalue)` creates a tunable real-valued parameter with name specified by the string paramname and initial value initvalue. Tunable real parameters can be scalar- or matrix- valued.

Input Arguments

`paramname`

String specifying the name of the `realp` parameter p. This input argument sets the value of the `Name` property of p.

`initvalue`

Initial numeric value of the parameter p. initvalue can be a real scalar value or a 2-dimensional matrix.

Output Arguments

`p`

`realp` parameter object.

Properties

Name

String containing the name of the `realp` parameter object. The value of `Name` is set by the paramname input argument to `realp` and cannot be changed.

Value

Value of the tunable parameter.

`Value` can be a real scalar value or a 2-dimensional matrix. The initial value is set by the initvalue input argument. The dimensions of `Value` are fixed on creation of the `realp` object.

Minimum

Lower bound for the parameter value. The dimension of the `Minimum` property matches the dimension of the `Value` property.

For matrix-valued parameters, use indexing to specify lower bounds on individual elements:

```
p = realp('K',eye(2));
p.Minimum([1 4]) = -5;
```

Use scalar expansion to set the same lower bound for all matrix elements:

```
p.Minimum = -5;
```

Default: `-Inf` for all entries

Maximum

Upper bound for the parameter value. The dimension of the `Maximum` property matches the dimension of the `Value` property.

For matrix-valued parameters, use indexing to specify upper bounds on individual elements:

```
p = realp('K',eye(2));
p.Maximum([1 4]) = 5;
```

Use scalar expansion to set the same upper bound for all matrix elements:

```
p.Maximum = 5;
```

Default: `Inf` for all entries

`Free`

Boolean value specifying whether the parameter is free to be tuned. Set the `Free` property to 1 (`true`) for tunable parameters, and 0 (`false`) for fixed parameters.

The dimension of the `Free` property matches the dimension of the `Value` property.

Default: 1 (`true`) for all entries

Examples

Tunable Low-Pass Filter

This example shows how to create the low-pass filter $F = a/(s + a)$ with one tunable parameter a.

You cannot use `ltiblock.tf` to represent F, because the numerator and denominator coefficients of an `ltiblock.tf` block are independent. Instead, construct F using the tunable real parameter object `realp`.

1. Create a tunable real parameter.

   ```
   a = realp('a',10);
   ```

   The `realp` object `a` is a tunable parameter with initial value 10.
2. Use `tf` to create the tunable filter `F`:

   ```
   F = tf(a,[1 a]);
   ```

`F` is a `genss` object which has the tunable parameter `a` in its `Blocks` property. You can connect `F` with other tunable or numeric models to create more complex models of control systems. For an example, see "Control System with Tunable Components".

Parametric Diagonal Matrix

This example shows how to create a parametric matrix whose off-diagonal terms are fixed to zero, and whose diagonal terms are tunable parameters.

1 Create a parametric matrix whose initial value is the identity matrix.

```
p = realp('P',eye(2));
```

`p` is a 2-by-2 parametric matrix. Because the initial value is the identity matrix, the off-diagonal initial values are zero.

2 Fix the values of the off-diagonal elements by setting the `Free` property to `false`.

```
p.Free(1,2) = false;
p.Free(2,1) = false;
```

More About

Tips

- Use arithmetic operators (`+`, `-`, `*`, `/`, `\`, and `^`) to combine `realp` objects into rational expressions or matrix expressions. You can use the resulting expressions in model-creation functions such as `tf`, `zpk`, and `ss` to create tunable models. For more information about tunable models, see “Models with Tunable Coefficients” in the *Control System Toolbox User's Guide*.

- “Models with Tunable Coefficients”

See Also

`genss` | `genmat` | `tf` | `ss`

reg

Form regulator given state-feedback and estimator gains

Syntax

```
rsys = reg(sys,K,L)
rsys = reg(sys,K,L,sensors,known,controls)
```

Description

`rsys = reg(sys,K,L)` forms a dynamic regulator or compensator `rsys` given a state-space model `sys` of the plant, a state-feedback gain matrix `K`, and an estimator gain matrix `L`. The gains `K` and `L` are typically designed using pole placement or LQG techniques. The function `reg` handles both continuous- and discrete-time cases.

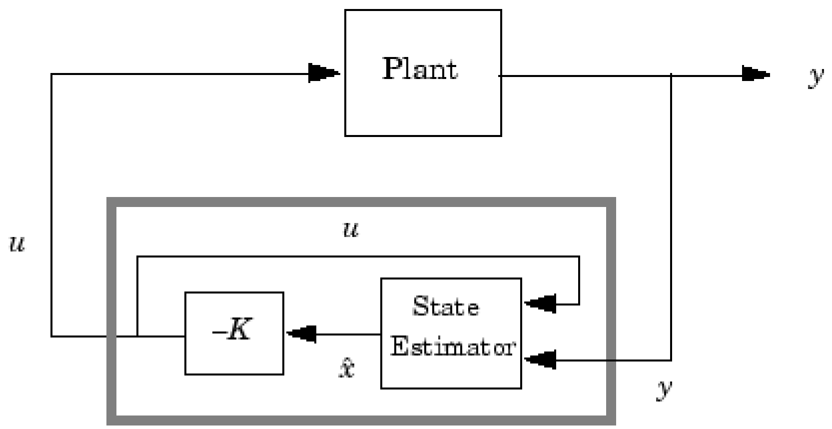
This syntax assumes that all inputs of `sys` are controls, and all outputs are measured. The regulator `rsys` is obtained by connecting the state-feedback law $u = -Kx$ and the state estimator with gain matrix `L` (see `estim`). For a plant with equations

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx + Du \end{aligned}$$

this yields the regulator

$$\begin{aligned} \dot{\hat{x}} &= [A - LC - (B - LD)K]\hat{x} + Ly \\ u &= -K\hat{x} \end{aligned}$$

This regulator should be connected to the plant using *positive* feedback.

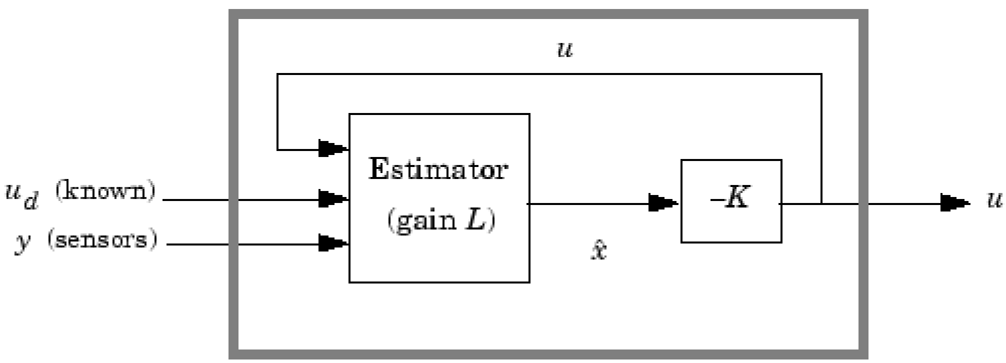


Regulator

`rsys = reg(sys,K,L,sensors,known,controls)` handles more general regulation problems where:

- The plant inputs consist of controls u, known inputs u_d, and stochastic inputs w.
- Only a subset y of the plant outputs is measured.

The index vectors `sensors`, `known`, and `controls` specify y, u_d, and u as subsets of the outputs and inputs of `sys`. The resulting regulator uses $[u_d\ ;\ y]$ as inputs to generate the commands u (see next figure).



Regulator `rsys`

Examples

Given a continuous-time state-space model

```
sys = ss(A,B,C,D)
```

with seven outputs and four inputs, suppose you have designed:

- A state-feedback controller gain `K` using inputs 1, 2, and 4 of the plant as control inputs
- A state estimator with gain `L` using outputs 4, 7, and 1 of the plant as sensors, and input 3 of the plant as an additional known input

You can then connect the controller and estimator and form the complete regulation system by

```
controls = [1,2,4];
sensors = [4,7,1];
known = [3];
regulator = reg(sys,K,L,sensors,known,controls)
```

See Also

`estim` | `kalman` | `lqr` | `dlqr` | `place` | `lqgreg`

replaceBlock

Replace or update Control Design Blocks in Generalized LTI model

Syntax

```
Mnew = replaceBlock(M,Block1,Value1,...,BlockN,ValueN)
Mnew = replaceBlock(M,blockvalues)
Mnew = replaceBlock(...,mode)
```

Description

`Mnew = replaceBlock(M,Block1,Value1,...,BlockN,ValueN)` replaces the Control Design Blocks Block1,...,BlockN of M with the specified values Value1,...,ValueN. M is a Generalized LTI model or a Generalized matrix.

`Mnew = replaceBlock(M,blockvalues)` specifies the block names and replacement values as field names and values of the structure blockvalues.

`Mnew = replaceBlock(...,mode)` performs block replacement on an array of models M using the substitution mode specified by the string mode.

Input Arguments

`M`

Generalized LTI model, Generalized matrix, or array of such models.

`Block1,...,BlockN`

Names of Control Design Blocks in M. The `replaceBlock` command replaces each listed block of M with the corresponding values Value1,...,ValueN that you supply.

If a specified `Block` is not a block of M, `replaceBlock` that block and the corresponding value.

`Value1,...,ValueN`

Replacement values for the corresponding blocks Block1,...,BlockN.

The replacement value for a block can be any value compatible with the size of the block, including a different Control Design Block, a numeric matrix, or an LTI model. If any value is `[]`, the corresponding block is replaced by its nominal (current) value.

`blockvalues`

Structure specifying blocks of M to replace and the values with which to replace those blocks.

The field names of blockvalues match names of Control Design Blocks of M. Use the field values to specify the replacement values for the corresponding blocks of M. The replacement values may be numeric values, Numeric LTI models, Control Design Blocks, or Generalized LTI models.

`mode`

String specifying the block replacement mode for an input array M of Generalized matrices or LTI models.

mode can take the following values:

- `'-once'` (default) — Vectorized block replacement across the model array M. Each block is replaced by a single value, but the value may change from model to model across the array.

  For vectorized block replacement, use a structure array for the input blockvalues, or cell arrays for the Value1,...,ValueN inputs. For example, if M is a 2-by-3 array of models:

  - `Mnew = replaceBlock(M,blockvalues,'-once')`, where blockvalues is a 2-by-3 structure array, specifies one set of block values `blockvalues(k)` for each model `M(:,:,k)` in the array.
  - `Mnew = replaceBlock(M,Block,Value,'-once')`, where `Value` is a 2-by-3 cell array, replaces `Block` by `Value{k}` in the model `M(:,:,k)` in the array.
- `'-batch'` — Batch block replacement. Each block is replaced by an array of values, and the same array of values is used for each model in M. The resulting array of model Mnew is of size `[size(M) Asize]`, where `Asize` is the size of the replacement value.

When the input M is a single model, `'-once'` and `'-batch'` return identical results.

Default: `'-once'`

Output Arguments

`Mnew`

Matrix or linear model or matrix where the specified blocks are replaced by the specified replacement values.

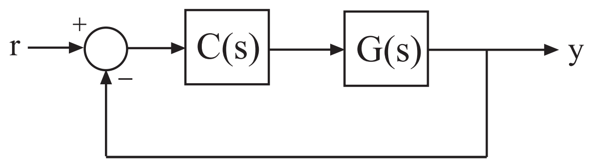
Mnew is a numeric array or numeric LTI model when all the specified replacement values are numeric values or numeric LTI models.

Examples

Replace Control Design Block with Numeric Values

This example shows how to replace a tunable PID controller (`ltiblock.pid`) in a Generalized LTI model by a pure gain, a numeric PI controller, or the current value of the tunable controller.

1 Create a Generalized LTI model of the following system:



where the plant $G(s)=\dfrac{(s-1)}{(s+1)^3}$, and C is a tunable PID controller.

```
G = zpk(1,[-1,-1,-1],1);
C = ltiblock.pid('C','pid');
Try = feedback(G*C,1)
```

2 Replace `C` by a pure gain of 5.

```
T1 = replaceBlock(Try,'C',5);
```

`T1` is a `ss` model that equals `feedback(G*5,1)`.

3 Replace `C` by a PI controller with proportional gain of 5 and integral gain of 0.1.

```
C2 = pid(5,0.1);
T2 = replaceBlock(Try,'C',C2);
```

`T2` is a `ss` model that equals `feedback(G*C2,1)`.

4 Replace `C` by its current (nominal) value.

```
T3 = replaceBlock(Try,'C',[]);
```

`T3` is a `ss` model where `C` has been replaced by `getValue(C)`.

Study Parameter Variation by Sampling Tunable Model

This example shows how to sample a parametric model of a second-order filter across a grid of parameter values using `replaceBlock`.

Consider the second-order filter represented by:

$$F(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}.$$

Sample this filter at varying values of the damping constant ζ and the natural frequency ω_n. Create a parametric model of the filter by using tunable elements for ζ and ω_n.

```
wn = realp('wn',3);
zeta = realp('zeta',0.8);
F = tf(wn^2,[1 2*zeta*wn wn^2])
```

```
F =

  Generalized continuous-time state-space model with 1 outputs, 1 inputs, 2 states, anc
    wn: Scalar parameter, 5 occurrences.
    zeta: Scalar parameter, 1 occurrences.

Type "ss(F)" to see the current value, "get(F)" to see all properties, and "F.Blocks" t
```

`F` is a `genss` model with two tunable Control Design Blocks, the `realp` blocks `wn` and `zeta`. The blocks `wn` and `zeta` have initial values of 3 and 0.8, respectively.

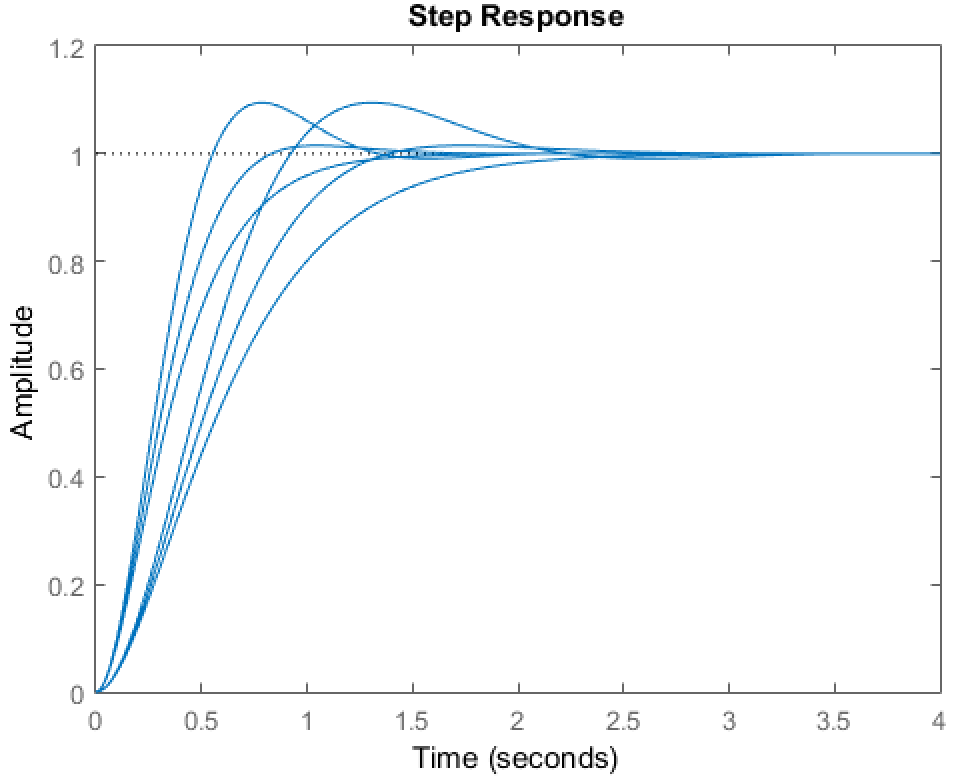
Sample `F` over a 2-by-3 grid of (`wn`, `zeta`) values.

```
wnvals = [3;5];
zetavals = [0.6 0.8 1.0];
Fsample = replaceBlock(F,'wn',wnvals,'zeta',zetavals);
```

`Fsample` is a 2-by-3 array of state-space models. Each entry in the array is a state-space model that represents `F` evaluated at the corresponding (`wn`, `zeta`) pair. For example, `Fsample(:,:,2,3)` has `wn` = 5 and `zeta` = 1.0.

Examine the step response of `Fsample`.

```
stepplot(Fsample)
```



The step response plots show the variation in the natural frequency and damping constant across the six models in the array `Fsample`.

You can set the `SamplingGrid` property of the model array to help keep track of which set of parameter values corresponds to which entry in the array. To do so, create a grid of parameter values that matches the dimensions of the array. Then, assign these values to `Fsample.SamplingGrid` with the parameter names.

```
[wngrid,zetagrid] = ndgrid(wnvals,zetavals);
Fsample.SamplingGrid = struct('wn',wngrid,'zeta',zetagrid);
```

When you display `Fsample`, the parameter values in `Fsample.SamplingGrid` are displayed along with the each transfer function in the array.

More About

Tips

- Use `replaceBlock` to perform parameter studies by sampling Generalized LTI models across a grid of parameters, or to evaluate tunable models for specific values of the tunable blocks. See “Examples” on page 1-627.

- “Generalized Matrices”
- “Generalized and Uncertain LTI Models”
- “Models with Tunable Coefficients”

See Also

`getValue` | `genss` | `genmat` | `nblocks`

repsys

Replicate and tile models

Syntax

```
rsys = repsys(sys,[M N])
rsys = repsys(sys,N)
rsys = repsys(sys,[M N S1,...,Sk])
```

Description

`rsys = repsys(sys,[M N])` replicates the model sys into an M-by-N tiling pattern. The resulting model rsys has `size(sys,1)*M` outputs and `size(sys,2)*N` inputs.

`rsys = repsys(sys,N)` creates an N-by-N tiling.

`rsys = repsys(sys,[M N S1,...,Sk])` replicates and tiles sys along both I/O and array dimensions to produce a model array. The indices S specify the array dimensions. The size of the array is `[size(sys,1)*M, size(sys,2)*N, size(sys,3)*S1, ...]`.

Input Arguments

`sys`

Model to replicate.

`M`

Number of replications of sys along the output dimension.

`N`

Number of replications of sys along the input dimension.

S

Numbers of replications of sys along array dimensions.

Output Arguments

rsys

Model having `size(sys,1)*M` outputs and `size(sys,2)*N` inputs.

If you provide array dimensions `S1,...,Sk`, rsys is an array of dynamic systems which each have `size(sys,1)*M` outputs and `size(sys,2)*N` inputs. The size of rsys is `[size(sys,1)*M, size(sys,2)*N, size(sys,3)*S1, ...]`.

Examples

Replicate a SISO transfer function to create a MIMO transfer function that has three inputs and two outputs.

```
sys = tf(2,[1 3]);
rsys = repsys(sys,[2 3]);
```

The preceding commands produce the same result as:

```
sys = tf(2,[1 3]);
rsys = [sys sys sys; sys sys sys];
```

Replicate a SISO transfer function into a 3-by-4 array of two-input, one-output transfer functions.

```
sys = tf(2,[1 3]);
rsys = repsys(sys, [1 2 3 4]);
```

To check the size of `rsys`, enter:

```
size(rsys)
```

This command produces the result:

```
3x4 array of transfer functions.
Each model has 1 outputs and 2 inputs.
```

More About

Tips

`rsys = repsys(sys,N)` produces the same result as `rsys = repsys(sys,[N N])`. To produce a diagonal tiling, use `rsys = sys*eye(N)`.

See Also

`append`

reshape

Change shape of model array

Syntax

```
sys = reshape(sys,s1,s2,...,sk)
sys = reshape(sys,[s1 s2 ... sk])
```

Description

`sys = reshape(sys,s1,s2,...,sk)` (or, equivalently, `sys = reshape(sys,[s1 s2 ... sk])`) reshapes the LTI array `sys` into an `s1`-by-`s2`-by-...-by-`sk` model array. With either syntax, there must be `s1*s2*...*sk` models in `sys` to begin with.

Examples

Change the shape of a model array from 2x3 to 6x1.

```
% Create a 2x3 model array.
sys = rss(4,1,1,2,3);
% Confirm the size of the array.
size(sys)
```

This input produces the following output:

```
2x3 array of state-space models
Each model has 1 output, 1 input, and 4 states.
```

Change the shape of the array.

```
sys1 = reshape(sys,6,1);
size(sys1)
```

This input produces the following output:

```
6x1 array of state-space models
Each model has 1 output, 1 input, and 4 states.
```

See Also

`size` | `ndims`

rlocus

Root locus plot of dynamic system

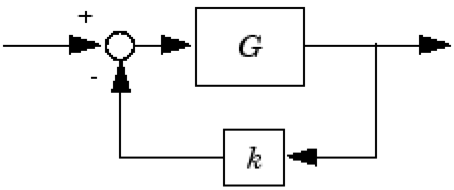
Syntax

```
rlocus(sys)
rlocus(sys1,sys2,...)
[r,k] = rlocus(sys)
r = rlocus(sys,k)
```

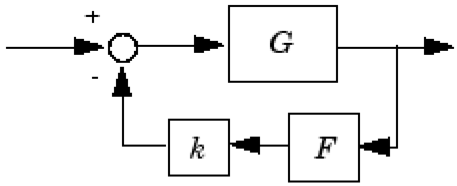
Description

`rlocus` computes the root locus of a SISO open-loop model. The root locus gives the closed-loop pole trajectories as a function of the feedback gain *k* (assuming negative feedback). Root loci are used to study the effects of varying feedback gains on closed-loop pole locations. In turn, these locations provide indirect information on the time and frequency responses.

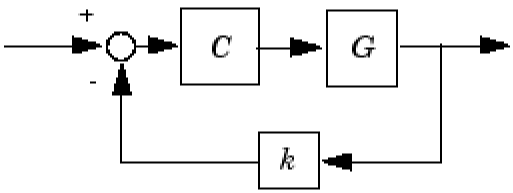
`rlocus(sys)` calculates and plots the root locus of the open-loop SISO model `sys`. This function can be applied to any of the following *negative* feedback loops by setting `sys` appropriately.



sys = G



sys = F * G



sys = G * C

If `sys` has transfer function

$$h(s) = \frac{n(s)}{d(s)}$$

the closed-loop poles are the roots of

$$d(s) + kn(s) = 0$$

`rlocus` adaptively selects a set of positive gains k to produce a smooth plot. Alternatively,

```
rlocus(sys,k)
```

uses the user-specified vector `k` of gains to plot the root locus.

`rlocus(sys1,sys2,...)` draws the root loci of multiple LTI models `sys1, sys2,...` on a single plot. You can specify a color, line style, and marker for each model, as in

```
rlocus(sys1,'r',sys2,'y:',sys3,'gx').
```

`[r,k] = rlocus(sys)` and `r = rlocus(sys,k)` return the vector `k` of selected gains and the complex root locations `r` for these gains. The matrix `r` has `length(k)` columns and its `j`th column lists the closed-loop roots for the gain `k(j)`.

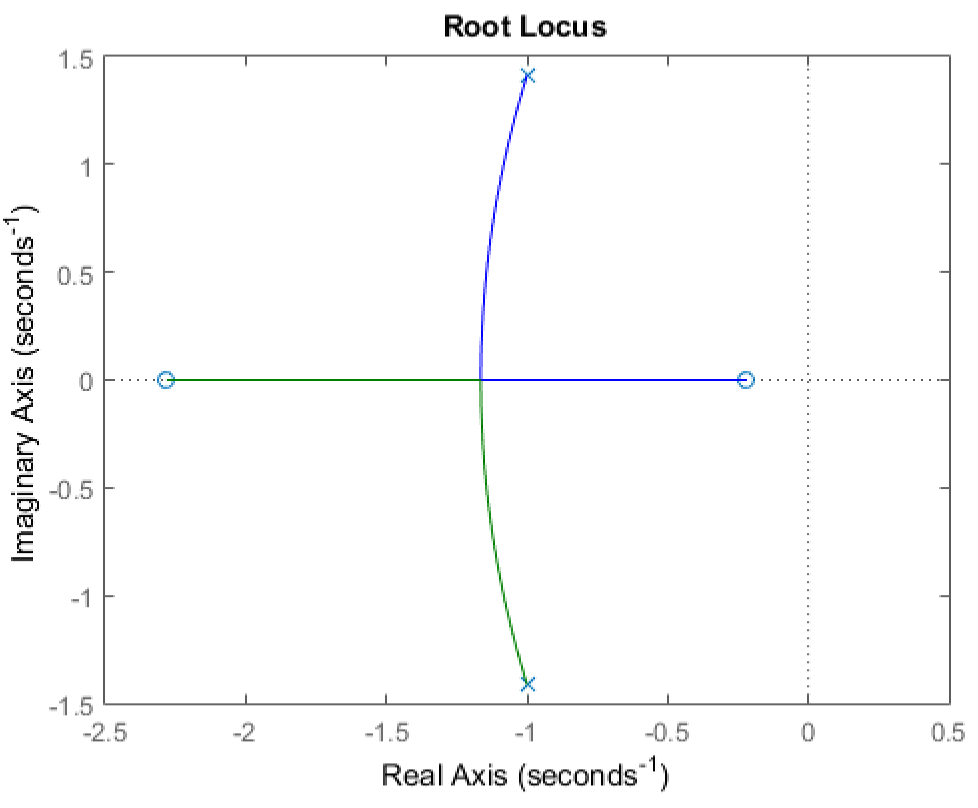
Examples

Root Locus Plot of Dynamic System

Plot the root-locus of the following system.

$$h(s) = \frac{2s^2 + 5s + 1}{s^2 + 2s + 3}.$$

```
h = tf([2 5 1],[1 2 3]);
rlocus(h)
```



You can use the right-click menu for rlocus to add grid lines, zoom in or out, and invoke the Property Editor to customize the plot. Also, click anywhere on the curve to activate a data marker that displays the gain value, pole, damping, overshoot, and frequency at the selected point.

More About

Tips

You can change the properties of your plot, for example the units. For information on the ways to change properties of your plots, see “Ways to Customize Plots”.

See Also

`pole` | `pzmap`

rlocusplot

Plot root locus and return plot handle

Syntax

```
h = rlocusplot(sys)
rlocusplot(sys,k)
rlocusplot(sys1,sys2,...)
rlocusplot(AX,...)
rlocusplot(..., plotoptions)
```

Description

`h = rlocusplot(sys)` computes and plots the root locus of the single-input, single-output LTI model `sys`. It also returns the plot handle `h`. You can use this handle to customize the plot with the `getoptions` and `setoptions` commands. Type

```
help pzoptions
```

for a list of available plot options.

See `rlocus` for a discussion of the feedback structure and algorithms used to calculate the root locus.

`rlocusplot(sys,k)` uses a user-specified vector `k` of gain values.

`rlocusplot(sys1,sys2,...)` draws the root loci of multiple LTI models `sys1`, `sys2`,... on a single plot. You can specify a color, line style, and marker for each model, as in

```
rlocusplot(sys1,'r',sys2,'y:',sys3,'gx')
```

`rlocusplot(AX,...)` plots into the axes with handle `AX`.

`rlocusplot(..., plotoptions)` plots the root locus with the options specified in `plotoptions`. Type

```
help pzoptions
```

for more details.

Examples

Use the plot handle to change the title of the plot.

```
sys = rss(3);
h = rlocusplot(sys);
p = getoptions(h); % Get options for plot.
p.Title.String = 'My Title'; % Change title in options.
setoptions(h,p); % Apply options to plot.
```

More About

Tips

You can change the properties of your plot, for example the units. For information on the ways to change properties of your plots, see “Ways to Customize Plots”.

See Also

getoptions | rlocus | pzoptions | setoptions

rss

Generate random continuous test model

Syntax

```
rss(n)
rss(n,p)
rss(n,p,m,s1,...,sn)
```

Description

`rss(n)` generates an `n`-th order model with one input and one output and returns the model in the state-space object `sys`. The poles of `sys` are random and stable with the possible exception of poles at `s = 0` (integrators).

`rss(n,p)` generates an `n`th order model with one input and `p` outputs, and `rss(n,p,m)` generates an `n`-th order model with `m` inputs and `p` outputs. The output `sys` is always a state-space model.

`rss(n,p,m,s1,...,sn)` generates an s1-by-...-by-sn array of n-th order state-space models with `m` inputs and `p` outputs.

Use `tf`, `frd`, or `zpk` to convert the state-space object `sys` to transfer function, frequency response, or zero-pole-gain form.

Examples

Obtain a random continuous LTI model with three states, two inputs, and two outputs by typing

```
sys = rss(3,2,2)
a =
                        x1          x2          x3
             x1   -0.54175     0.09729     0.08304
             x2    0.09729    -0.89491     0.58707
             x3    0.08304     0.58707    -1.95271
```

```
b =
                    u1           u2
           x1   -0.88844     -2.41459
           x2          0     -0.69435
           x3   -0.07162     -1.39139

c =
                    x1           x2           x3
           y1    0.32965      0.14718            0
           y2    0.59854     -0.10144      0.02805


d =
                    u1           u2
           y1   -0.87631     -0.32758
           y2          0            0

Continuous-time system.
```

See Also

drss | frd | tf | zpk

series

Series connection of two models

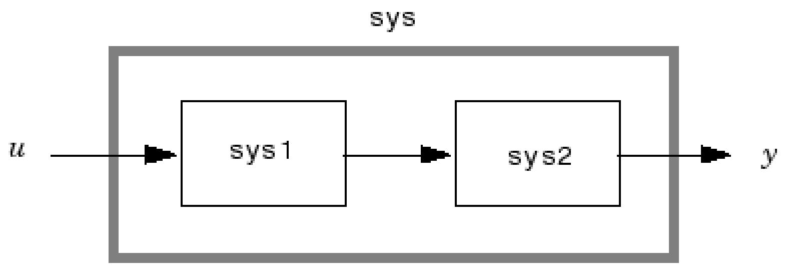
Syntax

```
series
sys = series(sys1,sys2)
sys = series(sys1,sys2,outputs1,inputs2)
```

Description

`series` connects two model objects in series. This function accepts any type of model. The two systems must be either both continuous or both discrete with identical sample time. Static gains are neutral and can be specified as regular matrices.

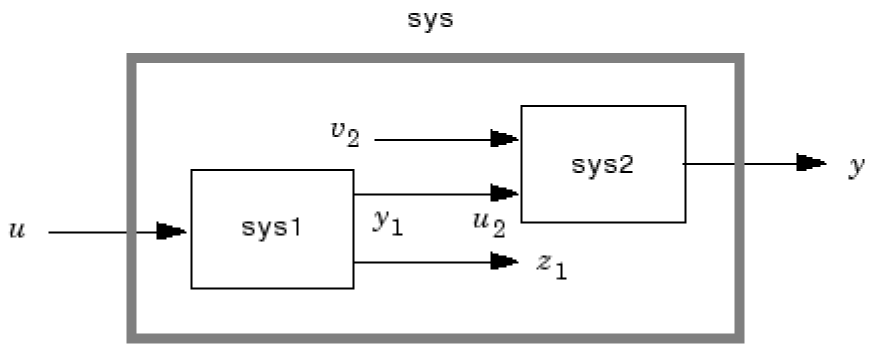
`sys = series(sys1,sys2)` forms the basic series connection shown below.



This command is equivalent to the direct multiplication

```
sys = sys2 * sys1
```

`sys = series(sys1,sys2,outputs1,inputs2)` forms the more general series connection.



The index vectors outputs1 and inputs2 indicate which outputs y_1 of sys1 and which inputs u_2 of sys2 should be connected. The resulting model sys has u as input and y as output.

Examples

Consider a state-space system sys1 with five inputs and four outputs and another system sys2 with two inputs and three outputs. Connect the two systems in series by connecting outputs 2 and 4 of sys1 with inputs 1 and 2 of sys2.

```
outputs1 = [2 4];
inputs2 = [1 2];
sys = series(sys1,sys2,outputs1,inputs2)
```

See Also

append | feedback | parallel

set

Set or modify model properties

Syntax

```
set(sys,'Property',Value)
set(sys,'Property1',Value1,'Property2',Value2,...)
sysnew = set(___)
set(sys,'Property')
```

Description

`set` is used to set or modify the properties of a dynamic system model. Like its Handle Graphics® counterpart, `set` uses property name/property value pairs to update property values.

`set(sys,'Property',Value)` assigns the value `Value` to the property of the model `sys` specified by the string `'Property'`. This string can be the full property name (for example, `'UserData'`) or any unambiguous case-insensitive abbreviation (for example, `'user'`). The specified property must be compatible with the model type. For example, if `sys` is a transfer function, `Variable` is a valid property but `StateName` is not. For a complete list of available system properties for any linear model type, see the reference page for that model type. This syntax is equivalent to `sys.Property = Value`.

`set(sys,'Property1',Value1,'Property2',Value2,...)` sets multiple property values with a single statement. Each property name/property value pair updates one particular property.

`sysnew = set(___)` returns the modified dynamic system model, and can be used with any of the previous syntaxes.

`set(sys,'Property')` displays help for the property specified by `'Property'`.

Examples

Consider the SISO state-space model created by

```
sys = ss(1,2,3,4);
```

You can add an input delay of 0.1 second, label the input as `torque`, reset the D matrix to zero, and store its DC gain in the `'Userdata'` property by

```
set(sys,'inputd',0.1,'inputn','torque','d',0,'user',dcgain(sys))
```

Note that `set` does not require any output argument. Check the result with `get` by typing

```
get(sys)
                a: 1
                b: 2
                c: 3
                d: 0
                e: []
        StateName: {''}
    InternalDelay: [0x1 double]
               Ts: 0
       InputDelay: 0.1
      OutputDelay: 0
        InputName: {'torque'}
       OutputName: {''}
       InputGroup: [1x1 struct]
      OutputGroup: [1x1 struct]
             Name: ''
            Notes: {}
         UserData: -2
```

More About

Tips

For discrete-time transfer functions, the convention used to represent the numerator and denominator depends on the choice of variable (see `tf` for details). Like `tf`, the syntax for `set` changes to remain consistent with the choice of variable. For example, if the `Variable` property is set to `'z'` (the default),

```
set(h,'num',[1 2],'den',[1 3 4])
```

produces the transfer function

$$h(z) = \frac{z+2}{z^2+3z+4}$$

However, if you change the `Variable` to `'z^-1'` by

```
set(h,'Variable','z^-1'),
```

the same command

```
set(h,'num',[1 2],'den',[1 3 4])
```

now interprets the row vectors `[1 2]` and `[1 3 4]` as the polynomials $1 + 2z^{-1}$ and $1 + 3z^{-1} + 4z^{-2}$ and produces:

$$\bar{h}\left(z^{-1}\right) = \frac{1+2z^{-1}}{1+3z^{-1}+4z^{-2}} = zh\left(z\right)$$

Note Because the resulting transfer functions are different, make sure to use the convention consistent with your choice of variable.

- "What Are Model Objects?"

See Also

`get` | `frd` | `ss` | `tf` | `zpk`

setDelayModel

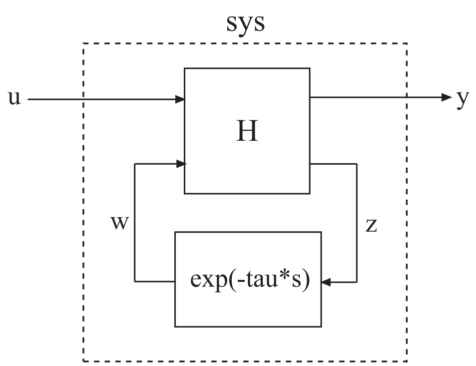
Construct state-space model with internal delays

Syntax

```
sys = setDelayModel(H,tau)
sys = setDelayModel(A,B1,B2,C1,C2,D11,D12,D21,D22,tau)
```

Description

`sys = setDelayModel(H,tau)` constructs the state-space model sys obtained by LFT interconnection of the state-space model H with the vector of internal delays tau, as shown:



`sys = setDelayModel(A,B1,B2,C1,C2,D11,D12,D21,D22,tau)` constructs the state-space model sys described by the following equations:

$$\frac{dx(t)}{dt} = Ax(t) + B_1u(t) + B_2w(t)$$
$$y(t) = C_1x(t) + D_{11}u(t) + D_{12}w(t)$$
$$z(t) = C_2x(t) + D_{21}u(t) + D_{22}w(t)$$
$$w(t) = z(t-\tau).$$

tau (τ) is the vector of internal delays in sys.

Input Arguments

H

State-space (`ss`) model to interconnect with internal delays tau.

tau

Vector of internal delays of sys.

For continuous-time models, express tau in seconds.

For discrete-time models, express tau as integer values that represent multiples of the sample time.

A,B1,B2,C1,C2,D11,D12,D21,D22

Set of state-space matrices that, with the internal delay vector tau, explicitly describe the state-space model sys.

Output Arguments

sys

State-space (`ss`) model with internal delays tau.

More About

Tips

- `setDelayModel` is an advanced operation and is not the natural way to construct models with internal delays. See "Models with Time Delays" for recommended ways of creating internal delays.
- The syntax `sys = setDelayModel(A,B1,B2,C1,C2,D11,D12,D21,D22,tau)` constructs a continuous-time model. You can construct the discrete-time model described by the state-space equations

$$
\begin{aligned}
x[k+1] &= Ax[k] + B_1 u[k] + B_2 w[k] \\
y[k] &= C_1 x[k] + D_{11} u[k] + D_{12} w[k] \\
z[k] &= C_2 x[k] + D_{21} u[k] + D_{22} w[k] \\
w[k] &= z[k-\tau].
\end{aligned}
$$

To do so, first construct sys using `sys = setDelayModel(A,B1,B2,C1,C2,D11,D12,D21,D22,tau)`. Then, use `sys.Ts` to set the sample time.

- “Internal Delays”
- “Models with Time Delays”

See Also

`getDelayModel` | `lft` | `ss`

setoptions

Set plot options for response plot

Syntax

```
setoptions(h, PlotOpts)
setoptions(h, 'Property1', 'value1', ...)
setoptions(h, PlotOpts, 'Property1', 'value1', ...)
```

Description

`setoptions(h, PlotOpts)` sets preferences for response plot using the plot handle. `h` is the plot handle, `PlotOpts` is a plot options handle containing information about plot options.

There are two ways to create a plot options handle:

- Use `getoptions`, which accepts a plot handle and returns a plot options handle.

  ```
  p = getoptions(h)
  ```

- Create a default plot options handle using one of the following commands:

  - `bodeoptions` — Bode plots
  - `hsvoptions` — Hankel singular values plots
  - `nicholsoptions` — Nichols plots
  - `nyquistoptions` — Nyquist plots
  - `pzoptions` — Pole/zero plots
  - `sigmaoptions` — Sigma plots
  - `timeoptions` — Time plots (step, initial, impulse, etc.)

  For example,

  ```
  p = bodeoptions
  ```

  returns a plot options handle for Bode plots.

`setoptions(h, 'Property1', 'value1', ...)` assigns values to property pairs instead of using `PlotOpts`. To find out what properties and values are available for a particular plot, type `help` <*function*>`options`. For example, for Bode plots type

```
help bodeoptions
```

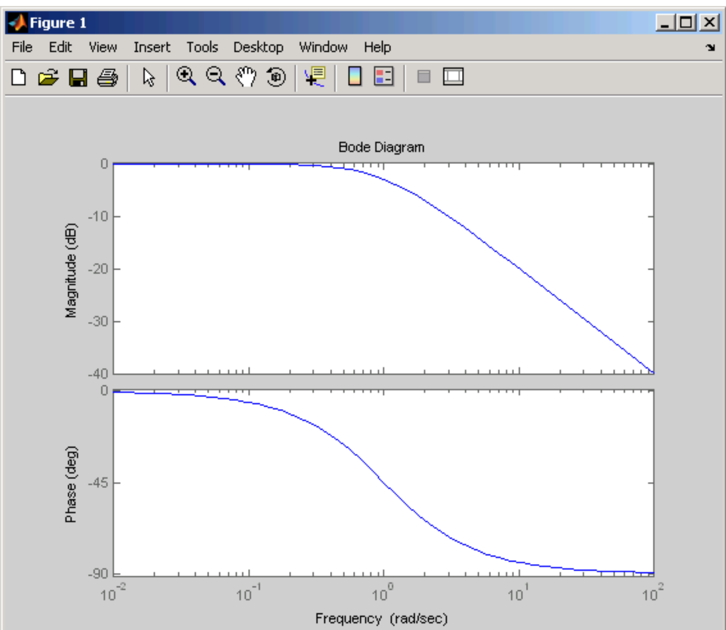
For a list of the properties and values available for each plot type, see “Properties and Values Reference”.

`setoptions(h, PlotOpts, 'Property1', 'value1', ...)` first assigns plot properties as defined in `@PlotOptions`, and then overrides any properties governed by the specified property/value pairs.

Examples

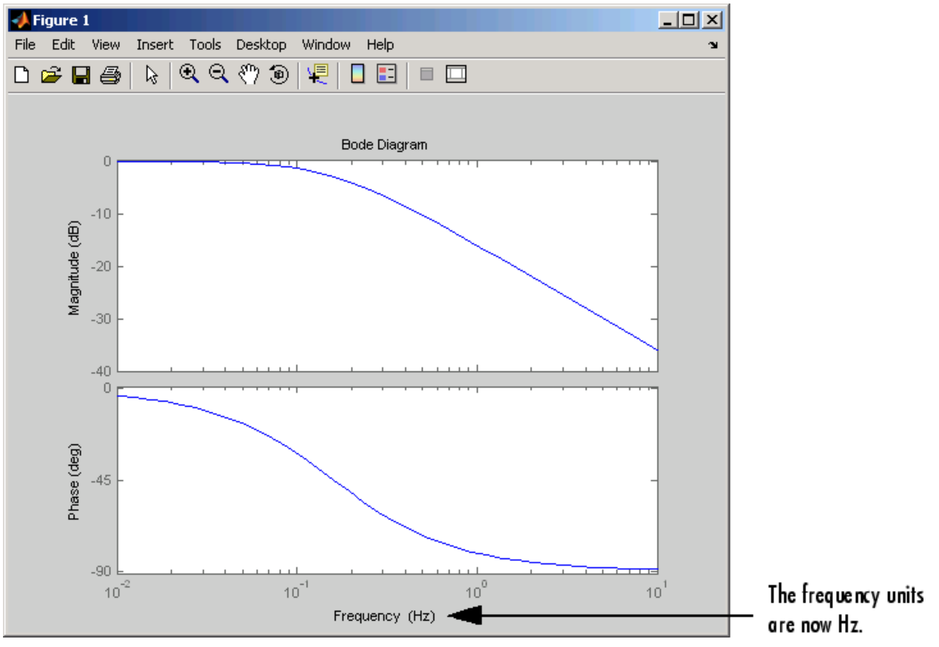
To change frequency units, first create a Bode plot.

```
sys=tf(1,[1 1]);
h=bodeplot(sys)     % Create a Bode plot with plot handle h.
```



Now, change the frequency units from rad/s to Hz.

```
p=getoptions(h);    % Create a plot options handle p.
p.FreqUnits = 'Hz'; % Modify frequency units.
setoptions(h,p);    % Apply plot options to the Bode plot and
                    % render.
```



To change the frequency units using property/value pairs, use this code.

```
sys=tf(1,[1 1]);
h=bodeplot(sys);
setoptions(h,'FreqUnits','Hz');
```

The result is the same as the first example.

See Also

getoptions

setBlockValue

Modify value of Control Design Block in Generalized Model

Syntax

```
M = setBlockValue(M0,blockname,val)
M = setBlockValue(M0,blockvalues)
M = setBlockValue(M0,Mref)
```

Description

`M = setBlockValue(M0,blockname,val)` modifies the current or nominal value of the Control Design Block blockname in the Generalized Model M0 to the value specified by val.

`M = setBlockValue(M0,blockvalues)` modifies the value of several Control Design Blocks at once. The structure blockvalues specifies the blocks and replacement values. Blocks of M0 not listed in blockvalues are unchanged.

`M = setBlockValue(M0,Mref)` takes replacement values from Control Design blocks in the Generalized Model Mref. This syntax modifies the Control Design Blocks in M0 to match the current values of all corresponding blocks in Mref.

Use this syntax to propagate block values, such as tuned parameter values, from one parametric model to other models that depend on the same parameters.

Input Arguments

`M0`

Generalized Model containing the blocks whose current or nominal value is modified to val. For the syntax `M = setBlockValue(M0,Mref)` M0 can be a single Control Design Block whose value is modified to match the value of the corresponding block in Mref.

`blockname`

Name of the Control Design Block in the model M0 whose current or nominal value is modified.

To get a list of the Control Design Blocks in M0, enter `M0.Blocks`.

`val`

Replacement value for the current or nominal value of the Control Design Block, blockname. The value val can be any value that is compatible with blockname without changing the size, type, or sample time of blockname.

For example, you can set the value of a tunable PID block (`ltiblock.pid`) to a `pid` controller model , or to a transfer function (`tf`) model that represents a PID controller.

`blockvalues`

Structure specifying Control Design Blocks of M0 to modify, and the corresponding replacement values. The fields of the structure are the names of the blocks to modify. The value of each field specifies the replacement current or nominal value for the corresponding block.

`Mref`

Generalized Model that shares some Control Design Blocks with M0. The values of these blocks in Mref are used to update their counterparts in M0.

Output Arguments

`M`

Generalized Model obtained from M0 by updating the values of the specified blocks.

Examples

Update Controller Model with Tuned Values

Propagate the values of tuned parameters to other Control Design Blocks.

You can use the Robust Control Toolbox tuning commands such as `systune`, `looptune`, or `hinfstruct` to tune blocks in a closed-loop model of a control system. If you do so, the tuned controller parameters are embedded in a Generalized LTI Model. You can use `setBlockValue` to propagate those parameters to a controller model.

Create a tunable model of the closed-loop response of a control system, and tune the parameters using `hinfstruct`.

```
G = tf([1,0.0007],[1,0.00034,0.00086]);
Cpi = ltiblock.pid('Cpi','pi');
a = realp('a',10);
F0 = tf(a,[1 a]);
C0 = Cpi*F0;
T0 = feedback(G*C0,1);

T = hinfstruct(T0);
```

The controller model `C0` is a Generalized LTI model with two tunable blocks, `Cpi` and `a`. The closed-loop model `T0` is also a Generalized LTI model with the same blocks. The model `T` contains the tuned values of these blocks.

Propagate the tuned values of the controller in `T` to the controller model `C0`.

```
C = setBlockValue(C0,T)

C =

Generalized continuous-time state-space model with 1 outputs,
1 inputs, 2 states, and the following blocks:
    Cpi: Parametric PID controller, 1 occurrences.
    a: Scalar parameter, 2 occurrences.

Type "ss(C)" to see the current value, "get(C)" to see all properties,
and "C.Blocks" to interact with the blocks.
```

`C` is still a Generalized model. The current value of the Control Design Blocks in `C` are set to the values the corresponding blocks of `T`.

Obtain a Numeric LTI model of the controller with the tuned values using `getValue`.

```
 CVal = getValue(C0,T);
```

This command returns a numerical state-space model of the tuned controller.

See Also

`getValue` | `getBlockValue` | `showBlockValue` | `genss` | `systune` | `looptune` | `hinfstruct`

setValue

Modify current value of Control Design Block

Syntax

```
blk = setValue(blk0,val)
```

Description

`blk = setValue(blk0,val)` modifies the parameter values in the tunable Control Design Block, blk0, to best match the values specified by val. An exact match can only occur when val is compatible with the structure of blk0.

Input Arguments

`blk0`

Control Design Block whose value is modified.

`val`

Specifies the replacement parameters values for blk0. The value val can be any value that is compatible with blk0 without changing the size, type, or sample time of blk0. For example, if blk0 is a `ltiblock.pid` block, valid types for val include `ltiblock.pid`, a numeric `pid` controller model, or a numeric `tf` model that represents a PID controller. `setValue` uses the parameter values of val to set the current value of blockname.

Output Arguments

`blk`

Control Design Block of the same type as blk0, whose parameters are updated to best match the parameters of val.

See Also

`getValue` | `setBlockValue` | `getBlockValue`

sgrid

Generate s-plane grid of constant damping factors and natural frequencies

Syntax

```
sgrid
sgrid(z,wn)
```

Description

`sgrid` generates, for pole-zero and root locus plots, a grid of constant damping factors from zero to one in steps of 0.1 and natural frequencies from zero to 10 rad/sec in steps of one rad/sec, and plots the grid over the current axis. If the current axis contains a continuous *s*-plane root locus diagram or pole-zero map, `sgrid` draws the grid over the plot.

`sgrid(z,wn)` plots a grid of constant damping factor and natural frequency lines for the damping factors and natural frequencies in the vectors `z` and `wn`, respectively. If the current axis contains a continuous *s*-plane root locus diagram or pole-zero map, `sgrid(z,wn)` draws the grid over the plot.

Alternatively, you can select **Grid** from the right-click menu to generate the same s-plane grid.

Examples

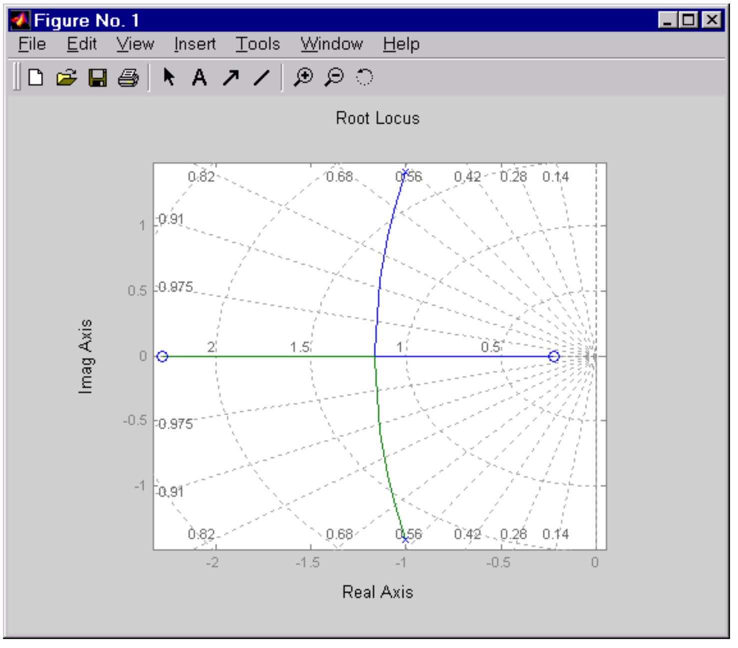
Plot *s*-plane grid lines on the root locus for the following system.

$$H(s) = \frac{2s^2 + 5s + 1}{s^2 + 2s + 3}$$

You can do this by typing

```
H = tf([2 5 1],[1 2 3])
Transfer function:
```

```
2 s^2 + 5 s + 1
---------------
 s^2 + 2 s + 3
rlocus(H)
sgrid
```



See Also

zgrid | pzmap | rlocus

showBlockValue

Display current value of Control Design Blocks in Generalized Model

Syntax

`showBlockValue(M)`

Description

`showBlockValue(M)` displays the current values of all Control Design Blocks in the Generalized Model, M. (For uncertain blocks, the "current value" is the nominal value of the block.)

Input Arguments

M

Generalized Model.

Examples

Create a tunable `genss` model, and display the current value of its tunable elements.

```
G = zpk([],[-1,-1],1);
C = ltiblock.pid('C','PID');
a = realp('a',10);
F = tf(a,[1 a]);
T = feedback(G*C,1)*F;

showBlockValue(T)

C =
Continuous-time I-only controller:

      1
```

```
Ki * ---
      s

With Ki = 0.001

-----------------------------------
a = 10
```

More About

Tips

- Displaying the current values of a model is useful, for example, after you have tuned the free parameters of the model using a Robust Control Toolbox tuning command such as `looptune`.
- `showBlockValue` displays the current values of all Control Design Blocks in a model, including tunable, uncertain, and switch blocks. To display the current values of only the tunable blocks, use `showTunable`.

See Also

`genss` | `getBlockValue` | `setBlockValue` | `showTunable`

showTunable

Display current value of tunable Control Design Blocks in Generalized Model

Syntax

```
showTunable(M)
```

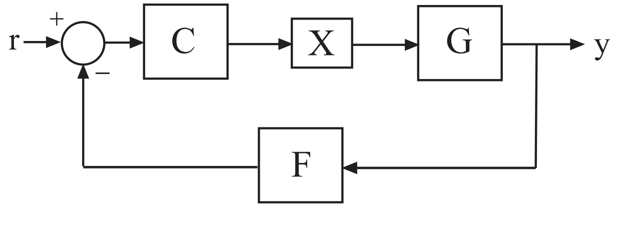
Description

`showTunable(M)` displays the current values of all tunable Control Design Blocks in a generalized LTI model. Tunable control design blocks are parametric blocks such as `realp`, `ltiblock.tf`, and `ltiblock.pid`.

Examples

Display Block Values of Tuned Control System Model

Tune the following control system using `systune`, and display the values of the tunable blocks.



The control structure includes a PI controller `C` and a tunable low-pass filter in the feedback path. The plant `G` is a third-order system.

Create models of the system components and connect them together to create a tunable closed-loop model of the control system.

```
s = tf('s');
num = 33000*(s^2 - 200*s + 90000);
den = (s + 12.5)*(s^2 + 25*s + 63000);
G = num/den;

C0 = ltiblock.pid('C','pi');
a = realp('a',1);
F0 = tf(a,[1 a]);
X = AnalysisPoint('X');

T0 = feedback(G*X*C0,F0);
T0.InputName = 'r';
T0.OutputName = 'y';
```

`T0` is a `genss` model that has two tunable blocks, the PI controller, `C`, and the parameter, `a`. `T0` also contains the switch block `X`.

Create a tuning requirement that forces the output `y` to track the input `r`, and tune the system to meet that requirement.

```
Req = TuningGoal.Tracking('r','y',0.05);
[T,fSoft,~] = systune(T0,Req);
```

`systune` finds values for the tunable parameters that optimally meet the tracking requirement. The output `T` is a `genss` model with the same Control Design Blocks as `T0`. The current values of those blocks are the tuned values.

Examine the tuned values of the tunable blocks of the control system.

```
showTunable(T)
```

```
C =

             1
  Kp + Ki * ---
             s

  with Kp = 0.000433, Ki = 0.00527

Name: C
Continuous-time PI controller in parallel form.
```

```
----------------------------------
a = 68.6
```

`showTunable` displays the values of the tunable blocks only. If you use `showBlockValue` instead, the display also includes the switch block `X`.

Input Arguments

`M` — Input model

generalized LTI model

Input model of which to display tunable block values, specified as a generalized LTI model such as a `genss` model.

More About

Tips

- Displaying the current values of tunable blocks is useful, for example, after you have tuned the free parameters of the model using a Robust Control Toolbox tuning command such as `systune`.
- `showTunable` displays the current values of the tunable blocks only. To display the current values of all Control Design Blocks in a model, including tunable, uncertain, and switch blocks, use `showBlockValue`.

- "Generalized Models"
- "Control Design Blocks"

See Also

`genss` | `getBlockValue` | `setBlockValue` | `showBlockValue` | `systune`

sigma

Singular values plot of dynamic system

Syntax

```
sigma(sys)
sigma(sys,w)
sigma(sys,[],type)
sigma(sys,w,type)
sigma(sys1,sys2,...,sysN,w,type)
sigma(sys1,'PlotStyle1',...,sysN,'PlotStyleN',w,type)
sv = sigma(sys,w)
[sv,w] = sigma(sys)
```

Description

`sigma` calculates the singular values of the frequency response of a dynamic system `sys`. For an FRD model, `sigma` computes the singular values of `sys.Response` at the frequencies, `sys.frequency`. For continuous-time TF, SS, or ZPK models with transfer function $H(s)$, `sigma` computes the singular values of $H(j\omega)$ as a function of the frequency ω. For discrete-time TF, SS, or ZPK models with transfer function $H(z)$ and sample time T_s, `sigma` computes the singular values of

$$H\left(e^{j\omega T_s}\right)$$

for frequencies ω between 0 and the Nyquist frequency $\omega_N = \pi/T_s$.

The singular values of the frequency response extend the Bode magnitude response for MIMO systems and are useful in robustness analysis. The singular value response of a SISO system is identical to its Bode magnitude response. When invoked without output arguments, `sigma` produces a singular value plot on the screen.

`sigma(sys)` plots the singular values of the frequency response of a model `sys`. This model can be continuous or discrete, and SISO or MIMO. The frequency points are chosen automatically based on the system poles and zeros, or from `sys.frequency` if `sys` is an FRD.

`sigma(sys,w)` explicitly specifies the frequency range or frequency points to be used for the plot. To focus on a particular frequency interval `[wmin,wmax]`, set `w = {wmin,wmax}`. To use particular frequency points, set `w` to the corresponding vector of frequencies. Use `logspace` to generate logarithmically spaced frequency vectors. Frequencies must be in `rad/TimeUnit`, where `TimeUnit` is the time units of the input dynamic system, specified in the TimeUnit property of sys.

`sigma(sys,[],type)` or `sigma(sys,w,type)` plots the following modified singular value responses:

`type = 1`	Singular values of the frequency response H^{-1}, where H is the frequency response of `sys`.
`type = 2`	Singular values of the frequency response $I + H$.
`type = 3`	Singular values of the frequency response $I + H^{-1}$.

These options are available only for square systems, that is, with the same number of inputs and outputs.

`sigma(sys1,sys2,...,sysN,w,type)` plots the singular value plots of several LTI models on a single figure. The arguments `w` and `type` are optional. The models `sys1,sys2,...,sysN` need not have the same number of inputs and outputs. Each model can be either continuous- or discrete-time.

`sigma(sys1,'PlotStyle1',...,sysN,'PlotStyleN',w,type)` specifies a distinctive color, linestyle, and/or marker for each system plot. See `bode` for an example.

`sv = sigma(sys,w)` and `[sv,w] = sigma(sys)` return the singular values `sv` of the frequency response at the frequencies `w`. For a system with `Nu` input and `Ny` outputs, the array `sv` has `min(Nu,Ny)` rows and as many columns as frequency points (length of `w`). The singular values at the frequency `w(k)` are given by `sv(:,k)`.

Examples

Compute and Plot Singular Values

Consider the following two-input, two-output dynamic system.

$$H(s) = \begin{bmatrix} 0 & \dfrac{3s}{s^2+s+10} \\ \dfrac{s+1}{s+5} & \dfrac{2}{s+6} \end{bmatrix}.$$

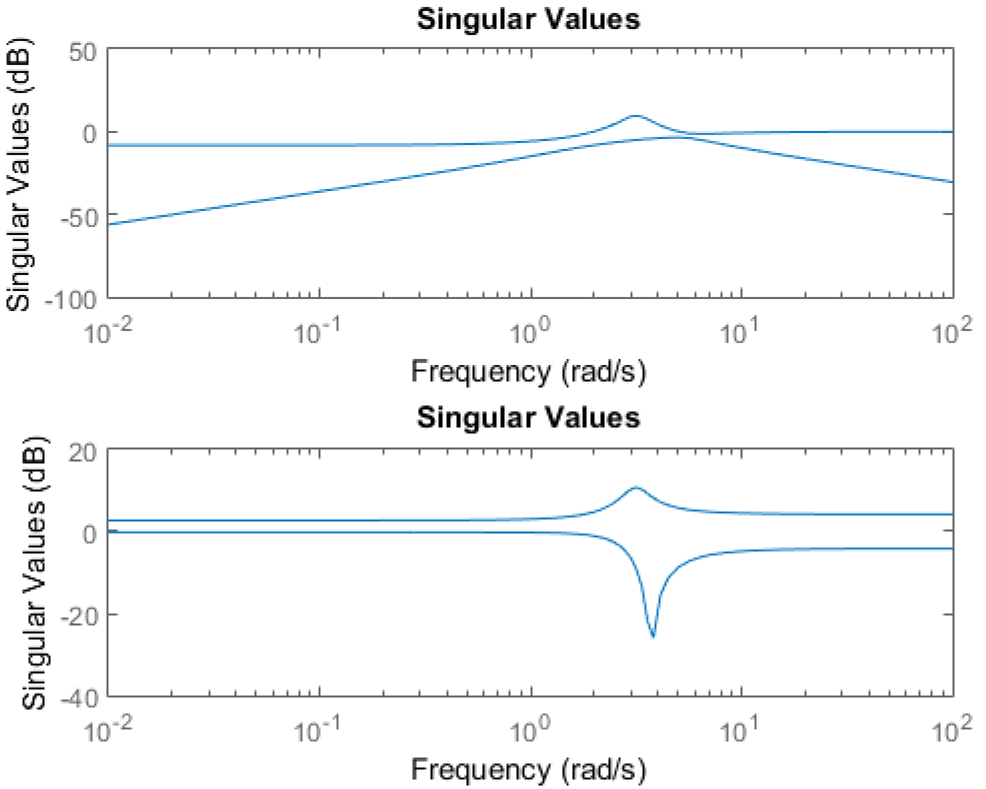
Compute the singular value responses of $H(s)$ and $I + H(s)$.

```
H = [0, tf([3 0],[1 1 10]) ; tf([1 1],[1 5]), tf(2,[1 6])];
[svH,wH] = sigma(H);
[scIH,wIH] = sigma(H,[],2);
```

In the last command, the input 2 selects the second response type, $I + H(s)$. The vectors `svH` and `svIH` contain the singular value response data, at the frequencies in `wH` and `wIH`.

Plot the singular value responses of both systems.

```
subplot(211)
sigma(H)
subplot(212)
sigma(H,[],2)
```



More About

Tips

You can change the properties of your plot, for example the units. For information on the ways to change properties of your plots, see “Ways to Customize Plots”.

Algorithms

`sigma` uses the MATLAB function `svd` to compute the singular values of a complex matrix.

For TF, ZPK, and SS models, `sigma` computes the frequency response using the `freqresp` algorithms. As a result, small discrepancies may exist between the `sigma` responses for equivalent TF, ZPK, and SS representations of a given model.

See Also

`bode` | `evalfr` | `freqresp` | `linearSystemAnalyzer` | `nichols` | `nyquist`

sigmaoptions

Create list of singular-value plot options

Syntax

```
P = sigmaoptions
P = sigmaoptions('cstprefs')
```

Description

`P = sigmaoptions` returns a list of available options for singular value plots with default values set. You can use these options to customize the singular value plot appearance from the command line.

`P = sigmaoptions('cstprefs')` initializes the plot options with the options you selected in the Control System Toolbox Preferences Editor. For more information about the editor, see “Toolbox Preferences Editor” in the User's Guide documentation.

This table summarizes the sigma plot options.

Option	Description
Title, XLabel, YLabel	Label text and style
TickLabel	Tick label style
Grid	Show or hide the grid Specified as one of the following strings: `'off' | 'on'` **Default**: `'off'`
XlimMode, YlimMode	Limit modes
Xlim, Ylim	Axes limits
IOGrouping	Grouping of input-output pairs Specified as one of the following strings: `'none' |'inputs'|'outputs'|'all'` **Default**: `'none'`
InputLabels, OutputLabels	Input and output label styles

Option	Description
InputVisible, OutputVisible	Visibility of input and output channels

Option	Description
FreqUnits	Frequency units, specified as one of the following strings: • `'Hz'` • `'rad/second'` • `'rpm'` • `'kHz'` • `'MHz'` • `'GHz'` • `'rad/nanosecond'` • `'rad/microsecond'` • `'rad/millisecond'` • `'rad/minute'` • `'rad/hour'` • `'rad/day'` • `'rad/week'` • `'rad/month'` • `'rad/year'` • `'cycles/nanosecond'` • `'cycles/microsecond'` • `'cycles/millisecond'` • `'cycles/hour'` • `'cycles/day'` • `'cycles/week'` • `'cycles/month'` • `'cycles/year'` **Default**: `'rad/s'` You can also specify `'auto'` which uses frequency units `rad/TimeUnit` relative

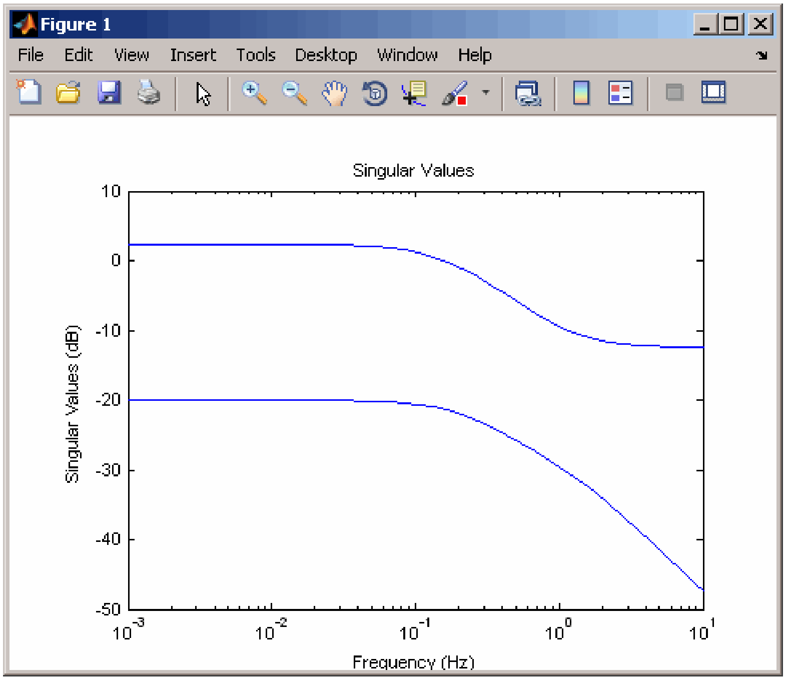
Option	Description
	to system time units specified in the `TimeUnit` property. For multiple systems with different time units, the units of the first system are used.
FreqScale	Frequency scale Specified as one of the following strings: `'linear' | 'log'` **Default**: `'log'`
MagUnits	Magnitude units Specified as one of the following strings: `'dB' | 'abs'` **Default**: `'dB'`
MagScale	Magnitude scale Specified as one of the following strings: `'linear' | 'log'` **Default**: `'linear'`

Examples

In this example, set the frequency units to Hz before creating a plot.

```
P = sigmaoptions; % Set the frequency units to Hz in options
P.FreqUnits = 'Hz'; % Create plot with the options specified by P
h = sigmaplot(rss(2,2,3),P);
```

The following singular value plot is created with the frequency units in Hz.



See Also

`getoptions` | `setoptions` | `sigmaplot`

sigmaplot

Plot singular values of frequency response and return plot handle

Syntax

```
h = sigmaplot(sys)
sigmaplot(sys,{wmin,wmax})
sigmaplot(sys,w)
sigmaplot(sys,w,TYPE)
sigmaplot(AX,...)
sigmaplot(..., plotoptions)
```

Description

`h = sigmaplot(sys)` produces a singular value (SV) plot of the frequency response of the dynamic system `sys`. It also returns the plot handle `h`. You can use this handle to customize the plot with the `getoptions` and `setoptions` commands. Type

```
help sigmaoptions
```

for a list of available plot options.

The frequency range and number of points are chosen automatically. See `bode` for details on the notion of frequency in discrete time.

`sigmaplot(sys,{wmin,wmax})` draws the SV plot for frequencies ranging between `wmin` and `wmax` (in `rad/TimeUnit`, where `TimeUnit` is the time units of the input dynamic system, specified in the TimeUnit property of sys).

`sigmaplot(sys,w)` uses the user-supplied vector `w` of frequencies, in `rad/TimeUnit`, at which the frequency response is to be evaluated. See `logspace` to generate logarithmically spaced frequency vectors.

`sigmaplot(sys,w,TYPE)` or `sigmaplot(sys,[],TYPE)` draws the following modified SV plots depending on the value of `TYPE`:

TYPE = 1	-->	SV of inv(SYS)
TYPE = 2	-->	SV of I + SYS
TYPE = 3	-->	SV of I + inv(SYS)

`sys` should be a square system when using this syntax.

`sigmaplot(AX,...)` plots into the axes with handle `AX`.

`sigmaplot(..., plotoptions)` plots the singular values with the options specified in plotoptions. Type

```
help sigmaoptions
```

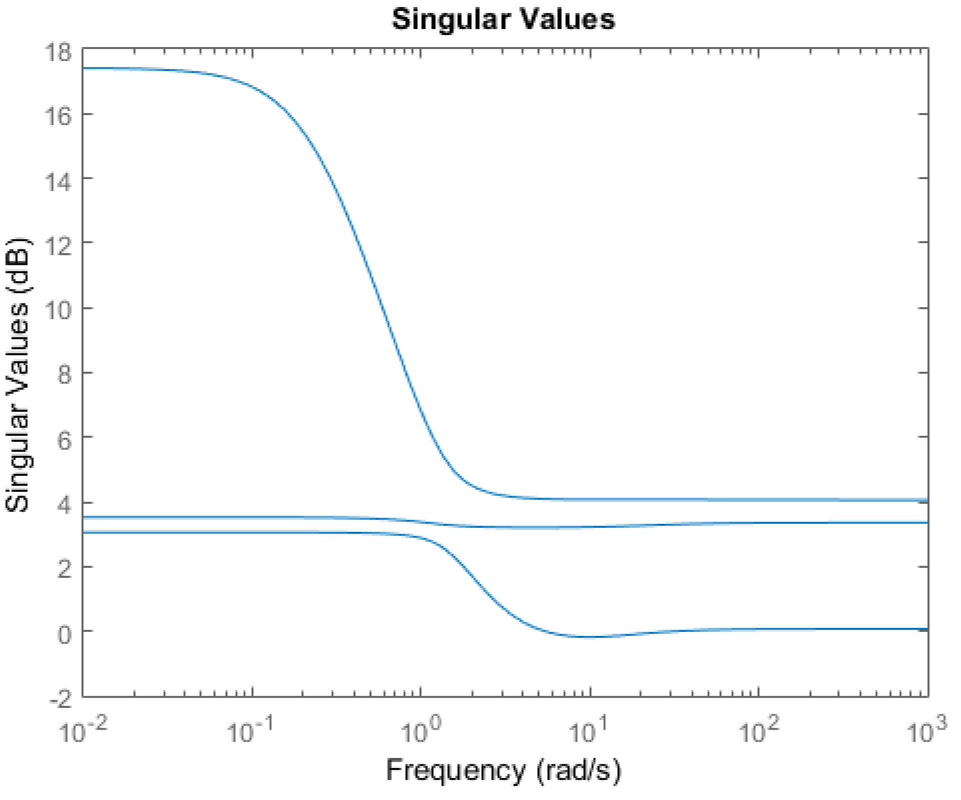
for more details.

Examples

Singular Value Response Plot with Custom Plot Options

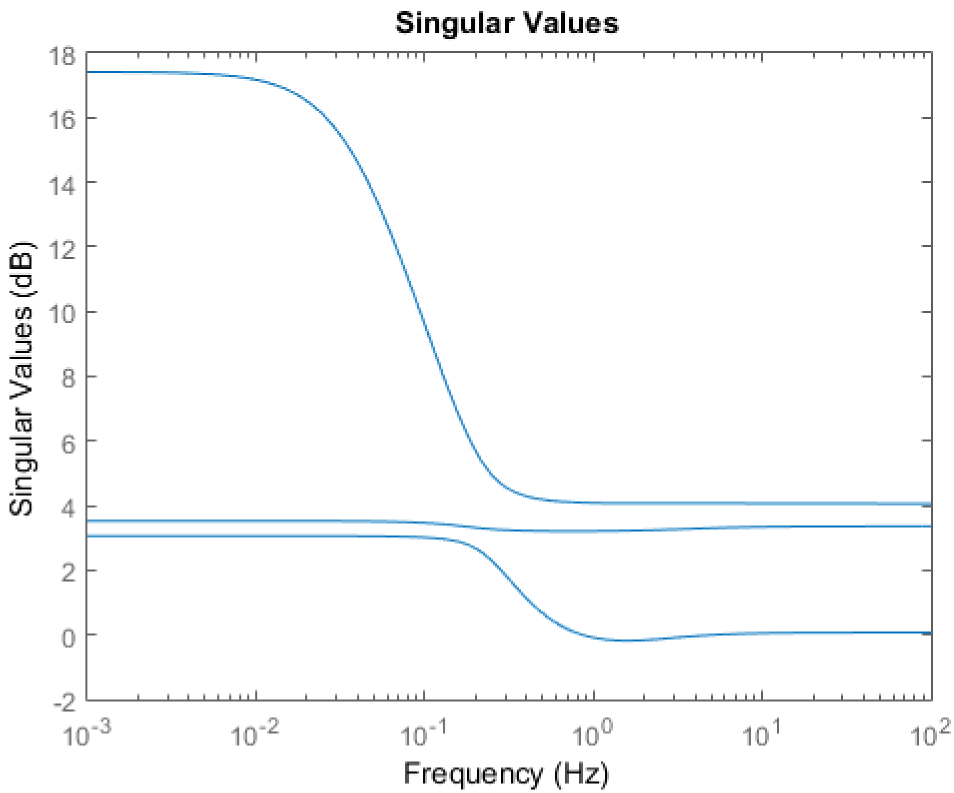
Plot the singular value responses of a dynamic system.

```
sys = rss(3,3,5);
h = sigmaplot(sys);
```



Set properties of the plot handle `h` to customize the plot. For example, change the plot units to Hz.

```
setoptions(h,'FreqUnits','Hz');
```



More About

Tips

You can change the properties of your plot, for example the units. For information on the ways to change properties of your plots, see “Ways to Customize Plots”.

See Also

`getoptions` | `sigma` | `setoptions` | `sigmaoptions`

sisoinit

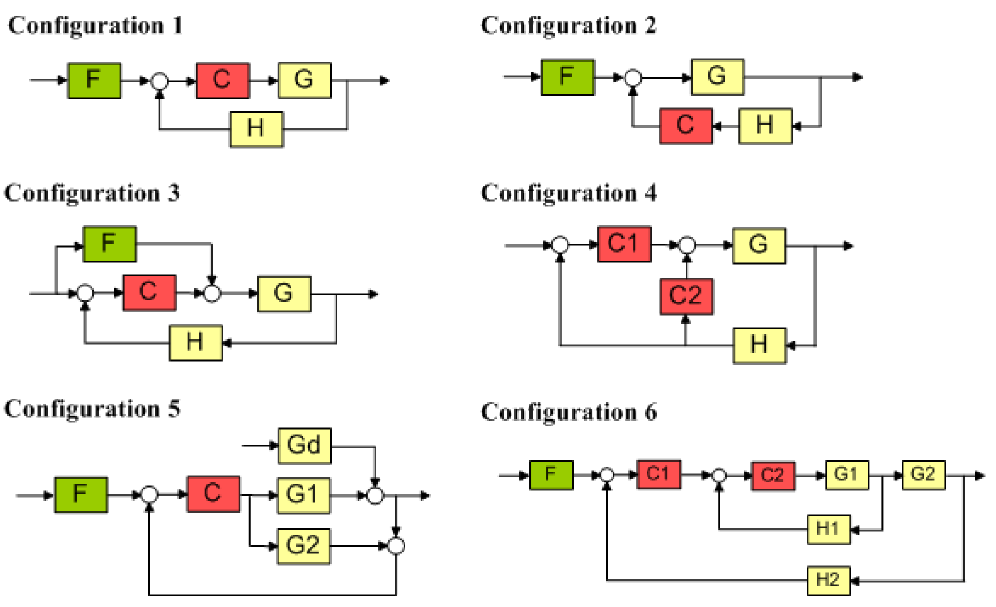
Configure SISO Design Tool at startup

Syntax

```
init_config = sisoinit(config)
```

Description

`init_config = sisoinit(config)` returns a template `init_config` for initializing Graphical Tuning window of the SISO Design Tool (Control System Designer) with the one of the following control system configurations:



`config` corresponds to the control system configuration. Available configurations include:

- `config = 1` (default) — C in forward path, F in series
- `config = 2` — C in feedback path, F in series
- `config = 3` — C in forward path, feedforward F
- `config = 4` — Nested loop configuration
- `config = 5` — Internal model control (IMC) structure
- `config = 6` — Cascade loop configuration

For each configuration, you can specify the plant models G and H, initialize the compensator C and prefilter F, and configure the open- and closed-loop views by specifying the corresponding fields of the structure `init_config`. Then use `controlSystemDesigner(init_config)` to start the SISO Design Tool in the specified configuration.

Output argument `init_config` is an object with properties. The following tables list the block and loop properties.

Block Properties

<table>
<tr><th>Block</th><th>Properties</th><th>Values</th></tr>
<tr><td rowspan="3"><code>F</code></td><td><code>Name</code></td><td>String</td></tr>
<tr><td><code>Description</code></td><td>String</td></tr>
<tr><td><code>Value</code></td><td>LTI object</td></tr>
<tr><td rowspan="2"><code>G</code></td><td><code>Name</code></td><td>String</td></tr>
<tr><td><code>Value</code></td><td>LTI object
Row or column array of LTI objects. If the sensor H is also an array of LTI objects, the lengths of G and H must match.</td></tr>
<tr><td rowspan="2"><code>H</code></td><td><code>Name</code></td><td>String</td></tr>
<tr><td><code>Value</code></td><td>LTI object
Row or column array of LTI objects. If the plant G is also an array of LTI objects, the lengths of H and G must match.</td></tr>
<tr><td rowspan="3"><code>C</code></td><td><code>Name</code></td><td>String</td></tr>
<tr><td><code>Description</code></td><td>String</td></tr>
<tr><td><code>Value</code></td><td>LTI object</td></tr>
</table>

Loop Properties

Loops	Properties	Values
OL1	Name Description View	String String 'rlocus' 'bode'
CL1	Name Description View	String String 'bode'

Examples

Initialize SISO Design Tool with C in feedback path using an LTI model:

```
 % Single-loop configuration with C in the feedback path.
T = sisoinit(2);
% Model for plant G.
T.G.Value = tf(1, [1 1]);
% Initial compensator value.
T.C.Value = tf(1,[1 2]);
% Views for tuning Open-Loop OL1.
T.OL1.View = {'rlocus','nichols'};
% Launch SISO Design Tool using configuration T
controlSystemDesigner(T)
```

Initialize SISO Design Tool with C in feedback path using an array of LTI models:

```
% Specify an initial configuration.
initconfig = sisoinit(2);
% Specify model parameters.
m = 3;
b = 0.5;
k = 8:1:10;
T = 0.1:.05:.2;
% Create an LTI array to model variations in plant G.
for ct = 1:length(k);
    G(:,:,ct) = tf(1,[m,b,k(ct)]);
end
% Assign G to the initial configuration.
initconfig.G.Value = G;
```

```
% Create an LTI array to model variations in sensor H.
for ct = 1:length(T);
    H(:,:,ct) = tf(1,[1/T(ct), 1]);
end
% Assign H to the initial configuration.
initconfig.H.Value = H;
% Specify initial controller.
initconfig.C.Value = tf(1,[1 2]);
% Views for tuning Open-Loop (OL1)
initconfig.OL1.View = {'rlocus','bode'};
% Launch SISO Design Tool using initconfig.
controlSystemDesigner(initconfig)
```

More About

- "SISO Design Tool"
- "Control Design Analysis of Multiple Models"

See Also

`controlSystemDesigner`

size

Query output/input/array dimensions of input–output model and number of frequencies of FRD model

Syntax

```
size(sys)
d = size(sys)
Ny = size(sys,1)
Nu = size(sys,2)
Sk = size(sys,2+k)
Nf = size(sys,'frequency')
```

Description

When invoked without output arguments, `size(sys)` returns a description of type and the input-output dimensions of `sys`. If `sys` is a model array, the array size is also described. For identified models, the number of free parameters is also displayed. The lengths of the array dimensions are also included in the response to size when `sys` is a model array.

`d = size(sys)` returns:

- The row vector `d = [Ny Nu]` for a single dynamic model `sys` with `Ny` outputs and `Nu` inputs
- The row vector `d = [Ny Nu S1 S2 ... Sp]` for an `S1`-by-`S2`-by-...-by-`Sp` array of dynamic models with `Ny` outputs and `Nu` inputs

`Ny = size(sys,1)` returns the number of outputs of `sys`.

`Nu = size(sys,2)` returns the number of inputs of `sys`.

`Sk = size(sys,2+k)` returns the length of the `k`-th array dimension when `sys` is a model array.

`Nf = size(sys,'frequency')` returns the number of frequencies when `sys` is a frequency response data model. This is the same as the length of `sys.frequency`.

Examples

Example 1

Consider the model array of random state-space models

```
sys = rss(5,3,2,3);
```

Its dimensions are obtained by typing

```
size(sys)
3x1 array of state-space models
Each model has 3 outputs, 2 inputs, and 5 states.
```

Example 2

Consider the process model:

```
sys = idproc({'p1d', 'p2'; 'p3uz', 'p0'});
```

It's input-output dimensions and number of free parameters are obtained by typing:

```
size(sys)
```

Process model with 2 outputs, 2 inputs and 12 free parameters.

See Also

issiso | ndims | isempty

sminreal

Structural pole/zero cancellations

Syntax

```
msys = sminreal(sys)
```

Description

`msys = sminreal(sys)` eliminates the states of the state-space model `sys` that don't affect the input/output response. All of the states of the resulting state-space model `msys` are also states of `sys` and the input/output response of `msys` is equivalent to that of `sys`.

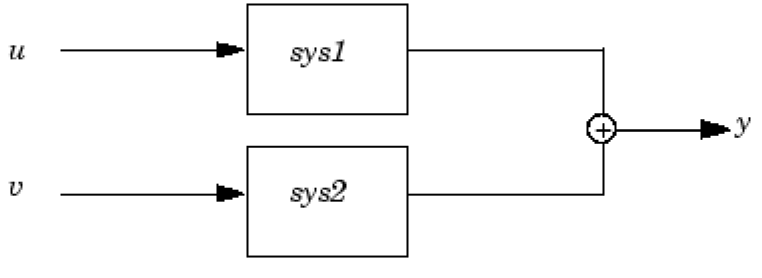
sminreal eliminates only structurally non minimal states, i.e., states that can be discarded by looking only at hard zero entries in the A, B, and C matrices. Such structurally nonminimal states arise, for example, when linearizing a Simulink model that includes some unconnected state-space or transfer function blocks.

Examples

Suppose you concatenate two SS models, `sys1` and `sys2`.

```
sys = [sys1,sys2];
```

This operation is depicted in the diagram below.



If you extract the subsystem `sys1` from `sys`, with

```
sys(1,1)
```

all of the states of `sys`, including those of `sys2` are retained. To eliminate the unobservable states from `sys2`, while retaining the states of `sys1`, type

```
sminreal(sys(1,1))
```

More About

Tips

The model resulting from `sminreal(sys)` is not necessarily minimal, and may have a higher order than one resulting from `minreal(sys)`. However, `sminreal(sys)` retains the state structure of `sys`, while, in general, `minreal(sys)` does not.

See Also

`minreal`

ss

Create state-space model, convert to state-space model

Syntax

```
sys = ss(a,b,c,d)
sys = ss(a,b,c,d,Ts)
sys = ss(d)
sys = ss(a,b,c,d,ltisys)
sys_ss = ss(sys)
sys_ss = ss(sys,'minimal')
sys_ss = ss(sys,'explicit')
sys_ss = ss(sys, 'measured')
sys_ss = ss(sys, 'noise')
sys_ss = ss(sys, 'augmented')
```

Description

Use `ss` to create state-space models (`ss` model objects) with real- or complex-valued matrices or to convert dynamic system models to state-space model form. You can also use `ss` to create Generalized state-space (`genss`) models.

Creation of State-Space Models

`sys = ss(a,b,c,d)` creates a state-space model object representing the continuous-time state-space model

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$

For a model with `Nx` states, `Ny` outputs, and `Nu` inputs:

- `a` is an `Nx`-by-`Nx` real- or complex-valued matrix.
- `b` is an `Nx`-by-`Nu` real- or complex-valued matrix.

- c is an Ny-by-Nx real- or complex-valued matrix.
- d is an Ny-by-Nu real- or complex-valued matrix.

To set D = 0 , set d to the scalar 0 (zero), regardless of the dimension.

sys = ss(*a*,*b*,*c*,*d*,*Ts*) creates the discrete-time model

$$x[n+1] = Ax[n] + Bu[n]$$
$$y[n] = Cx[n] + Du[n]$$

with sample time Ts (in seconds). Set Ts = -1 or Ts = [] to leave the sample time unspecified.

sys = ss(*d*) specifies a static gain matrix D and is equivalent to

```
sys = ss([],[],[],d)
```

sys = *ss*(*a*,*b*,*c*,*d*,*ltisys*) creates a state-space model with properties inherited from the model ltisys (including the sample time).

Any of the previous syntaxes can be followed by property name/property value pairs.

```
'PropertyName',PropertyValue
```

Each pair specifies a particular property of the model, for example, the input names or some notes on the model history. See "Properties" on page 1-692 for more information about available ss model object properties.

The following expression:

```
sys = ss(a,b,c,d,'Property1',Value1,...,'PropertyN',ValueN)
```

is equivalent to the sequence of commands:

```
sys = ss(a,b,c,d)
set(sys,'Property1',Value1,...,'PropertyN',ValueN)
```

Conversion to State Space

sys_ss = ss(sys) converts a dynamic system model sys to state-space form. The output sys_ss is an equivalent state-space model (ss model object). This operation is known as *state-space realization*.

`sys_ss = ss(sys,'minimal')` produces a state-space realization with no uncontrollable or unobservable states. This state-space realization is equivalent to `sys_ss = minreal(ss(sys))`.

`sys_ss = ss(sys,'explicit')` computes an explicit realization (E = I) of the dynamic system model `sys`. If `sys` is improper, `ss` returns an error.

Note: Conversions to state space are not uniquely defined in the SISO case. They are also not guaranteed to produce a minimal realization in the MIMO case. For more information, see "Recommended Working Representation".

Conversion of Identified Models

An identified model is represented by an input-output equation of the form $y(t) = Gu(t) + He(t)$, where *u(t)* is the set of measured input channels and *e(t)* represents the noise channels. *If* $\Lambda = LL'$ represents the covariance of noise *e(t)*, this equation can also be written as $y(t) = Gu(t) + HLv(t)$, where $cov(v(t)) = I$.

`sys_ss = ss(sys)` or `sys_ss = ss(sys, 'measured')` converts the measured component of an identified linear model into the state-space form. `sys` is a model of type `idss`, `idproc`, `idtf`, `idpoly`, or `idgrey`. `sys_ss` represents the relationship between *u* and *y*.

`sys_ss = ss(sys, 'noise')` converts the noise component of an identified linear model into the state space form. It represents the relationship between the noise input *v(t)* and output *y_noise* = *HL v(t)*. The noise input channels belong to the `InputGroup` 'Noise'. The names of the noise input channels are *v@yname*, where *yname* is the name of the corresponding output channel. `sys_ss` has as many inputs as outputs.

`sys_ss = ss(sys, 'augmented')` converts both the measured and noise dynamics into a state-space model. `sys_ss` has *ny+nu* inputs such that the first *nu* inputs represent the channels *u(t)* while the remaining by channels represent the noise channels *v(t)*. `sys_ss.InputGroup` contains 2 input groups- `'measured'` and `'noise'`. `sys_ss.InputGroup.Measured` is set to *1:nu* while `sys_ss.InputGroup.Noise` is set to *nu+1:nu+ny*. `sys_ss` represents the equation $y(t) = [G\ HL]\ [u;\ v]$

Tip An identified nonlinear model cannot be converted into a state-space form. Use linear approximation functions such as `linearize` and `linapp`.

Creation of Generalized State-Space Models

You can use the syntax:

```
gensys = ss(A,B,C,D)
```

to create a Generalized state-space (`genss`) model when one or more of the matrices `A`, `B`, `C`, `D` is a tunable `realp` or `genmat` model. For more information about Generalized state-space models, see "Models with Tunable Coefficients".

Properties

`ss` objects have the following properties:

`a,b,c,d,e`

State-space matrices.

- `a` — State matrix A. Square real- or complex-valued matrix with as many rows as states.
- `b` — Input-to-state matrix B. Real- or complex-valued matrix with as many rows as states and as many columns as inputs.
- `c` — State-to-output matrix C. Real- or complex-valued matrix with as many rows as outputs and as many columns as states.
- `d` — Feedthrough matrix D. Real- or complex-valued matrix with as many rows as outputs and as many columns as inputs.
- `e` — E matrix for implicit (descriptor) state-space models. By default `e = []`, meaning that the state equation is explicit. To specify an implicit state equation $E\, dx/dt = Ax + Bu$, set this property to a square matrix of the same size as `a`. See `dss` for more information about creating descriptor state-space models.

`Scaled`

Logical value indicating whether scaling is enabled or disabled.

When `Scaled = 0` (false), most numerical algorithms acting on the state-space model automatically rescale the state vector to improve numerical accuracy. You can disable such auto-scaling by setting `Scaled = 1` (true). For more information about scaling, see `prescale`.

Default: 0 (false)

StateName

State names. For first-order models, set `StateName` to a string. For models with two or more states, set `StateName` to a cell array of strings . Use an empty string `''` for unnamed states.

Default: Empty string `''` for all states

StateUnit

State units. Use `StateUnit` to keep track of the units each state is expressed in. For first-order models, set `StateUnit` to a string. For models with two or more states, set `StateUnit` to a cell array of strings. `StateUnit` has no effect on system behavior.

Default: Empty string `''` for all states

InternalDelay

Vector storing internal delays.

Internal delays arise, for example, when closing feedback loops on systems with delays, or when connecting delayed systems in series or parallel. For more information about internal delays, see “Closing Feedback Loops with Time Delays” in the *Control System Toolbox User's Guide*.

For continuous-time models, internal delays are expressed in the time unit specified by the `TimeUnit` property of the model. For discrete-time models, internal delays are expressed as integer multiples of the sample time `Ts`. For example, `InternalDelay = 3` means a delay of three sampling periods.

You can modify the values of internal delays. However, the number of entries in `sys.InternalDelay` cannot change, because it is a structural property of the model.

InputDelay

Input delay for each input channel, specified as a scalar value or numeric vector. For continuous-time systems, specify input delays in the time unit stored in the `TimeUnit` property. For discrete-time systems, specify input delays in integer multiples of the sample time `Ts`. For example, `InputDelay = 3` means a delay of three sample times.

For a system with `Nu` inputs, set `InputDelay` to an `Nu`-by-1 vector. Each entry of this vector is a numerical value that represents the input delay for the corresponding input channel.

You can also set `InputDelay` to a scalar value to apply the same delay to all channels.

Default: 0

`OutputDelay`

Output delays. `OutputDelay` is a numeric vector specifying a time delay for each output channel. For continuous-time systems, specify output delays in the time unit stored in the `TimeUnit` property. For discrete-time systems, specify output delays in integer multiples of the sample time `Ts`. For example, `OutputDelay = 3` means a delay of three sampling periods.

For a system with `Ny` outputs, set `OutputDelay` to an `Ny`-by-1 vector, where each entry is a numerical value representing the output delay for the corresponding output channel. You can also set `OutputDelay` to a scalar value to apply the same delay to all channels.

Default: 0 for all output channels

`Ts`

Sample time. For continuous-time models, `Ts = 0`. For discrete-time models, `Ts` is a positive scalar representing the sampling period. This value is expressed in the unit specified by the `TimeUnit` property of the model. To denote a discrete-time model with unspecified sample time, set `Ts = -1`.

Changing this property does not discretize or resample the model. Use `c2d` and `d2c` to convert between continuous- and discrete-time representations. Use `d2d` to change the sample time of a discrete-time system.

Default: `0` (continuous time)

`TimeUnit`

String representing the unit of the time variable. This property specifies the units for the time variable, the sample time `Ts`, and any time delays in the model. Use any of the following values:

- 'nanoseconds'
- 'microseconds'
- 'milliseconds'
- 'seconds'
- 'minutes'
- 'hours'
- 'days'
- 'weeks'
- 'months'
- 'years'

Changing this property has no effect on other properties, and therefore changes the overall system behavior. Use `chgTimeUnit` to convert between time units without modifying system behavior.

Default: 'seconds'

InputName

Input channel names. Set `InputName` to a string for single-input model. For a multi-input model, set `InputName` to a cell array of strings.

Alternatively, use automatic vector expansion to assign input names for multi-input models. For example, if `sys` is a two-input model, enter:

```
sys.InputName = 'controls';
```

The input names automatically expand to `{'controls(1)';'controls(2)'}`.

You can use the shorthand notation `u` to refer to the `InputName` property. For example, `sys.u` is equivalent to `sys.InputName`.

Input channel names have several uses, including:

- Identifying channels on model display and plots
- Extracting subsystems of MIMO systems
- Specifying connection points when interconnecting models

Default: Empty string '' for all input channels

InputUnit

Input channel units. Use `InputUnit` to keep track of input signal units. For a single-input model, set `InputUnit` to a string. For a multi-input model, set `InputUnit` to a cell array of strings. `InputUnit` has no effect on system behavior.

Default: Empty string `''` for all input channels

InputGroup

Input channel groups. The `InputGroup` property lets you assign the input channels of MIMO systems into groups and refer to each group by name. Specify input groups as a structure. In this structure, field names are the group names, and field values are the input channels belonging to each group. For example:

```
sys.InputGroup.controls = [1 2];
sys.InputGroup.noise = [3 5];
```

creates input groups named `controls` and `noise` that include input channels 1, 2 and 3, 5, respectively. You can then extract the subsystem from the `controls` inputs to all outputs using:

```
sys(:,'controls')
```

Default: Struct with no fields

OutputName

Output channel names. Set `OutputName` to a string for single-output model. For a multi-output model, set `OutputName` to a cell array of strings.

Alternatively, use automatic vector expansion to assign output names for multi-output models. For example, if `sys` is a two-output model, enter:

```
sys.OutputName = 'measurements';
```

The output names automatically expand to
`{'measurements(1)';'measurements(2)'}`.

You can use the shorthand notation `y` to refer to the `OutputName` property. For example, `sys.y` is equivalent to `sys.OutputName`.

Output channel names have several uses, including:

- Identifying channels on model display and plots
- Extracting subsystems of MIMO systems
- Specifying connection points when interconnecting models

Default: Empty string `''` for all output channels

OutputUnit

Output channel units. Use `OutputUnit` to keep track of output signal units. For a single-output model, set `OutputUnit` to a string. For a multi-output model, set `OutputUnit` to a cell array of strings. `OutputUnit` has no effect on system behavior.

Default: Empty string `''` for all output channels

OutputGroup

Output channel groups. The `OutputGroup` property lets you assign the output channels of MIMO systems into groups and refer to each group by name. Specify output groups as a structure. In this structure, field names are the group names, and field values are the output channels belonging to each group. For example:

```
sys.OutputGroup.temperature = [1];
sys.InputGroup.measurement = [3 5];
```

creates output groups named `temperature` and `measurement` that include output channels 1, and 3, 5, respectively. You can then extract the subsystem from all inputs to the `measurement` outputs using:

```
sys('measurement',:)
```

Default: Struct with no fields

Name

System name. Set `Name` to a string to label the system.

Default: `''`

Notes

Any text that you want to associate with the system. Set `Notes` to a string or a cell array of strings.

Default: {}

`UserData`

Any type of data you wish to associate with system. Set `UserData` to any MATLAB data type.

Default: [ ]

`SamplingGrid`

Sampling grid for model arrays, specified as a data structure.

For model arrays that are derived by sampling one or more independent variables, this property tracks the variable values associated with each model in the array. This information appears when you display or plot the model array. Use this information to trace results back to the independent variables.

Set the field names of the data structure to the names of the sampling variables. Set the field values to the sampled variable values associated with each model in the array. All sampling variables should be numeric and scalar valued, and all arrays of sampled values should match the dimensions of the model array.

For example, suppose you create a 11-by-1 array of linear models, `sysarr`, by taking snapshots of a linear time-varying system at times `t = 0:10`. The following code stores the time samples with the linear models.

```
 sysarr.SamplingGrid = struct('time',0:10)
```

Similarly, suppose you create a 6-by-9 model array, `M`, by independently sampling two variables, `zeta` and `w`. The following code attaches the `(zeta,w)` values to `M`.

```
[zeta,w] = ndgrid(<6 values of zeta>,<9 values of w>)
M.SamplingGrid = struct('zeta',zeta,'w',w)
```

When you display `M`, each entry in the array includes the corresponding `zeta` and `w` values.

```
M
```

```
M(:,:,1,1) [zeta=0.3, w=5] =

        25
```

```
  -------------
  s^2 + 3 s + 25


M(:,:,2,1) [zeta=0.35, w=5] =

         25
  ---------------
  s^2 + 3.5 s + 25

...
```

For model arrays generated by linearizing a Simulink model at multiple parameter values or operating points, the software populates `SamplingGrid` automatically with the variable values that correspond to each entry in the array. For example, the Simulink Control Design commands `linearize` and `slLinearizer` populate `SamplingGrid` in this way.

Default: `[]`

Examples

Discrete-Time State-Space Model

Create a state-space model with a sample time of 0.25 s and the following state-space matrices:

$$A = \begin{bmatrix} 0 & 1 \\ -5 & -2 \end{bmatrix} \quad B = \begin{bmatrix} 0 \\ 3 \end{bmatrix} \quad C = \begin{bmatrix} 0 & 1 \end{bmatrix} \quad D = \begin{bmatrix} 0 \end{bmatrix}$$

To do this, enter the following commands:

```
A = [0 1;-5 -2];
B = [0;3];
C = [0 1];
D = 0;
sys = ss(A,B,C,D,0.25);
```

The last argument sets the sample time.

Discrete-Time State-Space Model with Custom State and Input Names

Create a discrete-time model with matrices `A,B,C,D` and sample time 0.05 second.

```
sys = ss(A,B,C,D,0.05,'statename',{'position' 'velocity'},...
                        'inputname','force',...
                        'notes','Created 01/16/11');
```

This model has two states labeled `position` and `velocity`, and one input labeled `force` (the dimensions of `A,B,C,D` should be consistent with these numbers of states and inputs). Finally, a note is attached with the date of creation of the model.

Convert Transfer Function Model to State-Space Model

Convert a transfer function model to a state-space model.

$$H(s) = \begin{bmatrix} \dfrac{s+1}{s^3+3s^2+3s+2} \\ \dfrac{s^2+3}{s^2+s+1} \end{bmatrix}$$

by typing

```
H = [tf([1 1],[1 3 3 2]) ; tf([1 0 3],[1 1 1])];
sys = ss(H);
size(sys)
```

```
State-space model with 2 outputs, 1 input, and 5 states.
```

The number of states is equal to the cumulative order of the SISO entries of $H(s)$.

To obtain a minimal realization of $H(s)$, type

```
sys = ss(H,'min');
size(sys)
```

```
State-space model with 2 outputs, 1 input, and 3 states.
```

The resulting state-space model has order of three, which is the minimum number of states needed to represent $H(s)$. You can see this number of states by factoring $H(s)$ as the product of a first-order system with a second-order system.

$$H(s)=\begin{bmatrix}\dfrac{1}{s+2} & 0\\ 0 & 1\end{bmatrix}\begin{bmatrix}\dfrac{s+1}{s^2+s+1}\\ \dfrac{s^2+3}{s^2+s+1}\end{bmatrix}$$

Explicit Realization of Descriptor State-Space Model

Create a descriptor state-space model ($E \neq I$).

```
a = [2 -4; 4 2];
b = [-1; 0.5];
c = [-0.5, -2];
d = [-1];
e = [1 0; -3 0.5];
sysd = dss(a,b,c,d,e);
```

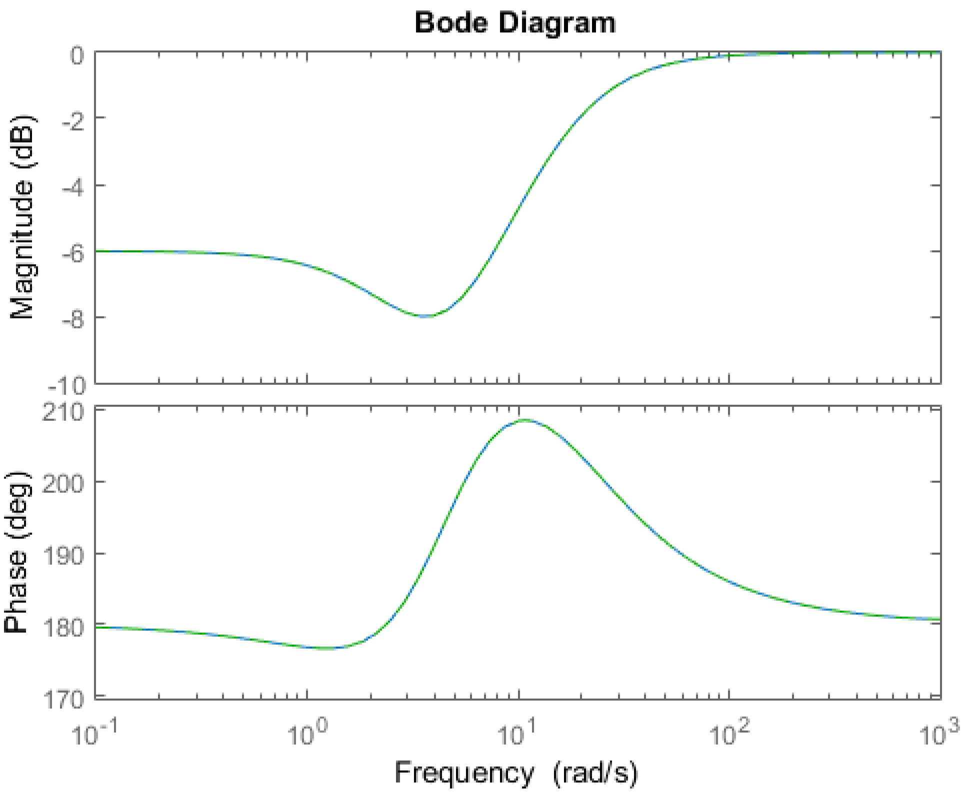
Compute an explicit realization of the system ($E = I$).

```
syse = ss(sysd,'explicit')
```

```
syse =

  a = 
        x1   x2
   x1    2   -4
   x2   20  -20

  b = 
       u1
   x1  -1
   x2  -5

  c = 
         x1     x2
   y1  -0.5     -2

  d = 
       u1
   y1  -1

Continuous-time state-space model.
```

Confirm that the descriptor and explicit realizations have equivalent dynamics.

```
bodeplot(sysd,syse,'g--')
```



Generalized State-Space Model

This example shows how to create a state-space (`genss`) model having both fixed and tunable parameters.

Create a state-space model having the following state-space matrices:

$$A = \begin{bmatrix} 1 & a+b \\ 0 & ab \end{bmatrix}, \quad B = \begin{bmatrix} -3.0 \\ 1.5 \end{bmatrix}, \quad C = \begin{bmatrix} 0.3 & 0 \end{bmatrix}, \quad D = 0,$$

where a and b are tunable parameters, whose initial values are –1 and 3, respectively.

1 Create the tunable parameters using `realp`.

```
a = realp('a',-1);
b = realp('b',3);
```

2 Define a generalized matrix using algebraic expressions of `a` and `b`.

```
A = [1 a+b;0 a*b]
```

`A` is a generalized matrix whose `Blocks` property contains `a` and `b`. The initial value of `A` is `M = [1 2;0 -3]`, from the initial values of `a` and `b`.

3 Create the fixed-value state-space matrices.

```
B = [-3.0;1.5];
C = [0.3 0];
D = 0;
```

4 Use `ss` to create the state-space model.

```
sys = ss(A,B,C,D)
```

`sys` is a generalized LTI model (`genss`) with tunable parameters `a` and `b`.

Extract Components from Identified State-Space Model

Extract the measured and noise components of an identified polynomial model into two separate state-space models. The former (measured component) can serve as a plant model while the latter can serve as a disturbance model for control system design.

```
load icEngine
z = iddata(y,u,0.04);
sys = ssest(z,3);

sysMeas = ss(sys,'measured')
sysNoise = ss(sys,'noise')
```

Alternatively, use `ss(sys)` to extract the measured component.

More About

Algorithms

For TF to SS model conversion, `ss(sys_tf)` returns a modified version of the controllable canonical form. It uses an algorithm similar to `tf2ss`, but further rescales the state vector to compress the numerical range in state matrix `A` and to improve numerics in subsequent computations.

For ZPK to SS conversion, `ss(sys_zpk)` uses direct form II structures, as defined in signal processing texts. See *Discrete-Time Signal Processing* by Oppenheim and Schafer for details.

For example, in the following code, `A` and `sys.a` differ by a diagonal state transformation:

```
n=[1 1];
d=[1 1 10];
[A,B,C,D]=tf2ss(n,d);
sys=ss(tf(n,d));
A

A =

    -1   -10
     1     0

sys.a

ans =
    -1    -5
     2     0
```

For details, see `balance`.

- “What Are Model Objects?”
- “State-Space Models”

See Also

`dss` | `frd` | `get` | `set` | `ssdata` | `tf` | `zpk`

ss2ss

State coordinate transformation for state-space model

Syntax

```
sysT = ss2ss(sys,T)
```

Description

Given a state-space model `sys` with equations

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx + Du \end{aligned}$$

or the innovations form used by the identified state-space (IDSS) models:

$$\begin{aligned} \frac{dx}{dt} &= Ax + Bu + Ke \\ y &= Cx + Du + e \end{aligned}$$

(or their discrete-time counterpart), `ss2ss` performs the similarity transformation $\bar{x} = Tx$ on the state vector x and produces the equivalent state-space model `sysT` with equations.

$$\begin{aligned} \dot{\bar{x}} &= TAT^{-1}\bar{x} + TBu \\ y &= CT^{-1}\bar{x} + Du \end{aligned}$$

or, in the case of an IDSS model:

$$\begin{aligned} \dot{\bar{x}} &= TAT^{-1}\bar{x} + TBu + TKe \\ y &= CT^{-1}\bar{x} + Du + e \end{aligned}$$

(IDSS models require System Identification Toolbox software.)

`sysT = ss2ss(sys,T)` returns the transformed state-space model `sysT` given `sys` and the state coordinate transformation `T`. The model `sys` must be in state-space form and the matrix `T` must be invertible. `ss2ss` is applicable to both continuous- and discrete-time models.

Examples

Perform a similarity transform to improve the conditioning of the *A* matrix.

```
T = balance(sys.a)
sysb = ss2ss(sys,inv(T))
```

See Also

`balreal` | `canon`

ssdata

Access state-space model data

Syntax

```
[a,b,c,d] = ssdata(sys)
[a,b,c,d,Ts] = ssdata(sys)
```

Description

`[a,b,c,d] = ssdata(sys)` extracts the matrix (or multidimensional array) data `A`, `B`, `C`, `D` from the state-space model (LTI array) `sys`. If `sys` is a transfer function or zero-pole-gain model (LTI array), it is first converted to state space. See `ss` for more information on the format of state-space model data.

If `sys` appears in descriptor form (nonempty `E` matrix), an equivalent explicit form is first derived.

If `sys` has internal delays, `A`, `B`, `C`, `D` are obtained by first setting all internal delays to zero (creating a zero-order Padé approximation). For some systems, setting delays to zero creates singular algebraic loops, which result in either improper or ill-defined, zero-delay approximations. For these systems, `ssdata` cannot display the matrices and returns an error. This error does not imply a problem with the model `sys` itself.

`[a,b,c,d,Ts] = ssdata(sys)` also returns the sample time `Ts`.

You can access the remaining LTI properties of `sys` with `get` or by direct referencing. For example:

```
sys.statename
```

For arrays of state-space models with variable numbers of states, use the syntax:

```
[a,b,c,d] = ssdata(sys,'cell')
```

to extract the state-space matrices of each model as separate cells in the cell arrays `a`, `b`, `c`, and `d`.

See Also

`dssdata` | `getdelaymodel` | `set` | `tfdata` | `zpkdata` | `get` | `ss`

stabsep

Stable-unstable decomposition

Syntax

```
[GS,GNS]=stabsep(G)
[G1,GNS] = stabsep(G,'abstol',ATOL,'reltol',RTOL)
[G1,G2]=stabsep(G, ...,'Mode', MODE,'Offset', ALPHA)
[G1,G2] = stabsep(G, opts)
```

Description

`[GS,GNS]=stabsep(G)` decomposes the LTI model `G` into its stable and unstable parts

```
G = GS + GNS
```

where `GS` contains all stable modes that can be separated from the unstable modes in a numerically stable way, and `GNS` contains the remaining modes. `GNS` is always strictly proper.

`[G1,GNS] = stabsep(G,'abstol',ATOL,'reltol',RTOL)` specifies absolute and relative error tolerances for the stable/unstable decomposition. The frequency responses of `G` and `GS + GNS` should differ by no more than `ATOL+RTOL*abs(G)`. Increasing these tolerances helps separate nearby stable and unstable modes at the expense of accuracy. The default values are `ATOL=0` and `RTOL=1e-8`.

`[G1,G2]=stabsep(G, ...,'Mode', MODE,'Offset', ALPHA)` produces a more general stable/unstable decomposition where `G1` includes all separable poles lying in the regions defined using offset `ALPHA`. This can be useful when there are numerical accuracy issues. For example, if you have a pair of poles close to, but slightly to the left of the *j*ω-axis, you can decide not to include them in the stable part of the decomposition if numerical considerations lead you to believe that the poles may be in fact unstable

This table lists the stable/unstable boundaries as defined by the offset `ALPHA`.

Mode	Continuous Time Region	Discrete Time Region
1	`Re(s)<-ALPHA*max(1,|Im(s)|)`	`1 |z| < 1-ALPHA`

Mode	Continuous Time Region	Discrete Time Region
2	`Re(s)> ALPHA*max(1,|Im(s)|)`	`2 |z| > 1+ALPHA`

The default values are `MODE=1` and `ALPHA=0`.

`[G1,G2] = stabsep(G, opts)` computes the stable/unstable decomposition of `G` using the options specified in the `stabsepOptions` object `opts`.

Examples

Compute a stable/unstable decomposition with absolute error no larger than 1e-5 and an offset of 0.1:

```
h = zpk(1,[-2 -1 1 -0.001],0.1)
[hs,hns] = stabsep(h,stabsepOptions('AbsTol',1e-5,'Offset',0.1));
```

The stable part of the decomposition has poles at -1 and -2.

```
hs

Zero/pole/gain:
-0.050075 (s+2.999)
-------------------
    (s+1) (s+2)
```

The unstable part of the decomposition has poles at +1 and -.001 (which is nominally stable).

```
hns

Zero/pole/gain:
0.050075 (s-1)
---------------
(s+0.001) (s-1)
```

See Also

`stabsepOptions` | `modsep`

stabsepOptions

Options for stable-unstable decomposition

Syntax

```
opts = stabsepOptions
opts = stabsepOptions('OptionName', OptionValue)
```

Description

`opts` `= stabsepOptions` returns the default options for the `stabsep` command.

`opts` `= stabsepOptions('`*`OptionName`*`',` *`OptionValue`*`)` accepts one or more comma-separated name/value pairs. Specify *`OptionName`* inside single quotes.

Input Arguments

Name-Value Pair Arguments

`'Focus'`

Focus of decomposition. Specified as one of the following values:

`'stable'`	First output of `stabsep` contains only stable dynamics.
`'unstable'`	First output of `stabsep` contains only unstable dynamics.

Default: `'stable'`

`'AbsTol, RelTol'`

Absolute and relative error tolerance for stable/unstable decomposition. Positive scalar values. When decomposing a model G, `stabsep` ensures that the frequency responses of G and $GS + GU$ differ by no more than `AbsTol` + `RelTol`*abs(G). Increasing these tolerances helps separate nearby stable and unstable modes at the expense of accuracy. See `stabsep` for more information.

Default: `AbsTol = 0; RelTol = 1e-8`

`'Offset'`

Offset for the stable/unstable boundary. Positive scalar value. The first output of `stabsep`includes only poles satisfying:

Continuous time:

- `Re(s) < -Offset * max(1,|Im(s)|)` `(Focus = 'stable')`
- `Re(s) > Offset * max(1,|Im(s)|)` `(Focus = 'unstable')`

Discrete time:

- `|z| < 1 - Offset` `(Focus = 'stable')`
- `|z| >1 + Offset` `(Focus = 'unstable')`

Increase the value of `Offset` to treat poles close to the stability boundary as unstable.

Default: `0`

For additional information on the options and how to use them, see the `stabsep` reference page.

Examples

Compute the stable/unstable decomposition of the system given by:

$$G(s) = \frac{10(s+0.5)}{\left(s+10^{-6}\right)(s+2-5i)(s+2+5i)}$$

Use the `Offset` option to force `stabsep` to exclude the pole at $s = 10^{-6}$ from the stable term of the stable/unstable decomposition.

```
G = zpk(-.5,[-1e-6 -2+5i -2-5i],10);
opts = stabsepOptions('Offset',.001); % Create option set
[G1,G2] = stabsep(G,opts)   % treats -1e-6 as unstable
```

These commands return the result:

```
Zero/pole/gain:
-0.17241 (s-54)
---------------
(s^2 + 4s + 29)


Zero/pole/gain:
 0.17241
----------
(s+1e-006)
```

The pole at $s = 10^{-6}$ is in the second (unstable) output.

See Also

`stabsep`

stack

Build model array by stacking models or model arrays along array dimensions

Syntax

```
sys = stack(arraydim,sys1,sys2,...)
```

Description

`sys = stack(arraydim,sys1,sys2,...)` produces an array of dynamic system models `sys` by stacking (concatenating) the models (or arrays) `sys1,sys2,...` along the array dimension `arraydim`. All models must have the same number of inputs and outputs (the same I/O dimensions), but the number of states can vary. The I/O dimensions are not counted in the array dimensions. For more information about model arrays and array dimensions, see "Model Arrays".

For arrays of state-space models with variable order, you cannot use the dot operator (e.g., `sys.a`) to access arrays. Use the syntax

```
[a,b,c,d] = ssdata(sys,'cell')
```

to extract the state-space matrices of each model as separate cells in the cell arrays `a`, `b`, `c`, and `d`.

Examples

Example 1

If `sys1` and `sys2` are two models:

- `stack(1,sys1,sys2)` produces a 2-by-1 model array.
- `stack(2,sys1,sys2)` produces a 1-by-2 model array.
- `stack(3,sys1,sys2)` produces a 1-by-1-by-2 model array.

Example 2

Stack identified state-space models derived from the same estimation data and compare their bode responses.

```
load iddata1 z1
sysc = cell(1,5);
opt = ssestOptions('Focus','simulation');
for i = 1:5
sysc{i} = ssest(z1,i-1,opt);
end
sysArray = stack(1, sysc{:});
bode(sysArray);
```

step

Step response plot of dynamic system

Syntax

```
step(sys)
step(sys,Tfinal)
step(sys,t)
step(sys1,sys2,...,sysN)
step(sys1,sys2,...,sysN,Tfinal)
step(sys1,sys2,...,sysN,t)
y = step(sys,t)
[y,t] = step(sys)
[y,t] = step(sys,Tfinal)
[y,t,x] = step(sys)
[y,t,x,ysd] = step(sys)
[y,...] = step(sys,...,options)
```

Description

`step` calculates the step response of a dynamic system. For the state space case, zero initial state is assumed. When it is invoked with no output arguments, this function plots the step response on the screen.

`step(sys)` plots the step response of an arbitrary dynamic system model `sys`. This model can be continuous or discrete, and SISO or MIMO. The step response of multi-input systems is the collection of step responses for each input channel. The duration of simulation is determined automatically, based on the system poles and zeros.

`step(sys,Tfinal)` simulates the step response from `t = 0` to the final time `t = Tfinal`. Express `Tfinal` in the system time units, specified in the `TimeUnit` property of `sys`. For discrete-time systems with unspecified sample time (`Ts = -1`), `step` interprets `Tfinal` as the number of sampling periods to simulate.

`step(sys,t)` uses the user-supplied time vector `t` for simulation. Express `t` in the system time units, specified in the `TimeUnit` property of `sys`. For discrete-time models, `t` should be of the form `Ti:Ts:Tf`, where `Ts` is the sample time. For continuous-time models, `t` should be of the form `Ti:dt:Tf`, where `dt` becomes the sample time of a discrete approximation to the continuous system (see "Algorithms" on page 1-726). The `step` command always applies the step input at `t=0`, regardless of `Ti`.

To plot the step response of several models`sys1`,..., `sysN` on a single figure, use

```
step(sys1,sys2,...,sysN)
```

```
step(sys1,sys2,...,sysN,Tfinal)
```

```
step(sys1,sys2,...,sysN,t)
```

All of the systems plotted on a single plot must have the same number of inputs and outputs. You can, however, plot a mix of continuous- and discrete-time systems on a single plot. This syntax is useful to compare the step responses of multiple systems.

You can also specify a distinctive color, linestyle, marker, or all three for each system. For example,

```
step(sys1,'y:',sys2,'g--')
```

plots the step response of `sys1` with a dotted yellow line and the step response of `sys2` with a green dashed line.

When invoked with output arguments:

```
y = step(sys,t)
```

```
[y,t] = step(sys)
```

```
[y,t] = step(sys,Tfinal)
```

```
[y,t,x] = step(sys)
```

`step` returns the output response `y`, the time vector `t` used for simulation (if not supplied as an input argument), and the state trajectories `x` (for state-space models only). No plot generates on the screen. For single-input systems, `y` has as many rows as time samples (length of `t`), and as many columns as outputs. In the multi-input case, the step responses of each input channel are stacked up along the third dimension of `y`. The dimensions of `y` are then

$$(length\ of\ t) \times (number\ of\ outputs) \times (number\ of\ inputs)$$

and `y(:,:,j)` gives the response to a unit step command injected in the `j`th input channel. Similarly, the dimensions of `x` are

$$(length\ of\ t) \times (number\ of\ states) \times (number\ of\ inputs)$$

For identified models (see `idlti` and `idnlmodlel`) `[y,t,x,ysd] = step(sys)` also computes the standard deviation `ysd` of the response y (`ysd` is empty if `sys` does not contain parameter covariance information).

`[y,...] = step(sys,...,options)` specifies additional options for computing the step response, such as the step amplitude or input offset. Use `stepDataOptions` to create the option set `options`.

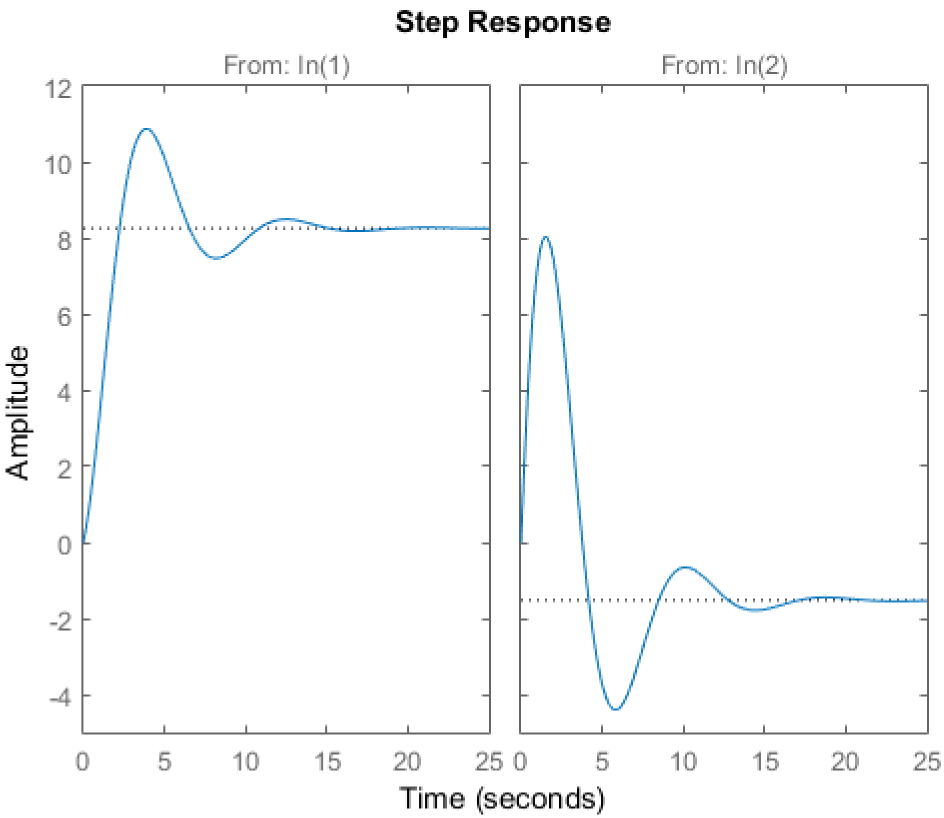
Examples

Step Response Plot of Dynamic System

Plot the step response of the following second-order state-space model:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} -0.5572 & -0.7814 \\ 0.7814 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 1 & -1 \\ 0 & 2 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix}$$
$$y = \begin{bmatrix} 1.9691 & 6.4493 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

```
a = [-0.5572,-0.7814;0.7814,0];
b = [1,-1;0,2];
c = [1.9691,6.4493];
sys = ss(a,b,c,0);
step(sys)
```

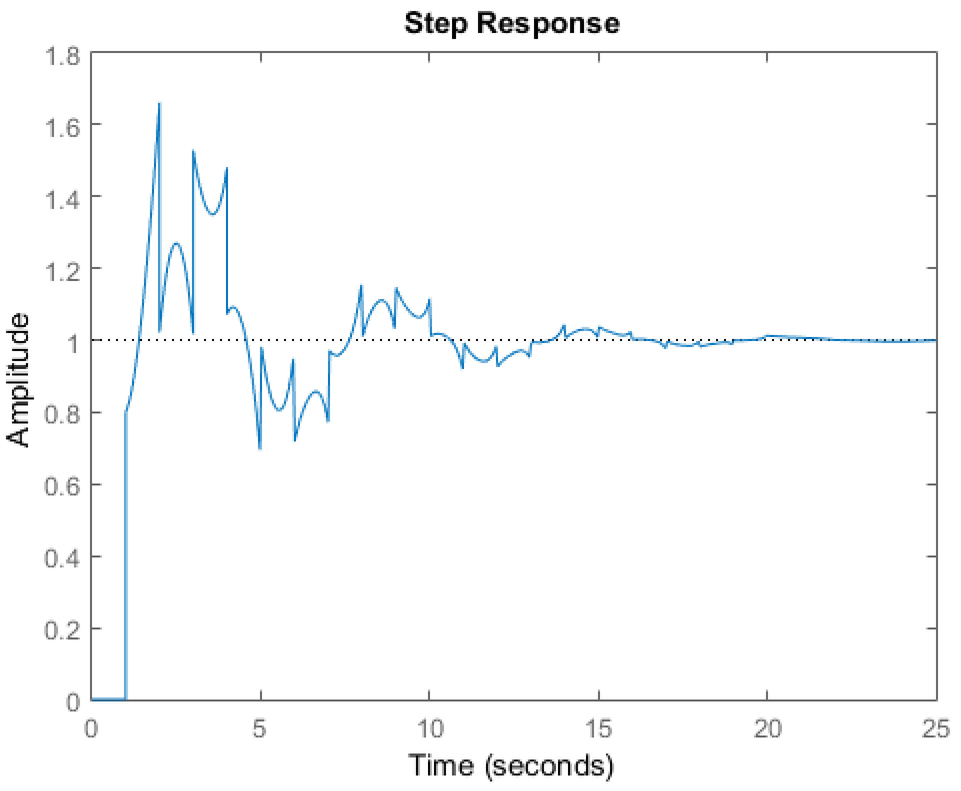


The left plot shows the step response of the first input channel, and the right plot shows the step response of the second input channel.

Step Response Plot of Feedback Loop with Delay

Create a feedback loop with delay and plot its step response.

```
s = tf('s');
G = exp(-s) * (0.8*s^2+s+2)/(s^2+s);
T = feedback(ss(G),1);
step(T)
```



The system step response displayed is chaotic. The step response of systems with internal delays may exhibit odd behavior, such as recurring jumps. Such behavior is a feature of the system and not software anomalies.

Step Responses of Identified Models with Confidence Regions

Compare the step response of a parametric identified model to a non-parametric (empirical) model. Also view their 3 σ confidence regions.

Load the data.

```
load iddata1 z1
```

Esimate a parametric model.

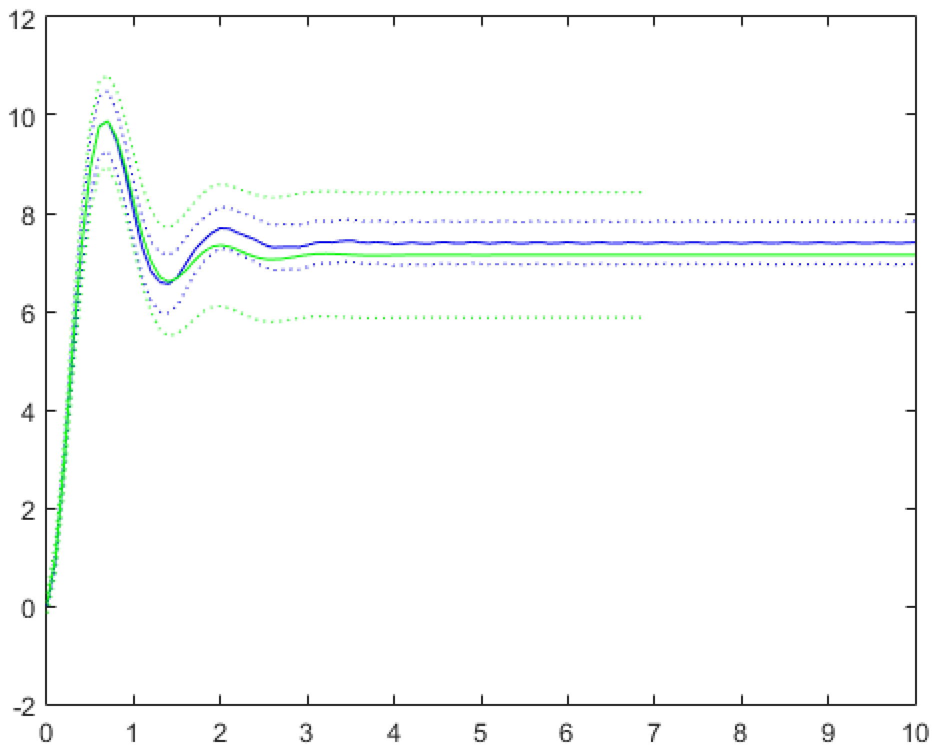
```
sys1 = ssest(z1,4);
```

Estimate a non-parametric model.

```
sys2 = impulseest(z1);
```

Plot the step responses for comparision.

```
t = (0:0.1:10)';
[y1, ~, ~, ysd1] = step(sys1,t);
[y2, ~, ~, ysd2] = step(sys2,t);
plot(t, y1, 'b', t, y1+3*ysd1, 'b:', t, y1-3*ysd1, 'b:')
hold on
plot(t, y2, 'g', t, y2+3*ysd2, 'g:', t, y2-3*ysd2, 'g:')
```



Validate Linearization of Identified Nonlinear ARX Model

Validate the linearization of a nonlinear ARX model by comparing the small amplitude step responses of the linear and nonlinear models.

Load the data.

```
load iddata2 z2;
```

Estimate a nonlinear ARX model.

```
nlsys = nlarx(z2,[4 3 10],'tree','custom',{'sin(y1(t-2)*u1(t))+y1(t-2)*u1(t)+u1(t).*u1
```

Determine an equilibrium operating point for `nlsys` corresponding to a steady-state input value of 1.

```
u0 = 1;
[X,~,r] = findop(nlsys, 'steady', 1);
y0 = r.SignalLevels.Output;
```

Obtain a linear approximation of `nlsys` at this operating point.

```
sys = linearize(nlsys,u0,X);
```

Validate the usefulness of `sys` by comparing its small-amplitude step response to that of `nlsys`.

The nonlinear system `nlsys` is operating at an equilibrium level dictated by `(u0, y0)`. Introduce a step perturbation of size 0.1 about this steady-state and compute the corresponding response.

```
opt = stepDataOptions;
opt.InputOffset = u0;
opt.StepAmplitude = 0.1;
t = (0:0.1:10)';
ynl = step(nlsys, t, opt);
```

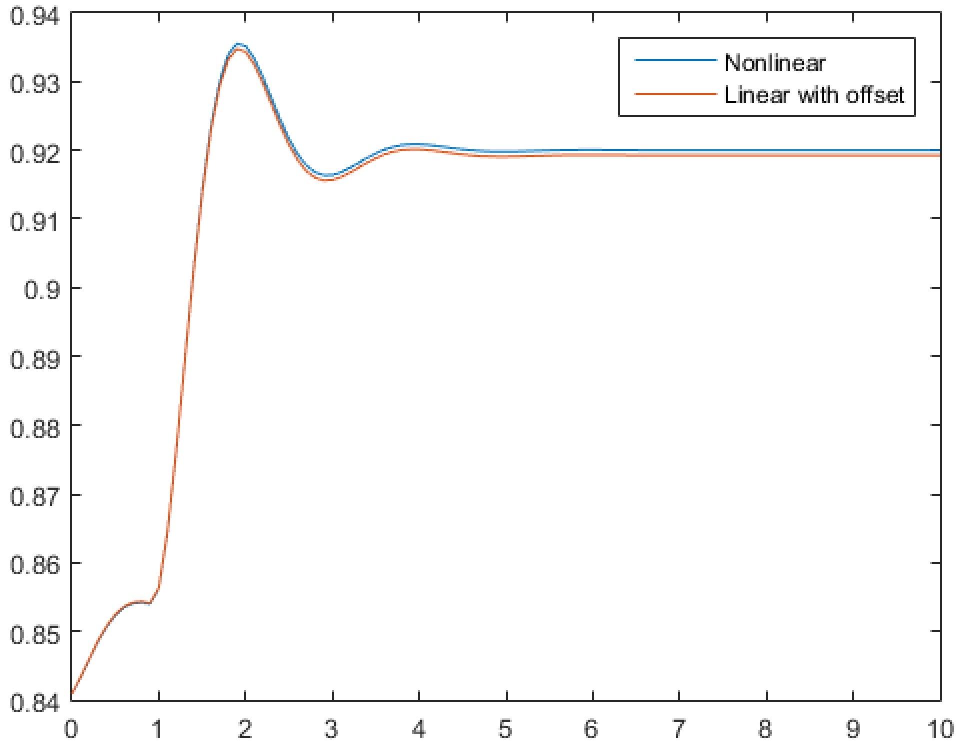
The linear system `sys` expresses the relationship between the perturbations in input to the corresponding perturbation in output. It is unaware of the nonlinear system's equilibrium values.

Plot the step response of the linear system.

```
opt = stepDataOptions;
opt.StepAmplitude = 0.1;
yl = step(sys, t, opt);
```

Add the steady-state offset, `y0` , to the response of the linear system and plot the responses.

```
plot(t, ynl, t, yl+y0)
legend('Nonlinear', 'Linear with offset')
```



Step Response of Identified Time-Series Model

Compute the step response of an identified time-series model.

A time-series model, also called a signal model, is one without measured input signals. The step plot of this model uses its (unmeasured) noise channel as the input channel to which the step signal is applied.

Load the data.

```
load iddata9;
```

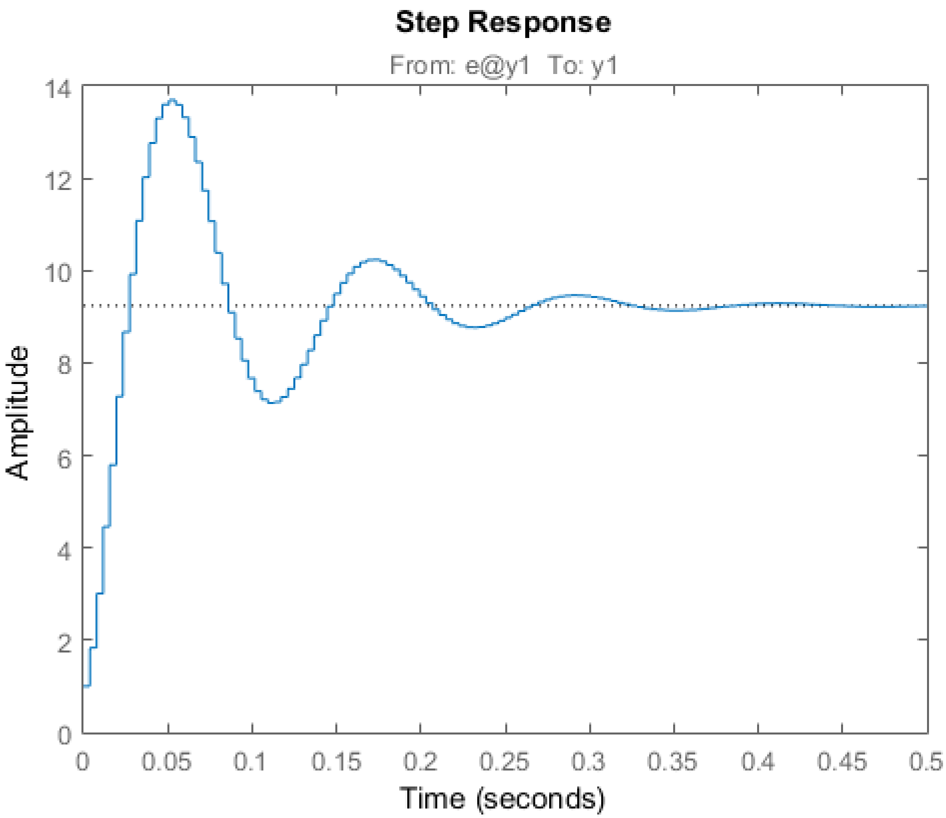
Estimate a time-series model.

```
sys = ar(z9, 4);
```

`ys` is a model of the form `A y(t) = e(t)` , where `e(t)` represents the noise channel. For computation of step response, `e(t)` is treated as an input channel, and is named `e@y1`.

Plot the step response.

```
step(sys)
```



More About

Tips

You can change the properties of your plot, for example the units. For information on the ways to change properties of your plots, see “Ways to Customize Plots”.

Algorithms

Continuous-time models without internal delays are converted to state space and discretized using zero-order hold on the inputs. The sample time is chosen automatically based on the system dynamics, except when a time vector `t = 0:dt:Tf` is supplied (`dt` is then used as sampling period). The resulting simulation time steps `t` are equisampled with spacing `dt`.

For systems with internal delays, Control System Toolbox software uses variable step solvers. As a result, the time steps `t` are not equisampled.

References

[1] L.F. Shampine and P. Gahinet, "Delay-differential-algebraic equations in control theory," *Applied Numerical Mathematics*, Vol. 56, Issues 3–4, pp. 574–588.

See Also

`stepDataOptions` | `lsim` | `impulse` | `initial` | `linearSystemAnalyzer`

stepDataOptions

Options set for `step`

Syntax

```
opt = stepDataOptions
opt = stepDataOptions(Name,Value)
```

Description

`opt = stepDataOptions` creates the default options for `step`.

`opt = stepDataOptions(Name,Value)` creates an options set with the options specified by one or more Name,Value pair arguments.

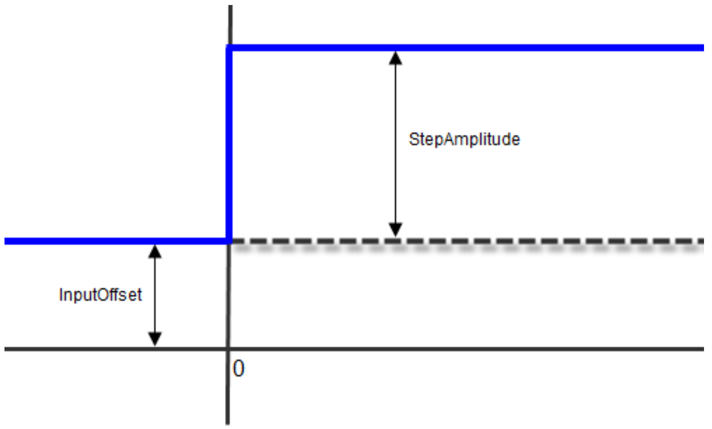
Input Arguments

Name-Value Pair Arguments

Specify optional comma-separated pairs of Name,Value arguments. `Name` is the argument name and `Value` is the corresponding value. `Name` must appear inside single quotes (`' '`). You can specify several name and value pair arguments in any order as `Name1,Value1,...,NameN,ValueN`.

`'InputOffset'`

Input signal level for all time t < 0, as shown in the next figure.



Default: 0

'StepAmplitude'

Change of input signal level which occurs at time t = 0, as shown in the previous figure.

Default: 1

Output Arguments

opt

Option set containing the specified options for `step`.

Examples

Specify Input Offset and Step Amplitude Level

Specify the input offset and amplitude level for step response.

```
sys = tf(1,[1,1]);
opt = stepDataOptions('InputOffset',-1,'StepAmplitude',2);
[y,t] = step(sys,opt)
```

See Also

`step`

stepinfo

Rise time, settling time, and other step response characteristics

Syntax

```
S = stepinfo(y,t,yfinal)
S = stepinfo(y,t)
S = stepinfo(y)
S = stepinfo(sys)
S = stepinfo(...,'SettlingTimeThreshold',ST)
S = stepinfo(...,'RiseTimeLimits',RT)
```

Description

`S = stepinfo(y,t,yfinal)` takes step response data `(t,y)` and a steady-state value `yfinal` and returns a structure `S` containing the following performance indicators:

- `RiseTime` — Rise time
- `SettlingTime` — Settling time
- `SettlingMin` — Minimum value of `y` once the response has risen
- `SettlingMax` — Maximum value of `y` once the response has risen
- `Overshoot` — Percentage overshoot (relative to `yfinal`)
- `Undershoot` — Percentage undershoot
- `Peak` — Peak absolute value of `y`
- `PeakTime` — Time at which this peak is reached

For SISO responses, `t` and `y` are vectors with the same length NS. For systems with NU inputs and NY outputs, you can specify `y` as an NS-by-NY-by-NU array (see `step`) and `yfinal` as an NY-by-NU array. `stepinfo` then returns a NY-by-NU structure array `S` of performance metrics for each I/O pair.

`S = stepinfo(y,t)` uses the last sample value of `y` as steady-state value `yfinal`. `S = stepinfo(y)` assumes `t = 1:ns`.

`S = stepinfo(sys)`computes the step response characteristics for an LTI model `sys` (see `tf`, `zpk`, or `ss` for details).

`S = stepinfo(...,'SettlingTimeThreshold',ST)` lets you specify the threshold `ST` used in the settling time calculation. The response has settled when the error `|y(t) - yfinal|` becomes smaller than a fraction `ST` of its peak value. The default value is `ST=0.02` (2%).

`S = stepinfo(...,'RiseTimeLimits',RT)` lets you specify the lower and upper thresholds used in the rise time calculation. By default, the rise time is the time the response takes to rise from 10 to 90% of the steady-state value (`RT=[0.1 0.9]`). Note that `RT(2)` is also used to calculate `SettlingMin` and `SettlingMax`.

Examples

Step Response Characteristics of Fifth-Order System

Create a fifth order system and ascertain the response characteristics.

```
sys = tf([1 5],[1 2 5 7 2]);
S = stepinfo(sys,'RiseTimeLimits',[0.05,0.95])
```

These commands return the following result:

```
S =

        RiseTime: 7.4454
    SettlingTime: 13.9378
     SettlingMin: 2.3737
     SettlingMax: 2.5201
       Overshoot: 0.8032
      Undershoot: 0
            Peak: 2.5201
        PeakTime: 15.1869
```

See Also

`lsiminfo` | `step`

stepplot

Plot step response and return plot handle

Syntax

```
h = stepplot(sys)
stepplot(sys,Tfinal)
stepplot(sys,t)
stepplot(sys1,sys2,...,sysN)
stepplot(sys1,sys2,...,sysN,Tfinal)
stepplot(sys1,sys2,...,sysN,t)
stepplot(AX,...)
stepplot(..., plotoptions)
stepplot(..., dataoptions)
```

Description

`h = stepplot(sys)` plots the step response of the dynamic system model `sys`. It also returns the plot handle `h`. You can use this handle to customize the plot with the `getoptions` and `setoptions` commands. Type

```
help timeoptions
```

for a list of available plot options.

For multiinput models, independent step commands are applied to each input channel. The time range and number of points are chosen automatically.

`stepplot(sys,Tfinal)` simulates the step response from `t = 0` to the final time `t = Tfinal`. Express `Tfinal` in the system time units, specified in the `TimeUnit` property of `sys`. For discrete-time systems with unspecified sample time (`Ts = -1`), `stepplot` interprets `Tfinal` as the number of sampling intervals to simulate.

`stepplot(sys,t)` uses the user-supplied time vector `t` for simulation. Express `t` in the system time units, specified in the `TimeUnit` property of `sys`. For discrete-time models, `t` should be of the form `Ti:Ts:Tf`, where `Ts` is the sample time. For continuous-time models, `t` should be of the form `Ti:dt:Tf`, where `dt` becomes the sample time of a discrete approximation to the continuous system (see `step`). The `stepplot` command always applies the step input at `t=0`, regardless of `Ti`.

To plot the step responses of multiple models `sys1`,`sys2`,... on a single plot, use:

`stepplot(sys1,sys2,...,sysN)`

`stepplot(sys1,sys2,...,sysN,Tfinal)`

`stepplot(sys1,sys2,...,sysN,t)`

You can also specify a color, line style, and marker for each system, as in

```
stepplot(sys1,'r',sys2,'y--',sys3,'gx')
```

`stepplot(AX,...)` plots into the axes with handle `AX`.

`stepplot(..., plotoptions)` customizes the plot appearance using the options set, `plotoptions`. Use `timeOptions` to create the options set.

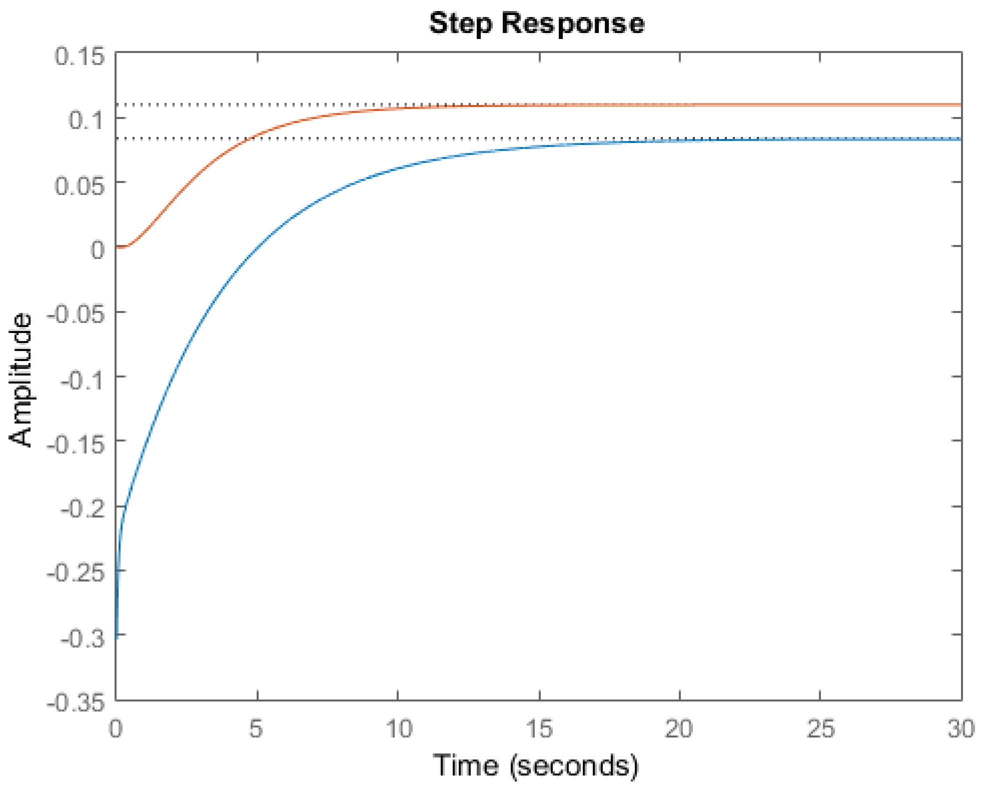
`stepplot(..., dataoptions)` specifies options such as the step amplitude and input offset using the options set, `dataoptions`. Use `stepDataOptions` to create the options set.

Examples

Normalized Response on Step Plot

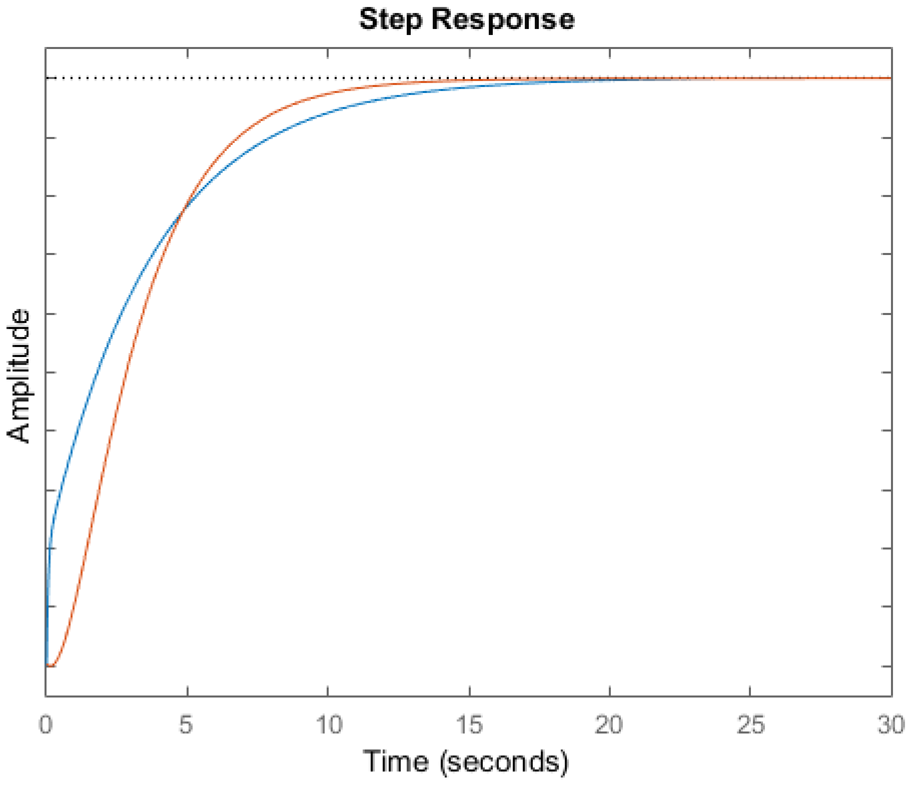
Generate a step response plot for two dynamic systems.

```
sys1 = rss(3);
sys2 = rss(3);
h = stepplot(sys1,sys2);
```



Each step response settles at a different steady-state value. Use the plot handle to normalize the plotted response.

```
setoptions(h,'Normalize','on')
```



Now, the responses settle at the same value expressed in arbitrary units.

Step Responses of Identified Models with Confidence Region

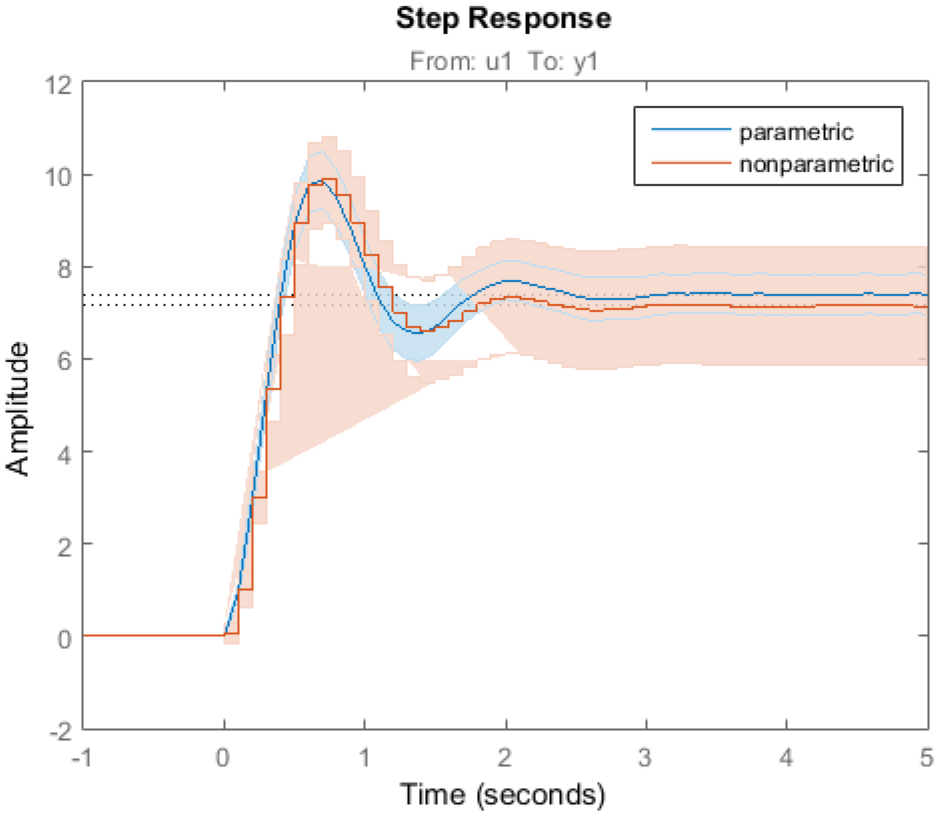
Compare the step response of a parametric identified model to a nonparametric (empirical) model, and view their 3-σ confidence regions. (Identified models require System Identification Toolbox™ software.)

Identify a parametric and a nonparametric model from sample data.

```
load iddata1 z1
sys1 = ssest(z1,4);
sys2 = impulseest(z1);
```

Plot the step responses of both identified models. Use the plot handle to display the 3-σ confidence regions.

```
t = -1:0.1:5;
h = stepplot(sys1,sys2,t);
showConfidence(h,3)
legend('parametric','nonparametric')
```



The nonparametric model `sys2` shows higher uncertainty.

Step Response of Nonlinear Model

Plot the step response of a nonlinear (Hammerstein-Wiener) model using a starting offset of 2 and step amplitude of 0.5. (Hammerstein-Weiner models require System Identification Toolbox software.)

```
load twotankdata
z = iddata(y, u, 0.2, 'Name', 'Two tank system');
sys = nlhw(z, [1 5 3], pwlinear, poly1d);

dataoptions = stepDataOptions('InputOffset', 2, 'StepAmplitude', 0.5);
stepplot(sys,60,dataoptions);
```

More About

Tips

You can change the properties of your plot, for example the units. For information on the ways to change properties of your plots, see “Ways to Customize Plots”.

See Also

`setoptions` | `getoptions` | `step`

strseq

Create sequence of indexed strings

Syntax

```
strvec = strseq(STR,INDICES)
```

Description

`strvec = strseq(STR,INDICES)` creates a sequence of indexed strings in the string vector `strvec` by appending the integer values `INDICES` to the string `STR`.

Note: You can use `strvec` to aid in system interconnection. For an example, see the `sumblk` reference page.

Examples

Create a string vector by indexing the string `'e'` at `1`, `2`, and `4`.

```
strseq('e',[1 2 4])
```

This command returns the following result:

```
ans =

    'e1'
    'e2'
    'e4'
```

See Also

`strcat` | `connect`

sumblk

Summing junction for name-based interconnections

Syntax

```
S = sumblk(formula)
S = sumblk(formula,signalsize)
S = sumblk(formula,signames1,signames2,...)
```

Description

`S = sumblk(formula)` creates the transfer function, S, of the summing junction described by the string formula. The string formula specifies an equation that relates the scalar input and output signals of S.

`S = sumblk(formula,signalsize)` returns a vector-valued summing junction. The input and output signals are vectors with signalsize elements.

`S = sumblk(formula,signames1,signames2,...)` replaces aliases (signal names beginning with `%`) in formula by the signal names signames. The number of signames arguments must match the number of aliases in formula. The first alias in formula is replaced by `signames1`, the second by `signames2`, and so on.

Input Arguments

`formula`

String specifying the equation that relates the input and output signals of the summing junction transfer function S. For example, the following command:

```
S = sumblk('e = r - y + d')
```

creates a summing junction with input names `'r'`, `'y'`, and `'d'`, output name `'e'` and equation `e = r-y+d`.

If you specify a signalsize greater than 1, the inputs and outputs of `S` are vector-valued signals. `sumblk` automatically performs vector expansion of the signal names of `S`. For example, the following command:

```
S = sumblk('v = u + d',2)
```

specifies a summing junction with input names `{'u(1)';'u(2)';'d(1)';'d(2)'}` and output names `{'v(1)';'v(2)'}`. The formulas of this summing junction are `v(1) = u(1) + d(1); v(2) = u(2) + d(2)`.

You can use one or more aliases in formula to refer to signal names defined in a variable. An alias is a signal name that begins with `%`. When formula contains aliases, `sumblk` replaces each alias with the corresponding signames argument.

Aliases are useful when you want to name individual entries in a vector-valued signal. Aliases also allow you to use input or output names of existing models. For example, if `C` and `G` are dynamic system models with nonempty `InputName` and `OutputName` properties, respectively, you can create a summing junction using the following expression.

```
S = sumblk('%e = r - %y',C.InputName,G.OutputName)
```

`sumblk` uses the values of `C.InputName` and `G.OutputName` in place of `%e` and `%y`, respectively. The vector dimension of `C.InputName` and `G.OutputName` must match. `sumblk` assigns the signal `r` the same dimension.

`signalsize`

Number of elements in each input and output signal of S. Setting signalsize greater than 1 lets you specify a summing junction that operates on vector-valued signals.

Default: 1

`signames`

Signal names to replace one alias (signal name beginning with `%`) in the formula string. You must provide one signames argument for each alias in formula.

Specify `signames` as:

- A cell array of name strings.
- The `InputName` or `OutputName` property of a model in the MATLAB workspace. For example:

```
S = sumblk('%e = r - y',C.InputName)
```

This command creates a summing junction whose outputs have the same name as the inputs of the model `C` in the MATLAB workspace.

Output Arguments

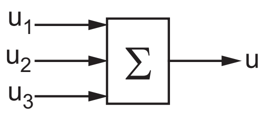
S

Transfer function for the summing junction, represented as a MIMO `tf` model object.

Examples

Summing Junction with Scalar-Valued Signals

Create the summing junction of the following illustration. All signals are scalar-valued.



This summing junction has the formula `u = u1 + u2 + u3`.

```
S = sumblk('u = u1+u2+u3');
```

`S` is the transfer function (`tf`) representation of the sum `u = u1 + u2 + u3`. The transfer function `S` gets its input and output names from the formula string.

```
S.OutputName,S.Inputname

ans =

    'u'


ans =

    'u1'
    'u2'
```

```
    'u3'
```

Summing Junction with Vector-Valued Signals

Create the summing junction `v = u - d` where `u,d,v` are vector-valued signals of length 2.

```
S = sumblk('v = u-d',2);
```

`sumblk` automatically performs vector expansion of the signal names of `S`.

```
S.OutputName,S.Inputname
```

```
ans =

    'v(1)'
    'v(2)'


ans =

    'u(1)'
    'u(2)'
    'd(1)'
    'd(2)'
```

Summing Junction with Vector-Valued Signals That Have Specified Signal Names

Create the summing junction

$$e(1) = \text{setpoint}(1) - \text{alpha} + d(1)$$
$$e(2) = \text{setpoint}(2) - q + d(2)$$

The signals `alpha` and `q` have custom names that are not merely the vector expansion of a single signal name. Therefore, use an alias in the formula specifying the summing junction.

```
S = sumblk('e = setpoint - %y + d', {'alpha';'q'});
```

`sumblk` replaces the alias `%y` with the cell array `{'alpha';'q'}`.

```
S.OutputName,S.Inputname
```

```
ans =

    'e(1)'
    'e(2)'


ans =

    'setpoint(1)'
    'setpoint(2)'
    'alpha'
    'q'
    'd(1)'
    'd(2)'
```

More About

Tips

- Use `sumblk` in conjunction with `connect` to interconnect dynamic system models and derive aggregate models for block diagrams.

- "Multi-Loop Control System"
- "MIMO Control System"

See Also

`connect` | `series` | `parallel` | `strseq`

tf

Create transfer function model, convert to transfer function model

Syntax

```
sys = tf(num,den)
sys = tf(num,den,Ts)
sys = tf(M)
sys = tf(num,den,ltisys)
tfsys = tf(sys)
tfsys = tf(sys, 'measured')
tfsys = tf(sys, 'noise')
tfsys = tf(sys, 'augmented')
```

Description

Use `tf` to create real- or complex-valued transfer function models (TF objects) or to convert state-space or zero-pole-gain models to transfer function form. You can also use `tf` to create generalized state-space (`genss`) models or uncertain state-space (`uss`) models.

Creation of Transfer Functions

`sys = tf(num,den)` creates a continuous-time transfer function with numerator(s) and denominator(s) specified by `num` and `den`. The output `sys` is:

- A `tf` model object, when `num` and `den` are numeric arrays.
- A generalized state-space model (`genss`) when `num` or `den` include tunable parameters, such as `realp` parameters or generalized matrices (`genmat`).
- An uncertain state-space model (`uss`) when `num` or `den` are uncertain (requires Robust Control Toolbox software).

In the SISO case, `num` and `den` are the real- or complex-valued row vectors of numerator and denominator coefficients ordered in *descending* powers of s. These two vectors need not have equal length and the transfer function need not be proper. For example, `h = tf([1 0],1)` specifies the pure derivative $h(s) = s$.

To create MIMO transfer functions, using one of the following approaches:

- Concatenate SISO `tf` models.
- Use the `tf` command with cell array arguments. In this case, `num` and `den` are cell arrays of row vectors with as many rows as outputs and as many columns as inputs. The row vectors `num{i,j}` and `den{i,j}` specify the numerator and denominator of the transfer function from input `j` to output `i`.

For examples of creating MIMO transfer functions, see “Examples” on page 1-747 and “MIMO Transfer Function Model” in the *Control System Toolbox User Guide*.

If all SISO entries of a MIMO transfer function have the same denominator, you can set `den` to the row vector representation of this common denominator. See "Examples" for more details.

`sys = tf(num,den,Ts)` creates a discrete-time transfer function with sample time `Ts` (in seconds). Set `Ts = -1` to leave the sample time unspecified. The input arguments `num` and `den` are as in the continuous-time case and must list the numerator and denominator coefficients in *descending* powers of *z*.

`sys = tf(M)` creates a static gain `M` (scalar or matrix).

`sys = tf(num,den,ltisys)` creates a transfer function with properties inherited from the dynamic system model `ltisys` (including the sample time).

There are several ways to create arrays of transfer functions. To create arrays of SISO or MIMO TF models, either specify the numerator and denominator of each SISO entry using multidimensional cell arrays, or use a `for` loop to successively assign each TF model in the array. See “Model Arrays”.

Any of the previous syntaxes can be followed by property name/property value pairs

```
'Property',Value
```

Each pair specifies a particular property of the model, for example, the input names or the transfer function variable. For information about the properties of `tf` objects, see “Properties” on page 1-752. Note that

```
sys = tf(num,den,'Property1',Value1,...,'PropertyN',ValueN)
```

is a shortcut for

```
sys = tf(num,den)
```

```
set(sys,'Property1',Value1,...,'PropertyN',ValueN)
```

Transfer Functions as Rational Expressions in s or z

You can also use real- or complex-valued rational expressions to create a TF model. To do so, first type either:

- `s = tf('s')` to specify a TF model using a rational function in the Laplace variable, `s`.
- `z = tf('z',Ts)` to specify a TF model with sample time `Ts` using a rational function in the discrete-time variable, `z`.

Once you specify either of these variables, you can specify TF models directly as rational expressions in the variable `s` or `z` by entering your transfer function as a rational expression in either `s` or `z`.

Conversion to Transfer Function

`tfsys = tf(sys)` converts the dynamic system model `sys` to transfer function form. The output `tfsys` is a `tf` model object representing `sys` expressed as a transfer function.

If `sys` is a model with tunable components, such as a `genss`, `genmat`, `ltiblock.tf`, or `ltiblock.ss` model, the resulting transfer function `tfsys` takes the current values of the tunable components.

Conversion of Identified Models

An identified model is represented by an input-output equation of the form `y(t) = Gu(t) + He(t)`, where `u(t)` is the set of measured input channels and `e(t)` represents the noise channels. If $\Lambda = LL'$ represents the covariance of noise `e(t)`, this equation can also be written as: `y(t) = Gu(t) + HLv(t)`, where `cov(v(t)) = I`.

`tfsys = tf(sys)`, or `tfsys = tf(sys, 'measured')` converts the measured component of an identified linear model into the transfer function form. `sys` is a model of type `idss`, `idproc`, `idtf`, `idpoly`, or `idgrey`. `tfsys` represents the relationship between `u` and `y`.

`tfsys = tf(sys, 'noise')` converts the noise component of an identified linear model into the transfer function form. It represents the relationship between the noise input, `v(t)` and output, `y_noise = HL v(t)`. The noise input channels belong to the

InputGroup 'Noise'. The names of the noise input channels are v@yname, where yname is the name of the corresponding output channel. tfsys has as many inputs as outputs.

tfsys = tf(sys, 'augmented') converts both the measured and noise dynamics into a transfer function. tfsys has ny+nu inputs such that the first nu inputs represent the channels u(t) while the remaining by channels represent the noise channels v(t). tfsys.InputGroup contains 2 input groups- 'measured' and 'noise'. tfsys.InputGroup.Measured is set to 1:nu while tfsys.InputGroup.Noise is set to nu+1:nu+ny. tfsys represents the equation y(t) = [G HL] [u; v].

Tip An identified nonlinear model cannot be converted into a transfer function. Use linear approximation functions such as linearize and linapp.

Creation of Generalized State-Space Models

You can use the syntax:

```
gensys = tf(num,den)
```

to create a Generalized state-space (genss) model when one or more of the entries num and den depends on a tunable realp or genmat model. For more information about Generalized state-space models, see "Models with Tunable Coefficients".

Examples

Example 1

Transfer Function Model with One-Input Two-Outputs

Create the one-input, two-output transfer function

$$H(p)=\begin{bmatrix} \dfrac{p+1}{p^2+2p+2} \\ \dfrac{1}{p} \end{bmatrix}$$

with input `current` and outputs `torque` and `ang velocity`.

To do this, enter

```
num = {[1 1] ; 1};
den = {[1 2 2] ; [1 0]};
H = tf(num,den,'inputn','current',...
                      'outputn',{'torque' 'ang. velocity'},...
                          'variable','p')
```

These commands produce the result:

```
Transfer function from input "current" to output...
              p + 1
 torque:  -------------
          p^2 + 2 p + 2

                 1
 ang. velocity:  -
                 p
```

Setting the `'variable'` property to `'p'` causes the result to be displayed as a transfer function of the variable *p*.

Example 2

Transfer Function Model Using Rational Expression

To use a rational expression to create a SISO TF model, type

```
s = tf('s');
H = s/(s^2 + 2*s +10);
```

This produces the same transfer function as

```
h = tf([1 0],[1 2 10]);
```

Example 3

Multiple-Input Multiple-Output Transfer Function Model

Specify the discrete MIMO transfer function

$$H(z)=\begin{bmatrix}\dfrac{1}{z+0.3} & \dfrac{z}{z+0.3}\\ \dfrac{-z+2}{z+0.3} & \dfrac{3}{z+0.3}\end{bmatrix}$$

with common denominator $d(z) = z + 0.3$ and sample time of 0.2 seconds.

```
nums = {1 [1 0];[-1 2] 3};
Ts = 0.2;
H = tf(nums,[1 0.3],Ts)     % Note: row vector for common den. d(z)
```

Example 4

Convert State-Space Model to Transfer Function

Compute the transfer function of the state-space model with the following data.

$$A=\begin{bmatrix}-2 & -1\\ 1 & -2\end{bmatrix},\quad B=\begin{bmatrix}1 & 1\\ 2 & -1\end{bmatrix},\quad C=\begin{bmatrix}1 & 0\end{bmatrix},\quad D=\begin{bmatrix}0 & 1\end{bmatrix}.$$

To do this, type

```
sys = ss([-2 -1;1 -2],[1 1;2 -1],[1 0],[0 1]);
tf(sys)
```

These commands produce the result:

```
Transfer function from input 1 to output:
s - 4.441e-016
--------------
s^2 + 4 s + 5

Transfer function from input 2 to output:
s^2 + 5 s + 8
-------------
s^2 + 4 s + 5
```

Example 5

Array of Transfer Function Models

You can use a `for` loop to specify a 10-by-1 array of SISO TF models.

```
H = tf(zeros(1,1,10));
s = tf('s')
for k=1:10,
  H(:,:,k) = k/(s^2+s+k);
end
```

The first statement pre-allocates the TF array and fills it with zero transfer functions.

Example 6

Tunable Low-Pass Filter

This example shows how to create the low-pass filter $F = a/(s + a)$ with one tunable parameter a.

You cannot use `ltiblock.tf` to represent F, because the numerator and denominator coefficients of an `ltiblock.tf` block are independent. Instead, construct F using the tunable real parameter object `realp`.

1. Create a tunable real parameter.

   ```
   a = realp('a',10);
   ```

   The `realp` object `a` is a tunable parameter with initial value 10.

2. Use `tf` to create the tunable filter `F`:

   ```
   F = tf(a,[1 a]);
   ```

`F` is a `genss` object which has the tunable parameter `a` in its `Blocks` property. You can connect `F` with other tunable or numeric models to create more complex models of control systems. For an example, see "Control System with Tunable Components".

Example 7

Extract the measured and noise components of an identified polynomial model into two separate transfer functions. The former (measured component) can serve as a plant model while the latter can serve as a disturbance model for control system design.

```
load icEngine;
z = iddata(y,u,0.04);
nb = 2; nf = 2; nc = 1; nd = 3; nk = 3;
sys = bj(z, [nb nc nd nf nk]);
```

`sys` is a model of the form: `y(t) = B/F u(t) + C/D e(t)`, where `B/F` represents the measured component and `C/D` the noise component.

```
sysMeas = tf(sys, 'measured')
sysNoise = tf(sys, 'noise')
```

Alternatively, use can simply use `tf(sys)` to extract the measured component.

Discrete-Time Conventions

The control and digital signal processing (DSP) communities tend to use different conventions to specify discrete transfer functions. Most control engineers use the z variable and order the numerator and denominator terms in descending powers of z, for example,

$$h(z) = \frac{z^2}{z^2 + 2z + 3}.$$

The polynomials z^2 and $z^2 + 2z + 3$ are then specified by the row vectors `[1 0 0]` and `[1 2 3]`, respectively. By contrast, DSP engineers prefer to write this transfer function as

$$h\left(z^{-1}\right) = \frac{1}{1 + 2z^{-1} + 3z^{-2}}$$

and specify its numerator as `1` (instead of `[1 0 0]`) and its denominator as `[1 2 3]`.

`tf` switches convention based on your choice of variable (value of the `'Variable'` property).

Variable	Convention
`'z'` (default), `'q'`	Use the row vector `[ak ... a1 a0]` to specify the polynomial $a_k z^k + \ldots + a_1 z + a_0$ (coefficients ordered in *descending* powers of z or q).
`'z^-1'`	Use the row vector `[b0 b1 ... bk]` to specify the polynomial $b_0 + b_1 z^{-1} + \ldots + b_k z^{-k}$ (coefficients in *ascending* powers of z^{-1}).

For example,

```
g = tf([1 1],[1 2 3],0.1);
```

specifies the discrete transfer function

$$g(z) = \frac{z+1}{z^2+2z+3}$$

because z is the default variable. In contrast,

```
h = tf([1 1],[1 2 3],0.1,'variable','z^-1');
```

uses the DSP convention and creates

$$h\left(z^{-1}\right) = \frac{1+z^{-1}}{1+2z^{-1}+3z^{-2}} = zg(z).$$

See also `filt` for direct specification of discrete transfer functions using the DSP convention.

Note that `tf` stores data so that the numerator and denominator lengths are made equal. Specifically, `tf` stores the values

```
num = [0 1 1]; den = [1 2 3];
```

for `g` (the numerator is padded with zeros on the left) and the values

```
num = [1 1 0]; den = [1 2 3];
```

for `h` (the numerator is padded with zeros on the right).

Properties

`tf` objects have the following properties:

`num`

Transfer function numerator coefficients.

For SISO transfer functions, `num` is a row vector of polynomial coefficients in order of descending power (for `Variable` values `s`, `z`, `p`, or `q`) or in order of ascending power (for `Variable` values `z^-1` or `q^-1`).

For MIMO transfer functions with Ny outputs and Nu inputs, num is a Ny-by-Nu cell array of the numerator coefficients for each input/output pair.

den

Transfer function denominator coefficients.

For SISO transfer functions, den is a row vector of polynomial coefficients in order of descending power (for Variable values s, z, p, or q) or in order of ascending power (for Variable values z^-1 or q^-1).

For MIMO transfer functions with Ny outputs and Nu inputs, den is a Ny-by-Nu cell array of the denominator coefficients for each input/output pair.

Variable

String specifying the transfer function display variable. Variable can take the following values:

- 's' — Default for continuous-time models
- 'z' — Default for discrete-time models
- 'p' — Equivalent to 's'
- 'q' — Equivalent to 'z'
- 'z^-1' — Inverse of 'z'
- 'q^-1' — Equivalent to 'z^-1'

The value of Variable is reflected in the display, and also affects the interpretation of the num and den coefficient vectors for discrete-time models. For Variable = 'z' or 'q', the coefficient vectors are ordered in descending powers of the variable. For Variable = 'z^-1' or 'q^-1', the coefficient vectors are ordered as ascending powers of the variable.

Default: 's'

ioDelay

Transport delays. ioDelay is a numeric array specifying a separate transport delay for each input/output pair.

For continuous-time systems, specify transport delays in the time unit stored in the TimeUnit property. For discrete-time systems, specify transport delays in integer multiples of the sample time, Ts.

For a MIMO system with Ny outputs and Nu inputs, set ioDelay to a Ny-by-Nu array. Each entry of this array is a numerical value that represents the transport delay for the corresponding input/output pair. You can also set ioDelay to a scalar value to apply the same delay to all input/output pairs.

Default: 0 for all input/output pairs

InputDelay

Input delay for each input channel, specified as a scalar value or numeric vector. For continuous-time systems, specify input delays in the time unit stored in the TimeUnit property. For discrete-time systems, specify input delays in integer multiples of the sample time Ts. For example, InputDelay = 3 means a delay of three sample times.

For a system with Nu inputs, set InputDelay to an Nu-by-1 vector. Each entry of this vector is a numerical value that represents the input delay for the corresponding input channel.

You can also set InputDelay to a scalar value to apply the same delay to all channels.

Default: 0

OutputDelay

Output delays. OutputDelay is a numeric vector specifying a time delay for each output channel. For continuous-time systems, specify output delays in the time unit stored in the TimeUnit property. For discrete-time systems, specify output delays in integer multiples of the sample time Ts. For example, OutputDelay = 3 means a delay of three sampling periods.

For a system with Ny outputs, set OutputDelay to an Ny-by-1 vector, where each entry is a numerical value representing the output delay for the corresponding output channel. You can also set OutputDelay to a scalar value to apply the same delay to all channels.

Default: 0 for all output channels

Ts

Sample time. For continuous-time models, Ts = 0. For discrete-time models, Ts is a positive scalar representing the sampling period. This value is expressed in the unit specified by the TimeUnit property of the model. To denote a discrete-time model with unspecified sample time, set Ts = -1.

Changing this property does not discretize or resample the model. Use `c2d` and `d2c` to convert between continuous- and discrete-time representations. Use `d2d` to change the sample time of a discrete-time system.

Default: `0` (continuous time)

`TimeUnit`

String representing the unit of the time variable. This property specifies the units for the time variable, the sample time `Ts`, and any time delays in the model. Use any of the following values:

- `'nanoseconds'`
- `'microseconds'`
- `'milliseconds'`
- `'seconds'`
- `'minutes'`
- `'hours'`
- `'days'`
- `'weeks'`
- `'months'`
- `'years'`

Changing this property has no effect on other properties, and therefore changes the overall system behavior. Use `chgTimeUnit` to convert between time units without modifying system behavior.

Default: `'seconds'`

`InputName`

Input channel names. Set `InputName` to a string for single-input model. For a multi-input model, set `InputName` to a cell array of strings.

Alternatively, use automatic vector expansion to assign input names for multi-input models. For example, if `sys` is a two-input model, enter:

```
sys.InputName = 'controls';
```

The input names automatically expand to `{'controls(1)';'controls(2)'}`.

You can use the shorthand notation `u` to refer to the `InputName` property. For example, `sys.u` is equivalent to `sys.InputName`.

Input channel names have several uses, including:

- Identifying channels on model display and plots
- Extracting subsystems of MIMO systems
- Specifying connection points when interconnecting models

Default: Empty string `''` for all input channels

InputUnit

Input channel units. Use `InputUnit` to keep track of input signal units. For a single-input model, set `InputUnit` to a string. For a multi-input model, set `InputUnit` to a cell array of strings. `InputUnit` has no effect on system behavior.

Default: Empty string `''` for all input channels

InputGroup

Input channel groups. The `InputGroup` property lets you assign the input channels of MIMO systems into groups and refer to each group by name. Specify input groups as a structure. In this structure, field names are the group names, and field values are the input channels belonging to each group. For example:

```
sys.InputGroup.controls = [1 2];
sys.InputGroup.noise = [3 5];
```

creates input groups named `controls` and `noise` that include input channels 1, 2 and 3, 5, respectively. You can then extract the subsystem from the `controls` inputs to all outputs using:

```
sys(:,'controls')
```

Default: Struct with no fields

OutputName

Output channel names. Set `OutputName` to a string for single-output model. For a multi-output model, set `OutputName` to a cell array of strings.

Alternatively, use automatic vector expansion to assign output names for multi-output models. For example, if `sys` is a two-output model, enter:

```
sys.OutputName = 'measurements';
```

The output names automatically expand to
`{'measurements(1)';'measurements(2)'}`.

You can use the shorthand notation `y` to refer to the `OutputName` property. For example, `sys.y` is equivalent to `sys.OutputName`.

Output channel names have several uses, including:

- Identifying channels on model display and plots
- Extracting subsystems of MIMO systems
- Specifying connection points when interconnecting models

Default: Empty string `''` for all output channels

OutputUnit

Output channel units. Use `OutputUnit` to keep track of output signal units. For a single-output model, set `OutputUnit` to a string. For a multi-output model, set `OutputUnit` to a cell array of strings. `OutputUnit` has no effect on system behavior.

Default: Empty string `''` for all output channels

OutputGroup

Output channel groups. The `OutputGroup` property lets you assign the output channels of MIMO systems into groups and refer to each group by name. Specify output groups as a structure. In this structure, field names are the group names, and field values are the output channels belonging to each group. For example:

```
sys.OutputGroup.temperature = [1];
sys.InputGroup.measurement = [3 5];
```

creates output groups named `temperature` and `measurement` that include output channels 1, and 3, 5, respectively. You can then extract the subsystem from all inputs to the `measurement` outputs using:

```
sys('measurement',:)
```

Default: Struct with no fields

Name

System name. Set `Name` to a string to label the system.

Default: `''`

Notes

Any text that you want to associate with the system. Set `Notes` to a string or a cell array of strings.

Default: `{}`

UserData

Any type of data you wish to associate with system. Set `UserData` to any MATLAB data type.

Default: `[]`

SamplingGrid

Sampling grid for model arrays, specified as a data structure.

For model arrays that are derived by sampling one or more independent variables, this property tracks the variable values associated with each model in the array. This information appears when you display or plot the model array. Use this information to trace results back to the independent variables.

Set the field names of the data structure to the names of the sampling variables. Set the field values to the sampled variable values associated with each model in the array. All sampling variables should be numeric and scalar valued, and all arrays of sampled values should match the dimensions of the model array.

For example, suppose you create a 11-by-1 array of linear models, `sysarr`, by taking snapshots of a linear time-varying system at times `t = 0:10`. The following code stores the time samples with the linear models.

```
sysarr.SamplingGrid = struct('time',0:10)
```

Similarly, suppose you create a 6-by-9 model array, `M`, by independently sampling two variables, `zeta` and `w`. The following code attaches the `(zeta,w)` values to `M`.

```
[zeta,w] = ndgrid(<6 values of zeta>,<9 values of w>)
M.SamplingGrid = struct('zeta',zeta,'w',w)
```

When you display M, each entry in the array includes the corresponding zeta and w values.

```
M
```

```
M(:,:,1,1) [zeta=0.3, w=5] =

        25
  --------------
  s^2 + 3 s + 25


M(:,:,2,1) [zeta=0.35, w=5] =

         25
  ----------------
  s^2 + 3.5 s + 25

...
```

For model arrays generated by linearizing a Simulink model at multiple parameter values or operating points, the software populates SamplingGrid automatically with the variable values that correspond to each entry in the array. For example, the Simulink Control Design commands linearize and slLinearizer populate SamplingGrid in this way.

Default: []

More About

Algorithms

tf uses the MATLAB function poly to convert zero-pole-gain models, and the functions zero and pole to convert state-space models.

- "What Are Model Objects?"
- "Transfer Functions"

See Also

filt | frd | get | set | ss | tfdata | zpk | genss | realp | genmat | ltiblock.tf

tfdata

Access transfer function data

Syntax

```
[num,den] = tfdata(sys)
[num,den,Ts] = tfdata(sys)
[num,den,Ts,sdnum,sdden]=tfdata(sys)
[num,den,Ts,...]=tfdata(sys,J1,...,Jn)
```

Description

`[num,den] = tfdata(sys)` returns the numerator(s) and denominator(s) of the transfer function for the TF, SS or ZPK model (or LTI array of TF, SS or ZPK models) `sys`. For single LTI models, the outputs `num` and `den` of `tfdata` are cell arrays with the following characteristics:

- `num` and `den` have as many rows as outputs and as many columns as inputs.
- The `(i,j)` entries `num{i,j}` and `den{i,j}` are row vectors specifying the numerator and denominator coefficients of the transfer function from input `j` to output `i`. These coefficients are ordered in *descending* powers of *s* or *z*.

For arrays `sys` of LTI models, `num` and `den` are multidimensional cell arrays with the same sizes as `sys`.

If `sys` is a state-space or zero-pole-gain model, it is first converted to transfer function form using `tf`. For more information on the format of transfer function model data, see the `tf` reference page.

For SISO transfer functions, the syntax

```
[num,den] = tfdata(sys,'v')
```

forces `tfdata` to return the numerator and denominator directly as row vectors rather than as cell arrays (see example below).

`[num,den,Ts] = tfdata(sys)` also returns the sample time `Ts`.

`[num,den,Ts,sdnum,sdden]=tfdata(sys)` also returns the uncertainties in the numerator and denominator coefficients of identified system `sys`. `sdnum{i,j}(k)` is the 1 standard uncertainty in the value `num{i,j}(k)` and `sdden{i,j}(k)` is the 1 standard uncertainty in the value `den{i,j}(k)`. If `sys` does not contain uncertainty information, `sdnum` and `sdden` are empty ([ ]).

`[num,den,Ts,...]=tfdata(sys,J1,...,Jn)` extracts the data for the `(J1,...,JN)`entry in the model array `sys`.

You can access the remaining LTI properties of `sys` with `get` or by direct referencing, for example,

```
sys.Ts
sys.variable
```

Examples

Example 1

Given the SISO transfer function

```
h = tf([1 1],[1 2 5])
```

you can extract the numerator and denominator coefficients by typing

```
[num,den] = tfdata(h,'v')
num =
     0     1     1

den =
     1     2     5
```

This syntax returns two row vectors.

If you turn `h` into a MIMO transfer function by typing

```
H = [h ; tf(1,[1 1])]
```

the command

```
[num,den] = tfdata(H)
```

now returns two cell arrays with the numerator/denominator data for each SISO entry. Use `celldisp` to visualize this data. Type

```
celldisp(num)
```

This command returns the numerator vectors of the entries of `H`.

```
num{1} =
     0     1     1

num{2} =
     0     1
```

Similarly, for the denominators, type

```
celldisp(den)
den{1} =
     1     2     5

den{2} =
     1     1
```

Example 2

Extract the numerator, denominator and their standard deviations for a 2-input, 1 output identified transfer function.

```
load iddata7
```

transfer function model

```
sys1 = tfest(z7, 2, 1, 'InputDelay',[1 0]);
```

an equivalent process model

```
sys2 = procest(z7, {'P2UZ', 'P2UZ'}, 'InputDelay',[1 0]);
```

```
[num1, den1, ~, dnum1, dden1] = tfdata(sys1);
[num2, den2, ~, dnum2, dden2] = tfdata(sys2);
```

See Also

`ssdata` | `zpkdata` | `get` | `tf`

thiran

Generate fractional delay filter based on Thiran approximation

Syntax

`sys = thiran(tau, Ts)`

Description

`sys = thiran(tau, Ts)` discretizes the continuous-time delay `tau` using a Thiran filter to approximate the fractional part of the delay. `Ts` specifies the sample time.

Input Arguments

`tau`

Time delay to discretize.

`Ts`

Sample time.

Output Arguments

`sys`

Discrete-time `tf` object.

Examples

Approximate and discretize a time delay that is a noninteger multiple of the target sample time.

```
sys1 = thiran(2.4, 1)

Transfer function:
0.004159 z^3 - 0.04813 z^2 + 0.5294 z + 1
-----------------------------------------
 z^3 + 0.5294 z^2 - 0.04813 z + 0.004159

Sample time: 1
```

The time delay is 2.4 s, and the sample time is 1 s. Therefore, `sys1` is a discrete-time transfer function of order 3.

Discretize a time delay that is an integer multiple of the target sample time.

```
sys2 = thiran(10, 1)

Transfer function:
 1
----
z^10

Sample time: 1
```

More About

Tips

- If `tau` is an integer multiple of `Ts`, then `sys` represents the pure discrete delay z^{-N}, with N = `tau/Ts`. Otherwise, `sys` is a discrete-time, all-pass, infinite impulse response (IIR) filter of order `ceil(tau/Ts)`.
- `thiran` approximates and discretizes a pure time delay. To approximate a pure continuous-time time delay without discretizing, use `pade`. To discretize continuous-time models having time delays, use `c2d`.

Algorithms

The Thiran fractional delay filter has the following form:

$$H(z) = \frac{a_N z^N + a_{N-1} z^{N-1} + \cdots + a_1}{a_0 z^N + a_1 z^{N-1} + \cdots + a_N}.$$

The coefficients a_0, ..., a_N are given by:

$$a_k = (-1)^k \binom{N}{k} \prod_{i=0}^{N} \frac{D-N+i}{D-N+k+i}, \quad \forall k : 1, 2, \ldots, N$$
$$a_0 = 1$$

where $D = \tau/T_s$ and $N = \text{ceil}(D)$ is the filter order. See [1].

References

[1] T. Laakso, V. Valimaki, “Splitting the Unit Delay”, *IEEE Signal Processing Magazine*, Vol. 13, No. 1, p.30-60, 1996.

See Also

`c2d` | `pade` | `tf`

timeoptions

Create list of time plot options

Syntax

```
P = timeoptions
P = timeoptions('cstprefs')
```

Description

`P = timeoptions` returns a list of available options for time plots with default values set. You can use these options to customize the time value plot appearance from the command line.

`P = timeoptions('cstprefs')` initializes the plot options you selected in the Control System and System Identification Toolbox Preferences Editor. For more information about the editor, see "Toolbox Preferences Editor" in the User's Guide documentation.

This table summarizes the available time plot options.

Option	Description
Title, XLabel, YLabel	Label text and style
TickLabel	Tick label style
Grid	Show or hide the grid Specified as one of the following strings: `'off' | 'on'` **Default**: `'off'`
XlimMode, YlimMode	Limit modes
Xlim, Ylim	Axes limits
IOGrouping	Grouping of input-output pairs Specified as one of the following strings: `'none' |'inputs'|'outputs'|'all'` **Default**: `'none'`
InputLabels, OutputLabels	Input and output label styles

Option	Description
InputVisible, OutputVisible	Visibility of input and output channels
Normalize	Normalize responses Specified as one of the following strings: `'on' |'off'` **Default**: `'off'`
SettleTimeThreshold	Settling time threshold
RiseTimeLimits	Rise time limits
TimeUnits	Time units, specified as one of the following strings: • `'nanoseconds'` • `'microseconds'` • `'milliseconds'` • `'seconds'` • `'minutes'` • `'hours'` • `'days'` • `'weeks'` • `'months'` • `'years'` **Default**: `'seconds'` You can also specify `'auto'` which uses time units specified in the `TimeUnit` property of the input system. For multiple systems with different time units, the units of the first system is used.

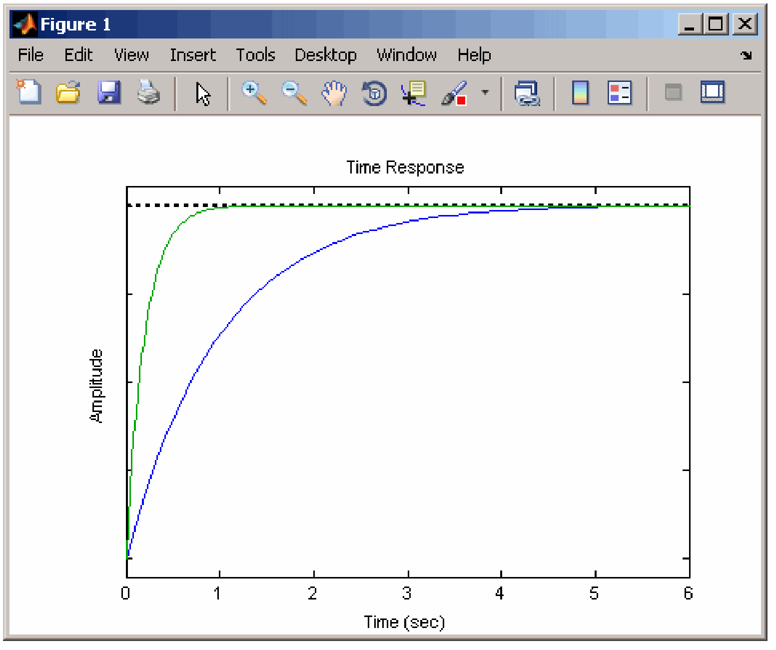
Examples

In this example, enable the normalized response option before creating a plot.

```
P = timeoptions;
```

```
% Set normalize response to on in options
P.Normalize = 'on';
% Create plot with the options specified by P
h = stepplot(tf(10,[1,1]),tf(5,[1,5]),P);
```

The following step plot is created with the responses normalized.



See Also

impulseplot | lsimplot | setoptions | stepplot | getoptions | initialplot

totaldelay

Total combined I/O delays for LTI model

Syntax

```
td = totaldelay(sys)
```

Description

`td = totaldelay(sys)` returns the total combined I/O delays for an LTI model `sys`. The matrix `td` combines contributions from the `InputDelay`, `OutputDelay`, and `ioDelayMatrix` properties.

Delays are expressed in seconds for continuous-time models, and as integer multiples of the sample period for discrete-time models. To obtain the delay times in seconds, multiply `td` by the sample time `sys.Ts`.

Examples

```
sys = tf(1,[1 0]);   % TF of 1/s
sys.inputd = 2;    % 2 sec input delay
sys.outputd = 1.5;   % 1.5 sec output delay
td = totaldelay(sys)
td =
    3.5000
```

The resulting I/O map is

$$e^{-2s} \times \frac{1}{s} e^{-1.5s} = e^{-3.5s} \frac{1}{s}$$

This is equivalent to assigning an I/O delay of 3.5 seconds to the original model `sys`.

See Also

`hasdelay` | `absorbDelay`

tzero

Invariant zeros of linear system

Syntax

```
z = tzero(sys)
z = tzero(A,B,C,D,E)
z = tzero( ___ ,tol)
[z,nrank] = tzero( ___ )
```

Description

`z = tzero(sys)` returns the invariant zeros of the multi-input, multi-output (MIMO) dynamic system, sys. If sys is a minimal realization, the invariant zeros coincide with the transmission zeros of sys.

`z = tzero(A,B,C,D,E)` returns the invariant zeros of the state-space model

$$E\frac{dx}{dt} = Ax + Bu$$
$$y = Cx + Du.$$

Omit `E` for an explicit state-space model ($E = I$).

`z = tzero( ___ ,tol)` specifies the relative tolerance, tol, controlling rank decisions.

`[z,nrank] = tzero( ___ )` also returns the normal rank of the transfer function of sys or of the transfer function $H(s) = D + C(sE - A)^{-1}B$.

Input Arguments

sys

MIMO dynamic system model. If sys is not a state-space model, then `tzero` computes `tzero(ss(sys))`.

A,B,C,D,E

State-space matrices describing the linear system

$$E\frac{dx}{dt} = Ax + Bu$$
$$y = Cx + Du.$$

`tzero` does not scale the state-space matrices when you use the syntax `z = tzero(A,B,C,D,E)`. Use `prescale` if you want to scale the matrices before using `tzero`.

Omit `E` to use $E = I$.

tol

Relative tolerance controlling rank decisions. Increasing tolerance helps detect nonminimal modes and eliminate very large zeros (near infinity). However, increased tolerance might artificially inflate the number of transmission zeros.

Default: `eps^(3/4)`

Output Arguments

z

Column vector containing the invariant zeros of sys or the state-space model described by A,B,C,D,E.

nrank

Normal rank of the transfer function of sys or of the transfer function $H(s) = D + C(sE - A)^{-1}B$. The *normal rank* is the rank for values of s other than the transmission zeros.

To obtain a meaningful result for nrank, the matrix `s*E-A` must be regular (invertible for most values of s). In other words, sys or the system described by A,B,C,D,E must have a finite number of poles.

Examples

Transmission Zeros of MIMO Transfer Function

Find the invariant zeros of a MIMO transfer function and confirm that they coincide with the transmission zeros.

Create a MIMO transfer function, and locate its invariant zeros.

```
s = tf('s');
H = [1/(s+1) 1/(s+2);1/(s+3) 2/(s+4)];
z = tzero(H)
```

```
z =

  -2.5000 + 1.3229i
  -2.5000 - 1.3229i
```

The output is a column vector listing the locations of the invariant zeros of `H`. This output shows that `H` a has complex pair of invariant zeros.

Check whether the first invariant zero is a transmission zero of `H`.

If z(1) is a transmission zero of `H`, then `H` drops rank at `s = z(1)`.

```
H1 = evalfr(H,z(1));
svd(H1)
```

```
ans =

    1.5000
    0.0000
```

`H1` is the transfer function, `H`, evaluated at `s = z(1)`. `H1` has a zero singular value, indicating that `H` drops rank at that value of `s`. Therefore, `z(1)` is a transmission zero of `H`. A similar analysis shows that `z(2)` is also a transmission zero.

Unobservable and Uncontrollable Modes of MIMO Model

Identify the unobservable and uncontrollable modes of a MIMO model using the state-space matrix syntax of `tzero`.

Obtain a MIMO model.

```
load ltiexamples gasf
size(gasf)
```

```
State-space model with 4 outputs, 6 inputs, and 25 states.
```

`gasf` is a MIMO model that might contain uncontrollable or unobservable states.

Scale the state-space matrices of `gasf`.

```
[A,B,C,D] = ssdata(prescale(gasf));
```

To identify the unobservable and uncontrollable modes of `gasf`, you need access to the state-space matrices `A`, `B`, `C`, and `D` of the model. `tzero` does not scale state-space matrices when you use the syntax. Therefore, use `prescale` with `ssdata` to extract scaled values of these matrices.

Use `tzero` to identify the uncontrollable states of `gasf`.

```
 uncon = tzero(A,B,[],[])
```

```
uncon =

   -0.0568
   -0.0568
   -0.0568
   -0.0568
   -0.0568
   -0.0568
```

When you provide `A` and `B` matrices to `tzero`, but no `C` and `D` matrices, the command returns the eigenvalues of the uncontrollable modes of `gasf`. The output shows that there are six degenerate uncontrollable modes.

Identify the unobservable states of `gasf`.

```
unobs = tzero(A,[],C,[])
```

```
unobs =

   Empty matrix: 0-by-1
```

When you provide `A` and `C` matrices, but no `B` and `D` matrices, the command returns the eigenvalues of the unobservable modes. The empty result shows that `gasf` contains no unobservable states.

Alternatives

To calculate the zeros and gain of a single-input, single-output (SISO) system, use `zero`.

More About

Invariant zeros

For a MIMO state-space model

$$\begin{aligned} E\frac{dx}{dt} &= Ax + Bu \\ y &= Cx + Du, \end{aligned}$$

the *invariant zeros* are the complex values of s for which the rank of the system matrix

$$\begin{bmatrix} A - sE & B \\ C & D \end{bmatrix}$$

drops from its normal value. (For explicit state-space models, $E = I$).

Transmission zeros

For a MIMO state-space model

$$\begin{aligned} E\frac{dx}{dt} &= Ax + Bu \\ y &= Cx + Du, \end{aligned}$$

the *transmission zeros* are the complex values of s for which the rank of the equivalent transfer function $H(s) = D + C(sE - A)^{-1}B$ drops from its normal value. (For explicit state-space models, $E = I$.)

Transmission zeros are a subset of the invariant zeros. For minimal realizations, the transmission zeros and invariant zeros are identical.

Tips

- You can use the syntax `z = tzero(A,B,C,D,E)` to find the uncontrollable or unobservable modes of a state-space model. When `C` and `D` are empty or zero, `tzero` returns the uncontrollable modes of `(A-sE,B)`. Similarly, when `B` and `D` are empty or zero, `tzero` returns the unobservable modes of `(C,A-sE)`. See "Unobservable and Uncontrollable Modes of MIMO Model" on page 1-772 for an example.

Algorithms

`tzero` is based on SLICOT routines AB08ND, AG08BD, and AB8NXZ. `tzero` implements the algorithms in [1] and [2].

References

[1] Emami-Naeini, A. and P. Van Dooren, "Computation of Zeros of Linear Multivariable Systems," *Automatica*, 18 (1982), pp. 415–430.

[2] Misra, P, P. Van Dooren, and A. Varga, “Computation of Structural Invariants of Generalized State-Space Systems,” *Automatica*, 30 (1994), pp. 1921-1936.

See Also

`pole` | `pzmap` | `zero`

updateSystem

Update dynamic system data in a response plot

Syntax

```
updateSystem(h,sys)
updateSystem(h,sys,N)
```

Description

`updateSystem(h,sys)` replaces the dynamic system used to compute a response plot with the dynamic system model or model array sys, and updates the plot. If the plot with handle h contains more than one system response, this syntax replaces the first response in the plot. `updateSystem` is useful, for example, to cause a plot in a GUI to update in response to interactive input. See "Build GUI With Interactive Plot Updates".

`updateSystem(h,sys,N)` replaces the data used to compute the Nth response in the plot.

Examples

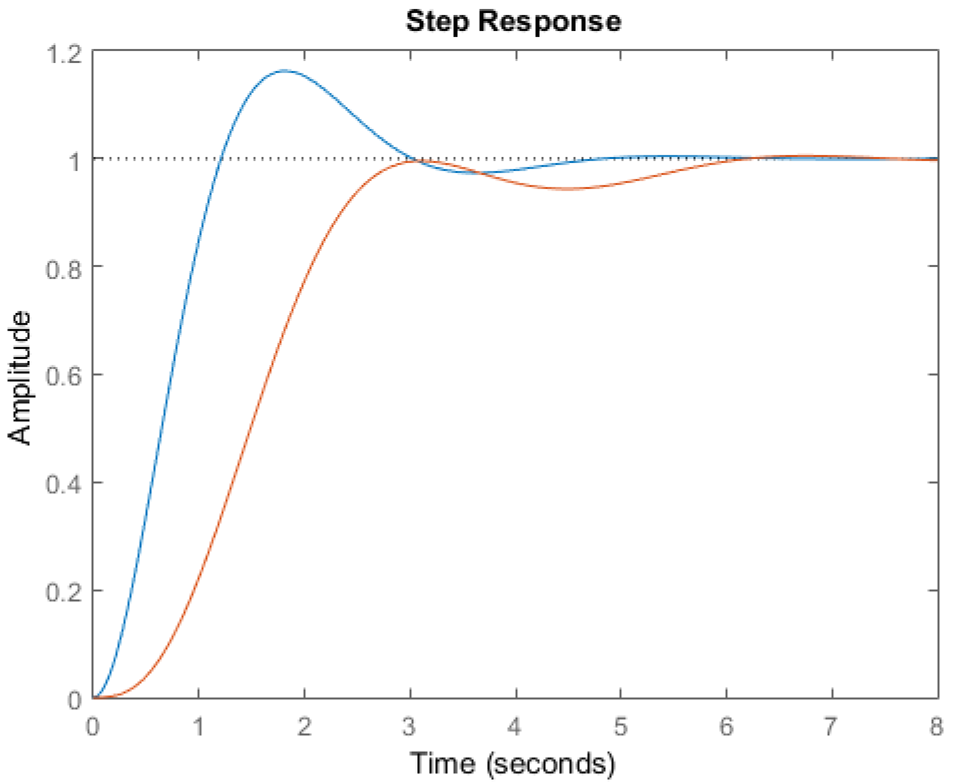
Update System Data in Plot

Replace plotted step response data with data computed from a different dynamic system model.

Suppose you have a plant model and pure integrator controller that you designed for that plant. Plot the step responses of the plant and the closed-loop system.

```
w = 2;
zeta = 0.5;
G = tf(w^2,[1,2*zeta*w,w^2]);

C1 = pid(0,0.621);
CL1 = feedback(G*C1,1);
```

```
h = stepplot(G,CL1);
```



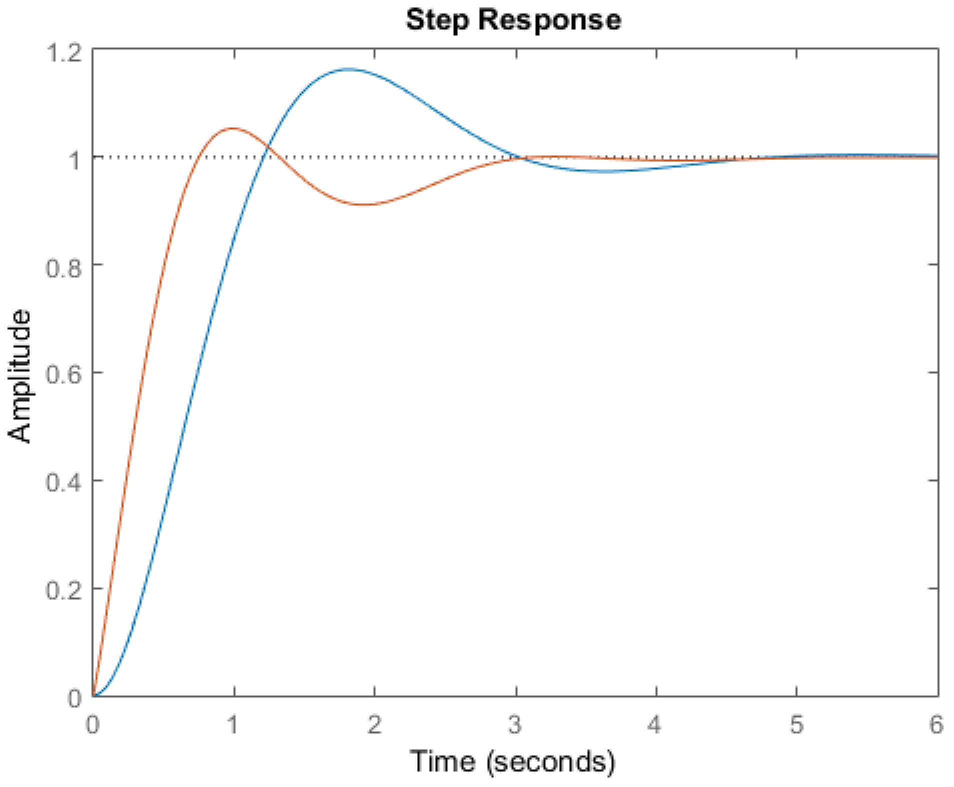
`h` is the plot handle that identifies the plot created by `stepplot`. In this figure, `G` is used to compute the first response, and `CL1` is used to compute the second response. This ordering corresponds to the order of inputs to `stepplot`.

Suppose you also have a PID controller design that you want to analyze. Create a model of the closed-loop system using this alternate controller.

```
C2 = pid(2,2.6,0.4,0.002);
CL2 = feedback(G*C2,1);
```

Update the step plot to display the second closed-loop system instead of the first. The closed-loop system is the second response in the plot, so specify the index value 2.

```
updateSystem(h,CL2,2);
```



The `updateSystem` command replaces the system used to compute the second response displayed in the plot. Instead of displaying response data derived from `CL1`, the plot now shows data derived from `CL2`.

- "Build GUI With Interactive Plot Updates"

Input Arguments

h — Plot to update
plot handle

Plot to update with new system data, specified as a plot handle. Typically, you obtain the plot handle as an output argument of a response plotting command such as `stepplot` or `bodeplot`. For example, the command `h = bodeplot(G)` returns a handle to a plot containing the Bode response of a dynamic system, `G`.

`sys` — System for new response data

dynamic system model | model array

System from which to compute new response data for the response plot, specified as a dynamic system model or model array.

sys must match the plotted system that it replaces in both I/O dimensions and array dimensions. For example, suppose h refers to a plot that displays the step responses of a 5-element vector of 2-input, 2-output systems. In this case, sys must also be a 5-element vector of 2-input, 2-output systems. The number of states in the elements of sys need not match the number of states in the plotted systems.

`N` — Index of system to replace

1 (default) | positive integer

Index of system to replace in the plot, specified as a positive integer. For example, suppose you create a plot using the following command.

```
h = impulseplot(G1,G2,G3,G4);
```

To replace the impulse data of `G3` with data from a new system, `sys`, use the following command.

```
updateSystem(h,sys,3);
```

upsample

Upsample discrete-time models

Syntax

```
sysl = upsample(sys,L)
```

Description

`sysl = upsample(sys,L)` resamples the discrete-time dynamic system model `sys` at a sampling rate that is `L`-times faster than the sample time of `sys` (Ts_0). `L` must be a positive integer. When `sys` is a TF model, $H(z)$, `upsample` returns `sysl` as $H(z^L)$ with the sample time Ts_0 / `L`.

The responses of models `sys` and `sysl` have the following similarities:

- The time responses of `sys` and `sysl` match at multiples of Ts_0.
- The frequency responses of `sys` and `sysl` match up to the Nyquist frequency π / Ts_0.

Note: `sysl` has `L` times as many states as `sys`.

Examples

Create a transfer function with a sample time that is 14 times faster than that of the following transfer function:

```
sys = tf(0.75,[1 10 2],2.25)

Transfer function:
     0.75
--------------
z^2 + 10 z + 2

Sample time: 2.25
```

To create the upsampled transfer function `sys1`, type the following commands:

```
L=14;
sys1 = upsample(sys,L)
```

These commands return the result:

```
Transfer function:
       0.75
------------------
z^28 + 10 z^14 + 2

Sample time: 0.16071
```

The sample time of `sys1` is `0.16071` seconds, which is 14 times faster than the `2.25` second sample time of `sys`.

See Also

`d2c` | `c2d` | `d2d`

view (genmat)

Visualize gain surface as a function of scheduling variables

Syntax

```
view(M)
view(M,xvar)
view(M,xvar,yvar)
view(M,xvar,xdata)
view(M,xvar,xdata,yvar,ydata)
```

Description

`view(M)` plots the values of a 1-D or 2-D array of generalized matrices on a 1-D or 2-D plot. Typically, M is a tunable gain surface that you create with `gainsurf`. The plot uses the independent variable values specified in `M.SamplingGrid` if available. Otherwise, The plot uses the indices along each array dimension for the X and Y values.

`view(M,xvar)` plots a 1-D plot of values in the generalized matrix array against a specified independent variable, xvar. For a 2-D array, the plot contains multiple traces corresponding to the other dimension in the array. xvar must refer to a sampling variable listed in `M.SamplingGrid`.

`view(M,xvar,yvar)` plots the values in the generalized matrix array against the specified independent variables, placing xvar on the X axis and yvar on the Y axis. xvar and yvar must refer to sampling variables listed in `M.SamplingGrid`. Use this syntax:

- To specify the order of independent variables plotted along the X and Y axes.
- To select the independent variable values when `M.SamplingGrid` lists more than two independent variables.

`view(M,xvar,xdata)` plots a 1-D plot of values in the generalized matrix array, using xvar to name the X axis. This plot also uses the values in xdata as the values along the X axis. Use this syntax when `M.SamplingGrid` is empty.

`view(M,xvar,xdata,yvar,ydata)` plots a 2-D plot of values in the generalized matrix array, using xvar and yvar to name the X and Y axes, respectively. This plot also uses the values in xdata and ydata as values along the X and Y axes, respectively. Use this syntax when `M.SamplingGrid` is empty.

Examples

View Gain Surface

Display a tunable gain surface that depends on two independent variables.

Create a scalar gain, K, that is a bilinear function of two independent variables, α and β:

$$K(\alpha,\beta) = K_0 + K_1\alpha + K_2\beta + K_3\alpha\beta.$$

```
[alpha,beta] = ndgrid(0:1:15,300:50:600);
F1 = alpha;
F2 = beta;
F3 = alpha.*beta;
K = gainsurf('K',1,F1,F2,F3);
K.SamplingGrid = struct('alpha',alpha,'beta',beta);
```

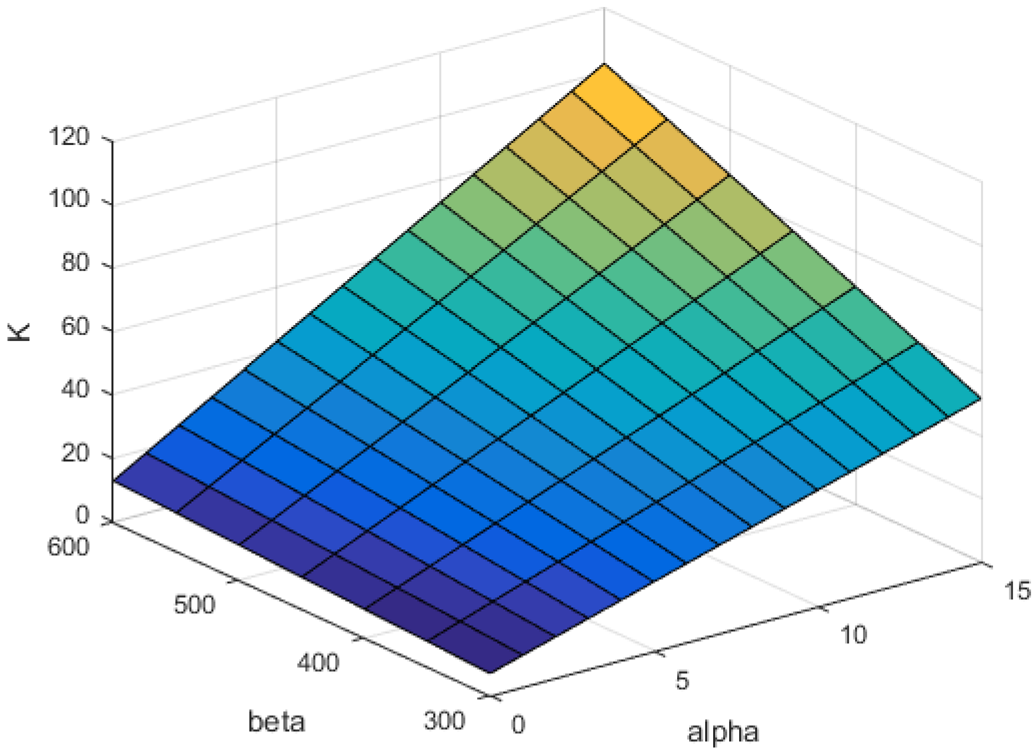
`gainsurf` initializes all gain surface coefficients to zero. For this example, manually set the coefficients to nonzero values.

```
K.Blocks.K_1.Value = -0.015;
K.Blocks.K_2.Value = 0.02;
K.Blocks.K_3.Value = 0.01;
```

Typically, you would tune the coefficients as part of a control system. You would then use `setBlockValue` to write the tuned coefficients back to `K`, and view the tuned gain surface.

Plot the gain surface.

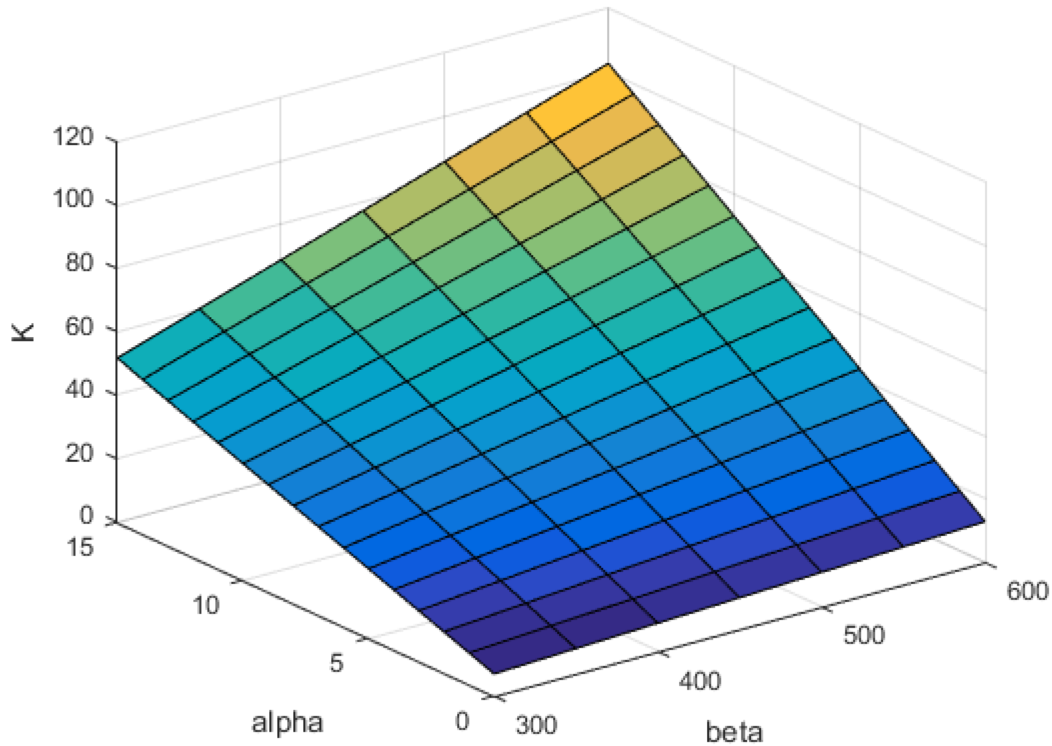
```
view(K);
```



`view` automatically applies the axis labels and scaling stored in the `SamplingGrid` property of the gain surface (see the `genmat` reference page). If the `SamplingGrid` property is empty, the independent variable axes are unlabeled and the values are index values.

By default, `view` puts `alpha` on the X-axis. This ordering arises because `SamplingGrid` associates `alpha` with the first dimension of the gain matrix. Reverse the ordering of the independent variables on the X- and Y-axes.

```
view(K,'beta','alpha')
```



View 1-Dimensional Projections of Gain Surface

Plot gain surface values as a function of one independent variable, for a gain surface that depends on two independent variables.

Create a gain surface that is a bilinear function of two independent variables, α and β.

```
[alpha,beta] = ndgrid(0:1:15,300:50:600);
F1 = alpha;
F2 = beta;
F3 = alpha.*beta;
K = gainsurf('K',1,F1,F2,F3);
SG = struct('alpha',alpha,'beta',beta);
K.SamplingGrid = SG;
```

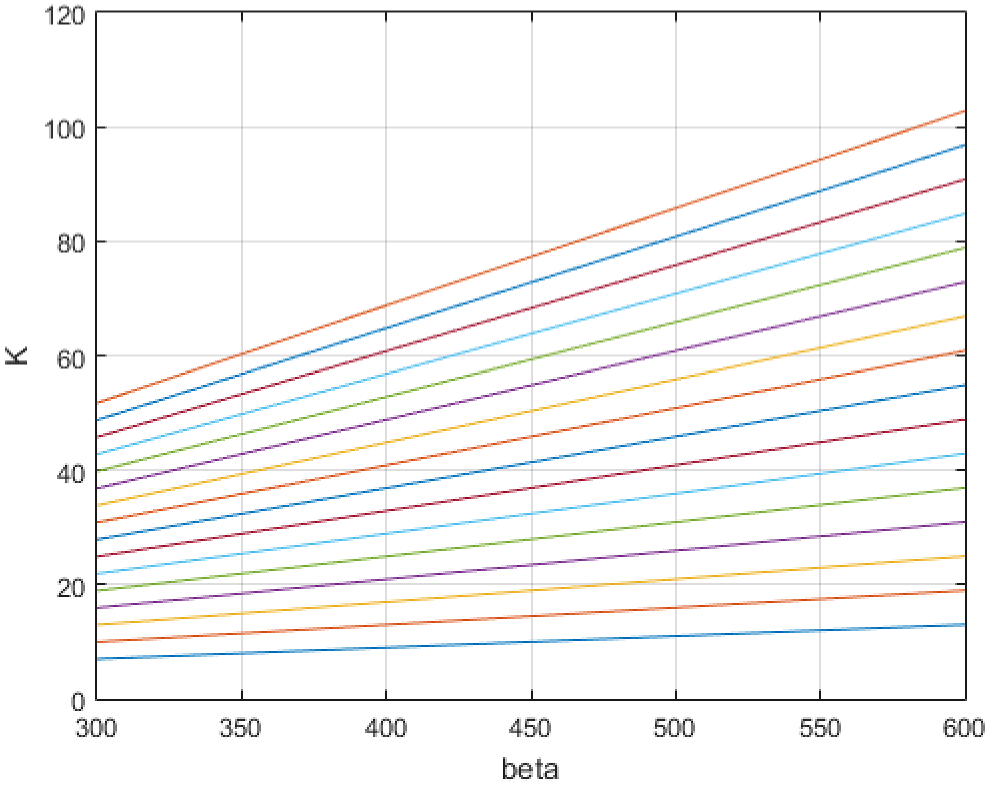
`gainsurf` initializes all gain surface coefficients to zero. For this example, manually set the coefficients to nonzero values.

```
K.Blocks.K_1.Value = -0.015;
K.Blocks.K_2.Value = 0.02;
K.Blocks.K_3.Value = 0.01;
```

Typically, you would tune the coefficients as part of a control system. You would then use `setBlockValue` to write the tuned coefficients back to `K`, and view the tuned gain surface.

Plot the gain as a function of β for all values of α in the grid of the gain surface.

```
view(K,'beta')
```



`view` scales the X-axis using the `beta` values stored in the `SamplingGrid` property of the gain surface. This plot is useful to visualize the full range of gain variation due to one independent variable.

View Gain Surface With Specified Independent Variable Names and Values

Plot a gain surface for which you provide variable names and values.

When plotting a gain surface for which you have not specified a `SamplingGrid` property value, `view` cannot label the independent variable axes. In addition, the independent variable values are just the index values of the gain matrix. (For information about `SamplingGrid`, see the `genmat` reference page). In this case, you can specify variable names and values for the purpose of the plot.

Create a gain surface that is a bilinear function of two independent variables, α and β.

```
[alpha,beta] = ndgrid(0:1:15,300:50:600);
F1 = alpha;
F2 = beta;
F3 = alpha.*beta;
K = gainsurf('K',1,F1,F2,F3);
```

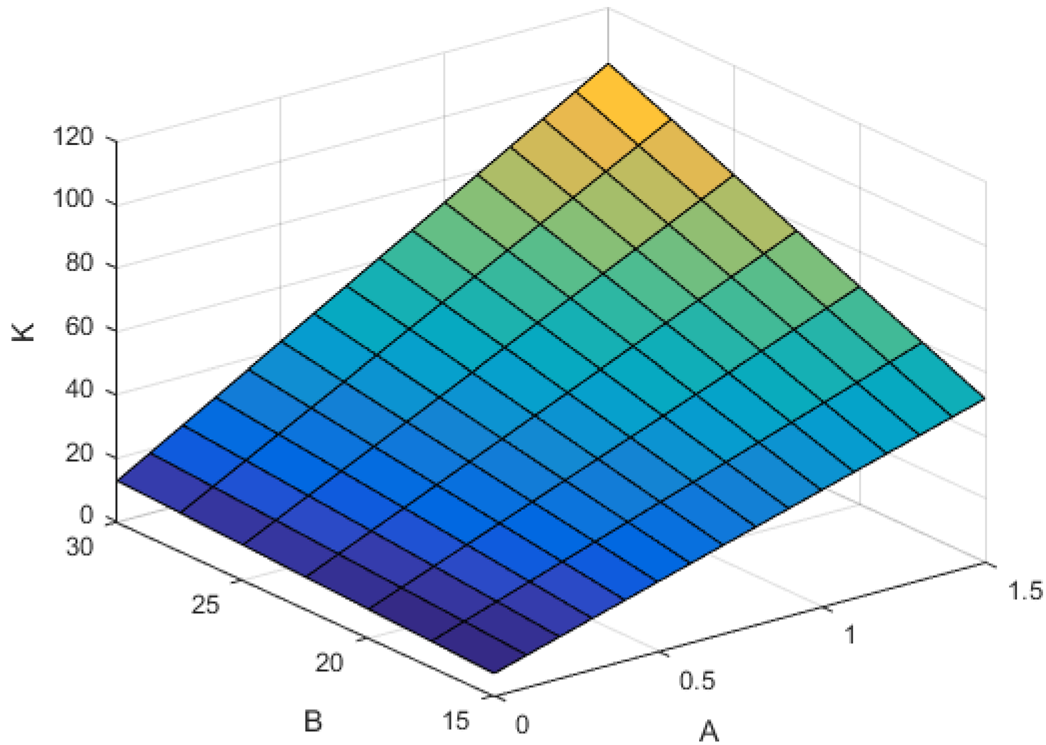
`gainsurf` initializes all gain surface coefficients to zero. For this example, manually set the coefficients to nonzero values.

```
K.Blocks.K_1.Value = -0.015;
K.Blocks.K_2.Value = 0.02;
K.Blocks.K_3.Value = 0.01;
```

Typically, you would tune the coefficients as part of a control system. You would then use `setBlockValue` to write the tuned coefficients back to `K`, and view the tuned gain surface.

View the gain surface, specifying variable names and values.

```
view(K,'A',0:0.1:1.5,'B',15:2.5:30)
```



You can use any variable name and values that you like. The name and value only label the axes and do not affect the gain values themselves, which are stored in `K`. However, the vectors you supply for the variable values must match the sampling dimensions of the gain surface. For example, `K` is created using an 16-element vector for its first dimension. Therefore, the vector you provide of values for that dimension must also have 16 elements.

Input Arguments

`M` — Array of generalized matrices

`genmat` array

Array of generalized matrices to plot, specified as a `genmat` array. Typically, M represents a variable gain surface that you create using the `gainsurf`command. Optionally, you can set the `SamplingGrid` property of M to list the independent variable names and values corresponding to entries in the array. See the `genmat` reference page for more information.

`xvar` — X-axis variable

string

X-axis variable in the plot, specified as a string.

If the `SamplingGrid` property of M specifies independent variable names and values, xvar must match one of those variable names. In this case, `view` uses the values stored in `M.SamplingGrid` for the X axis of the plot.

If the `SamplingGrid` property of M is empty, `view` uses xvar to label the X axis of the plot. In this case, you must also specify values for the X axis using the xvar input argument.

`yvar` — Y-axis variable

string

Y-axis variable in the plot, specified as a string.

If the `SamplingGrid` property of M specifies independent variable names and values, yvar must match one of those variable names. In this case, `view` uses the values stored in `M.SamplingGrid` for the Y axis of the plot.

If the `SamplingGrid` property of M is empty, `view` uses yvar to label the Y axis of the plot. In this case, you must also specify values for the Y axis using the yvar input argument.

`xdata` — X-axis values

numeric vector

X-axis values in the plots, specified as a numeric vector. If the `SamplingGrid` property of M is empty, use xdata to specify values for `view` to display along the X axis of the plot. The length of xdata must match the first array dimension of M.

`ydata` — Y-axis values

numeric vector

Y-axis values in the plots, specified as a numeric vector. If the `SamplingGrid` property of M is empty, use ydata to specify values for `view` to display along the Y axis of the plot. The length of ydata must match the first array dimension of M.

See Also

Functions

`gainsurf` | `genmat` | `getValue` | `setBlockValue`

xperm

Reorder states in state-space models

Syntax

```
sys = xperm(sys,P)
```

Description

`sys = xperm(sys,P)` reorders the states of the state-space model `sys` according to the permutation `P`. The vector `P` is a permutation of 1:*NX*, where *NX* is the number of states in `sys`. For information about creating state-space models, see `ss` and `dss`.

Examples

Order the states in the `ssF8` model in alphabetical order.

1 Load the ssF8 model by typing the following commands:

```
load ltiexamples
ssF8
```

These commands return:

```
a =
                PitchRate    Velocity         AOA  PitchAngle
   PitchRate         -0.7     -0.0458       -12.2           0
   Velocity             0      -0.014     -0.2904      -0.562
   AOA                  1     -0.0057        -1.4           0
   PitchAngle           1           0           0           0

b =
               Elevator  Flaperon
   PitchRate      -19.1      -3.1
   Velocity     -0.0119   -0.0096
   AOA            -0.14     -0.72
   PitchAngle         0         0

c =
                  PitchRate    Velocity         AOA  PitchAngle
```

```
  FlightPath             0           0          -1           1
  Acceleration           0           0       0.733           0

d =
              Elevator  Flaperon
  FlightPath         0         0
  Acceleration  0.0768    0.1134

Continuous-time model.
```

2 Order the states in alphabetical order by typing the following commands:

```
[y,P]=sort(ssF8.StateName);
sys=xperm(ssF8,P)
```

These commands return:

```
a =
                   AOA  PitchAngle   PitchRate    Velocity
  AOA             -1.4           0           1     -0.0057
  PitchAngle         0           0           1           0
  PitchRate      -12.2           0        -0.7     -0.0458
  Velocity     -0.2904      -0.562           0      -0.014

b =
            Elevator  Flaperon
  AOA          -0.14     -0.72
  PitchAngle       0         0
  PitchRate    -19.1      -3.1
  Velocity   -0.0119   -0.0096

c =
                   AOA  PitchAngle   PitchRate    Velocity
  FlightPath        -1           1           0           0
  Acceleration   0.733           0           0           0

d =
              Elevator  Flaperon
  FlightPath         0         0
  Acceleration  0.0768    0.1134

Continuous-time model.
```

The states in `ssF8` now appear in alphabetical order.

See Also

`ss` | `dss`

zero

Zeros and gain of SISO dynamic system

Syntax

```
z = zero(sys)
[z,gain] = zero(sys)
[z,gain] = zero(sysarr,J1,...,JN)
```

Description

`z = zero(sys)` returns the zeros of the single-input, single-output (SISO) dynamic system model, sys.

`[z,gain] = zero(sys)` also returns the overall gain of sys.

`[z,gain] = zero(sysarr,J1,...,JN)` returns the zeros and gain of the model with subscripts J1,...,JN in the model array sysarr.

Input Arguments

sys

SISO dynamic system model.

If sys has internal delays, `zero` sets all internal delays to zero, creating a zero-order Padé approximation. This approximation ensures that the system has a finite number of zeros. `zero` returns an error if setting internal delays to zero creates singular algebraic loops.

sysarr

Array of dynamic system models.

J1,...,JN

Indices identifying the model `sysarr(J1,...,JN)` in the array sysarr.

Output Arguments

z

Column vector containing the locations of zeros in sys. The zero locations are expressed in the reciprocal of the time units of sys. For example, the zeros are in units of 1/minutes if the `TimeUnit` property of sys is `minutes`.

gain

Gain of sys (in the zero-pole-gain sense).

Examples

Zero Locations and Gain of Transfer Function

Calculate the zero locations and overall gain of the transfer function

$$H(s) = \frac{4.2s^2 + 0.25s - 0.004}{s^2 + 9.6s + 17}.$$

```
H = tf([4.2,0.25,-0.004],[1,9.6,17]);
[z,gain] = zero(H)
```

```
z =

   -0.0726
    0.0131


gain =

    4.2000
```

The zero locations are expressed in radians per second, because the time unit of the transfer function (`H.TimeUnit`) is seconds. Change the model time units, and `zero` returns pole locations relative to the new unit.

```
H = chgTimeUnit(H,'minutes');
[z,gain] = zero(H)
```

```
z =
```

```
   -4.3581
    0.7867


gain =

    4.2000
```

Alternatives

To calculate the transmission zeros of a multi-input, multi-output system, use `tzero`.

See Also

`pzmap` | `pole` | `tzero`

zgrid

Generate z-plane grid of constant damping factors and natural frequencies

Syntax

```
zgrid
zgrid(z,wn)
zgrid([],[])
```

Description

`zgrid` generates, for root locus and pole-zero maps, a grid of constant damping factors from zero to one in steps of 0.1 and natural frequencies from zero to π in steps of π/10, and plots the grid over the current axis. If the current axis contains a discrete *z*-plane root locus diagram or pole-zero map, `zgrid` draws the grid over the plot without altering the current axis limits.

`zgrid(z,wn)` plots a grid of constant damping factor and natural frequency lines for the damping factors and normalized natural frequencies in the vectors `z` and `wn`, respectively. If the current axis contains a discrete *z*-plane root locus diagram or pole-zero map, `zgrid(z,wn)` draws the grid over the plot. The frequency lines for unnormalized (true) frequencies can be plotted using

```
zgrid(z,wn/Ts)
```

where `Ts` is the sample time.

`zgrid([],[])` draws the unit circle.

Alternatively, you can select **Grid** from the right-click menu to generate the same z-plane grid.

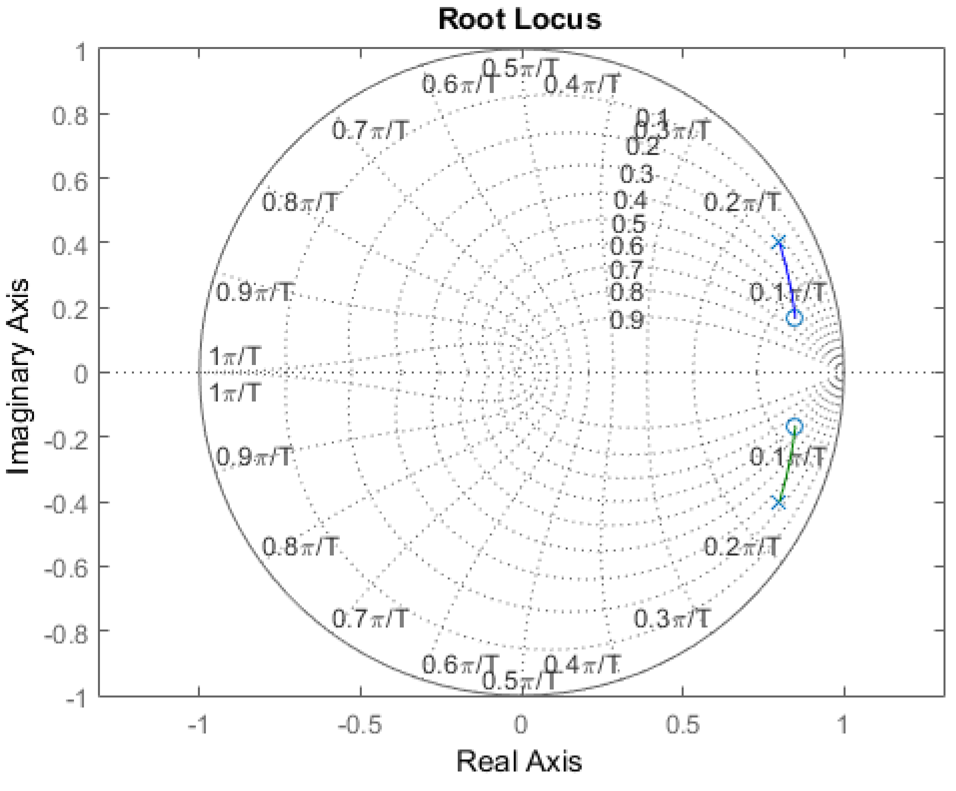
Examples

Plot z-plane grid lines on the root locus

To see the z-plane grid on the root locus plot, type

```
H = tf([2 -3.4 1.5],[1 -1.6 0.8],-1)
rlocus(H)
zgrid
axis('equal')
```

```
H =

  2 z^2 - 3.4 z + 1.5
  -------------------
   z^2 - 1.6 z + 0.8

Sample time: unspecified
Discrete-time transfer function.
```



See Also

`sgrid` | `pzmap` | `rlocus`

zpk

Create zero-pole-gain model; convert to zero-pole-gain model

Syntax

```
sys = zpk(z,p,k)
sys = zpk(z,p,k,Ts)
sys = zpk(M)
sys = zpk(z,p,k,ltisys)
s = zpk('s')
z = zpk('z',Ts)
zsys = zpk(sys)
zsys = zpk(sys, 'measured')
zsys = zpk(sys, 'noise')
zsys = zpk(sys, 'augmented')
```

Description

Used `zpk` to create zero-pole-gain models (`zpk` model objects), or to convert dynamic systems to zero-pole-gain form.

Creation of Zero-Pole-Gain Models

`sys = zpk(z,p,k)` creates a continuous-time zero-pole-gain model with zeros `z`, poles `p`, and gain(s) `k`. The output `sys` is a `zpk` model object storing the model data.

In the SISO case, `z` and `p` are the vectors of real- or complex-valued zeros and poles, and `k` is the real- or complex-valued scalar gain:

$$h(s) = k\frac{(s-z(1))(s-z(2))\ldots(s-z(m))}{(s-p(1))(s-p(2))\ldots(s-p(n))}$$

Set `z` or `p` to `[]` for systems without zeros or poles. These two vectors need not have equal length and the model need not be proper (that is, have an excess of poles).

To create a MIMO zero-pole-gain model, specify the zeros, poles, and gain of each SISO entry of this model. In this case:

- `z` and `p` are cell arrays of vectors with as many rows as outputs and as many columns as inputs, and `k` is a matrix with as many rows as outputs and as many columns as inputs.
- The vectors `z{i,j}` and `p{i,j}` specify the zeros and poles of the transfer function from input `j` to output `i`.
- `k(i,j)` specifies the (scalar) gain of the transfer function from input `j` to output `i`.

See below for a MIMO example.

`sys = zpk(z,p,k,Ts)` creates a discrete-time zero-pole-gain model with sample time `Ts` (in seconds). Set `Ts = -1` or `Ts = []` to leave the sample time unspecified. The input arguments `z`, `p`, `k` are as in the continuous-time case.

`sys = zpk(M)` specifies a static gain `M`.

`sys = zpk(z,p,k,ltisys)` creates a zero-pole-gain model with properties inherited from the LTI model `ltisys` (including the sample time).

To create an array of `zpk` model objects, use a `for` loop, or use multidimensional cell arrays for `z` and `p`, and a multidimensional array for `k`.

Any of the previous syntaxes can be followed by property name/property value pairs.

```
'PropertyName',PropertyValue
```

Each pair specifies a particular property of the model, for example, the input names or the input delay time. For more information about the properties of `zpk` model objects, see “Properties” on page 1-802. Note that

```
sys = zpk(z,p,k,'Property1',Value1,...,'PropertyN',ValueN)
```

is a shortcut for the following sequence of commands.

```
sys = zpk(z,p,k)
set(sys,'Property1',Value1,...,'PropertyN',ValueN)
```

Zero-Pole-Gain Models as Rational Expressions in s or z

You can also use rational expressions to create a ZPK model. To do so, first type either:

- `s = zpk('s')` to specify a ZPK model using a rational function in the Laplace variable, `s`.
- `z = zpk('z',Ts)` to specify a ZPK model with sample time `Ts` using a rational function in the discrete-time variable, `z`.

Once you specify either of these variables, you can specify ZPK models directly as rational expressions in the variable `s` or `z` by entering your transfer function as a rational expression in either `s` or `z`.

Conversion to Zero-Pole-Gain Form

`zsys = zpk(sys)` converts an arbitrary LTI model `sys` to zero-pole-gain form. The output `zsys` is a ZPK object. By default, `zpk` uses `zero` to compute the zeros when converting from state-space to zero-pole-gain. Alternatively,

```
zsys = zpk(sys,'inv')
```

uses inversion formulas for state-space models to compute the zeros. This algorithm is faster but less accurate for high-order models with low gain at $s = 0$.

Conversion of Identified Models

An identified model is represented by an input-output equation of the form `y(t) = Gu(t) + He(t)`, where `u(t)` is the set of measured input channels and `e(t)` represents the noise channels. If $\Lambda = LL'$ represents the covariance of noise `e(t)`, this equation can also be written as `y(t) = Gu(t) + HLv(t)`, where `cov(v(t)) = I`.

`zsys = zpk(sys)`, or `zsys = zpk(sys, 'measured')` converts the measured component of an identified linear model into the ZPK form. `sys` is a model of type `idss`, `idproc`, `idtf`, `idpoly`, or `idgrey`. `zsys` represents the relationship between `u` and `y`.

`zsys = zpk(sys, 'noise')` converts the noise component of an identified linear model into the ZPK form. It represents the relationship between the noise input, `v(t)` and output, `y_noise = HL v(t)`. The noise input channels belong to the `InputGroup 'Noise'`. The names of the noise input channels are `v@yname`, where `yname` is the name of the corresponding output channel. `zsys` has as many inputs as outputs.

`zsys = zpk(sys, 'augmented')` converts both the measured and noise dynamics into a ZPK model. `zsys` has `ny+nu` inputs such that the first `nu` inputs represent the channels `u(t)` while the remaining by channels represent the noise channels v(t). zsys.InputGroup contains 2 input groups, 'measured' and 'noise'. zsys.InputGroup.Measured is set to 1:nu while zsys.InputGroup.Noise is set to nu+1:nu+ny. zsys represents the equation y(t) = [G HL] [u; v].

Tip An identified nonlinear model cannot be converted into a ZPK system. Use linear approximation functions such as linearize and linapp.

Variable Selection

As for transfer functions, you can specify which variable to use in the display of zero-pole-gain models. Available choices include *s* (default) and *p* for continuous-time models, and *z* (default), z^{-1}, q^{-1} (equivalent to z^{-1}), or *q* (equivalent to *z*) for discrete-time models. Reassign the 'Variable' property to override the defaults. Changing the variable affects only the display of zero-pole-gain models.

Properties

zpk objects have the following properties:

z

System zeros.

The z property stores the transfer function zeros (the numerator roots). For SISO models, z is a vector containing the zeros. For MIMO models with Ny outputs and Nu inputs, z is a Ny-by-Nu cell array of vectors of the zeros for each input/output pair.

p

System poles.

The p property stores the transfer function poles (the denominator roots). For SISO models, p is a vector containing the poles. For MIMO models with Ny outputs and Nu inputs, p is a Ny-by-Nu cell array of vectors of the poles for each input/output pair.

k

System gains.

The `k` property stores the transfer function gains. For SISO models, `k` is a scalar value. For MIMO models with `Ny` outputs and `Nu` inputs, `k` is a `Ny`-by-`Nu` matrix storing the gains for each input/output pair.

DisplayFormat

String specifying the way the numerator and denominator polynomials are factorized for display purposes.

The numerator and denominator polynomials are each displayed as a product of first- and second-order factors. `DisplayFormat` controls the display of those factors. `DisplayFormat` can take the following values:

- `'roots'` (default) — Display factors in terms of the location of the polynomial roots.
- `'frequency'` — Display factors in terms of root natural frequencies ω_0 and damping ratios ζ.

  The `'frequency'` display format is not available for discrete-time models with `Variable` value `'z^-1'` or `'q^-1'`.
- `'time constant'` — Display factors in terms of root time constants τ and damping ratios ζ.

  The `'time constant'` display format is not available for discrete-time models with `Variable` value `'z^-1'` or `'q^-1'`.

For continuous-time models, the following table shows how the polynomial factors are written in each display format.

`DisplayName` Value	First-Order Factor (Real Root *R*)	Second-Order Factor (Complex Root pair $R = a \pm jb$)
`'roots'`	$(s - R)$	$(s^2 - \alpha s + \beta)$, where $\alpha = 2a$, $\beta = a^2 + b^2$
`'frequency'`	$(1 - s/\omega_0)$, where $\omega_0 = R$	$1 - 2\zeta(s/\omega_0) + (s/\omega_0)^2$, where ${\omega_0}^2 = a^2 + b^2$, $\zeta = a/\omega_0$
`'time constant'`	$(1 - \tau s)$, where $\tau = 1/R$	$1 - 2\zeta(\tau s) + (\tau s)^2$, where $\tau = 1/\omega_0$, $\zeta = a\tau$

For discrete-time models, the polynomial factors are written as in continuous time, with the following variable substitutions:

$$s \to w = \frac{z-1}{T_s}; \quad R \to \frac{R-1}{T_s},$$

where T_s is the sample time. In discrete time, τ and ω_0 closely match the time constant and natural frequency of the equivalent continuous-time root, provided $|z–1| \ll T_s$ ($\omega_0 \ll \pi/T_s$ = Nyquist frequency).

Default: `'roots'`

`Variable`

String specifying the transfer function display variable. `Variable` can take the following values:

- `'s'` — Default for continuous-time models
- `'z'` — Default for discrete-time models
- `'p'` — Equivalent to `'s'`
- `'q'` — Equivalent to `'z'`
- `'z^-1'` — Inverse of `'z'`
- `'q^-1'` — Equivalent to `'z^-1'`

The value of `Variable` only affects the display of `zpk` models.

Default: `'s'`

`ioDelay`

Transport delays. `ioDelay` is a numeric array specifying a separate transport delay for each input/output pair.

For continuous-time systems, specify transport delays in the time unit stored in the `TimeUnit` property. For discrete-time systems, specify transport delays in integer multiples of the sample time, `Ts`.

For a MIMO system with `Ny` outputs and `Nu` inputs, set `ioDelay` to a `Ny`-by-`Nu` array. Each entry of this array is a numerical value that represents the transport delay for the corresponding input/output pair. You can also set `ioDelay` to a scalar value to apply the same delay to all input/output pairs.

Default: `0` for all input/output pairs

InputDelay

Input delay for each input channel, specified as a scalar value or numeric vector. For continuous-time systems, specify input delays in the time unit stored in the `TimeUnit` property. For discrete-time systems, specify input delays in integer multiples of the sample time `Ts`. For example, `InputDelay = 3` means a delay of three sample times.

For a system with `Nu` inputs, set `InputDelay` to an `Nu`-by-1 vector. Each entry of this vector is a numerical value that represents the input delay for the corresponding input channel.

You can also set `InputDelay` to a scalar value to apply the same delay to all channels.

Default: 0

OutputDelay

Output delays. `OutputDelay` is a numeric vector specifying a time delay for each output channel. For continuous-time systems, specify output delays in the time unit stored in the `TimeUnit` property. For discrete-time systems, specify output delays in integer multiples of the sample time `Ts`. For example, `OutputDelay = 3` means a delay of three sampling periods.

For a system with `Ny` outputs, set `OutputDelay` to an `Ny`-by-1 vector, where each entry is a numerical value representing the output delay for the corresponding output channel. You can also set `OutputDelay` to a scalar value to apply the same delay to all channels.

Default: 0 for all output channels

Ts

Sample time. For continuous-time models, `Ts = 0`. For discrete-time models, `Ts` is a positive scalar representing the sampling period. This value is expressed in the unit specified by the `TimeUnit` property of the model. To denote a discrete-time model with unspecified sample time, set `Ts = -1`.

Changing this property does not discretize or resample the model. Use `c2d` and `d2c` to convert between continuous- and discrete-time representations. Use `d2d` to change the sample time of a discrete-time system.

Default: `0` (continuous time)

`TimeUnit`

String representing the unit of the time variable. This property specifies the units for the time variable, the sample time `Ts`, and any time delays in the model. Use any of the following values:

- `'nanoseconds'`
- `'microseconds'`
- `'milliseconds'`
- `'seconds'`
- `'minutes'`
- `'hours'`
- `'days'`
- `'weeks'`
- `'months'`
- `'years'`

Changing this property has no effect on other properties, and therefore changes the overall system behavior. Use `chgTimeUnit` to convert between time units without modifying system behavior.

Default: `'seconds'`

`InputName`

Input channel names. Set `InputName` to a string for single-input model. For a multi-input model, set `InputName` to a cell array of strings.

Alternatively, use automatic vector expansion to assign input names for multi-input models. For example, if `sys` is a two-input model, enter:

```
sys.InputName = 'controls';
```

The input names automatically expand to `{'controls(1)';'controls(2)'}`.

You can use the shorthand notation `u` to refer to the `InputName` property. For example, `sys.u` is equivalent to `sys.InputName`.

Input channel names have several uses, including:

- Identifying channels on model display and plots
- Extracting subsystems of MIMO systems
- Specifying connection points when interconnecting models

Default: Empty string '' for all input channels

InputUnit

Input channel units. Use InputUnit to keep track of input signal units. For a single-input model, set InputUnit to a string. For a multi-input model, set InputUnit to a cell array of strings. InputUnit has no effect on system behavior.

Default: Empty string '' for all input channels

InputGroup

Input channel groups. The InputGroup property lets you assign the input channels of MIMO systems into groups and refer to each group by name. Specify input groups as a structure. In this structure, field names are the group names, and field values are the input channels belonging to each group. For example:

```
sys.InputGroup.controls = [1 2];
sys.InputGroup.noise = [3 5];
```

creates input groups named controls and noise that include input channels 1, 2 and 3, 5, respectively. You can then extract the subsystem from the controls inputs to all outputs using:

```
sys(:,'controls')
```

Default: Struct with no fields

OutputName

Output channel names. Set OutputName to a string for single-output model. For a multi-output model, set OutputName to a cell array of strings.

Alternatively, use automatic vector expansion to assign output names for multi-output models. For example, if sys is a two-output model, enter:

```
sys.OutputName = 'measurements';
```

The output names automatically expand to
{'measurements(1)';'measurements(2)'}.

You can use the shorthand notation `y` to refer to the `OutputName` property. For example, `sys.y` is equivalent to `sys.OutputName`.

Output channel names have several uses, including:

- Identifying channels on model display and plots
- Extracting subsystems of MIMO systems
- Specifying connection points when interconnecting models

Default: Empty string `''` for all output channels

OutputUnit

Output channel units. Use `OutputUnit` to keep track of output signal units. For a single-output model, set `OutputUnit` to a string. For a multi-output model, set `OutputUnit` to a cell array of strings. `OutputUnit` has no effect on system behavior.

Default: Empty string `''` for all output channels

OutputGroup

Output channel groups. The `OutputGroup` property lets you assign the output channels of MIMO systems into groups and refer to each group by name. Specify output groups as a structure. In this structure, field names are the group names, and field values are the output channels belonging to each group. For example:

```
sys.OutputGroup.temperature = [1];
sys.InputGroup.measurement = [3 5];
```

creates output groups named `temperature` and `measurement` that include output channels 1, and 3, 5, respectively. You can then extract the subsystem from all inputs to the `measurement` outputs using:

```
sys('measurement',:)
```

Default: Struct with no fields

Name

System name. Set `Name` to a string to label the system.

Default: `''`

Notes

Any text that you want to associate with the system. Set `Notes` to a string or a cell array of strings.

Default: `{}`

UserData

Any type of data you wish to associate with system. Set `UserData` to any MATLAB data type.

Default: `[]`

SamplingGrid

Sampling grid for model arrays, specified as a data structure.

For model arrays that are derived by sampling one or more independent variables, this property tracks the variable values associated with each model in the array. This information appears when you display or plot the model array. Use this information to trace results back to the independent variables.

Set the field names of the data structure to the names of the sampling variables. Set the field values to the sampled variable values associated with each model in the array. All sampling variables should be numeric and scalar valued, and all arrays of sampled values should match the dimensions of the model array.

For example, suppose you create a 11-by-1 array of linear models, `sysarr`, by taking snapshots of a linear time-varying system at times `t = 0:10`. The following code stores the time samples with the linear models.

```
 sysarr.SamplingGrid = struct('time',0:10)
```

Similarly, suppose you create a 6-by-9 model array, `M`, by independently sampling two variables, `zeta` and `w`. The following code attaches the `(zeta,w)` values to `M`.

```
[zeta,w] = ndgrid(<6 values of zeta>,<9 values of w>)
M.SamplingGrid = struct('zeta',zeta,'w',w)
```

When you display `M`, each entry in the array includes the corresponding `zeta` and `w` values.

```
M
```

```
M(:,:,1,1) [zeta=0.3, w=5] =

        25
  --------------
  s^2 + 3 s + 25


M(:,:,2,1) [zeta=0.35, w=5] =

         25
  ----------------
  s^2 + 3.5 s + 25

...
```

For model arrays generated by linearizing a Simulink model at multiple parameter values or operating points, the software populates `SamplingGrid` automatically with the variable values that correspond to each entry in the array. For example, the Simulink Control Design commands `linearize` and `slLinearizer` populate `SamplingGrid` in this way.

Default: `[]`

Examples

Example 1

Create the continuous-time SISO transfer function:

$$h(s) = \frac{-2s}{(s-1+j)(s-1-j)(s-2)}$$

Create $h(s)$ as a `zpk` object using:

```
h = zpk(0, [1-i 1+i 2], -2);
```

Example 2

Specify the following one-input, two-output zero-pole-gain model:

$$H(z) = \begin{bmatrix} \dfrac{1}{z-0.3} \\ \dfrac{2(z+0.5)}{(z-0.1+j)(z-0.1-j)} \end{bmatrix}.$$

To do this, enter:

```
z = {[] ; -0.5};
p = {0.3 ; [0.1+i 0.1-i]};
k = [1 ; 2];
H = zpk(z,p,k,-1);    % unspecified sample time
```

Example 3

Convert the transfer function

```
h = tf([-10 20 0],[1 7 20 28 19 5]);
```

to zero-pole-gain form, using:

```
zpk(h)
```

This command returns the result:

```
Zero/pole/gain:
     -10 s (s-2)
----------------------
(s+1)^3 (s^2 + 4s + 5)
```

Example 4

Create a discrete-time ZPK model from a rational expression in the variable `z`.

```
z = zpk('z',0.1);
H = (z+.1)*(z+.2)/(z^2+.6*z+.09)
```

This command returns the following result:

```
Zero/pole/gain:
(z+0.1) (z+0.2)
---------------
   (z+0.3)^2
```

```
Sample time: 0.1
```

Example 5

Create a MIMO `zpk` model using cell arrays of zeros and poles.

Create the two-input, two-output zero-pole-gain model

$$H(s) = \begin{bmatrix} \dfrac{-1}{s} & \dfrac{3(s+5)}{(s+1)^2} \\ \dfrac{2(s^2-2s+2)}{(s-1)(s-2)(s-3)} & 0 \end{bmatrix}$$

by entering:

```
Z = {[],-5;[1-i 1+i] []};

P = {0,[-1 -1];[1 2 3],[]};

K = [-1 3;2 0];

H = zpk(Z,P,K);
```

Use `[]` as a place holder in `Z` or `P` when the corresponding entry of $H(s)$ has no zeros or poles.

Example 6

Extract the measured and noise components of an identified polynomial model into two separate ZPK models. The former (measured component) can serve as a plant model while the latter can serve as a disturbance model for control system design.

```
load icEngine
z = iddata(y,u,0.04);
nb = 2; nf = 2; nc = 1; nd = 3; nk = 3;
sys = bj(z, [nb nc nd nf nk]);
```

`sys` is a model of the form, `y(t) = B/F u(t) + C/D e(t)`, where `B/F` represents the measured component and `C/D` the noise component.

```
sysMeas = zpk(sys, 'measured')
```

Alternatively, use can simply use `zpk(sys)` to extract the measured component.

```
sysNoise = zpk(sys, 'noise')
```

More About

Algorithms

`zpk` uses the MATLAB function `roots` to convert transfer functions and the functions `zero` and `pole` to convert state-space models.

See Also

`frd` | `get` | `set` | `ss` | `tf` | `zpkdata`

zpkdata

Access zero-pole-gain data

Syntax

```
[z,p,k] = zpkdata(sys)
[z,p,k,Ts] = zpkdata(sys)
[z,p,k,Ts,covz,covp,covk] = zpkdata(sys)
```

Description

`[z,p,k] = zpkdata(sys)` returns the zeros `z`, poles `p`, and gain(s) `k` of the zero-pole-gain model `sys`. The outputs `z` and `p` are cell arrays with the following characteristics:

- `z` and `p` have as many rows as outputs and as many columns as inputs.
- The `(i,j)` entries `z{i,j}` and `p{i,j}` are the (column) vectors of zeros and poles of the transfer function from input `j` to output `i`.

The output `k` is a matrix with as many rows as outputs and as many columns as inputs such that `k(i,j)` is the gain of the transfer function from input `j` to output `i`. If `sys` is a transfer function or state-space model, it is first converted to zero-pole-gain form using `zpk`.

For SISO zero-pole-gain models, the syntax

```
[z,p,k] = zpkdata(sys,'v')
```

forces `zpkdata` to return the zeros and poles directly as column vectors rather than as cell arrays (see example below).

`[z,p,k,Ts] = zpkdata(sys)` also returns the sample time `Ts`.

`[z,p,k,Ts,covz,covp,covk] = zpkdata(sys)` also returns the covariances of the zeros, poles and gain of the identified model `sys`. `covz` is a cell array such that `covz{ky,ku}` contains the covariance information about the zeros in the vector `z{ky,ku}`. `covz{ky,ku}` is a 3-D array of dimension 2-by-2-by-Nz, where `Nz` is the length of `z{ky,ku}`, so that the `(1,1)` element is the variance of the real part, the `(2,2)` element is the variance of the imaginary part, and the `(1,2)` and `(2,1)` elements contain the covariance between the real and imaginary parts. `covp` has a similar relationship to `p.covk` is a matrix containing the variances of the elements of `k`.

You can access the remaining LTI properties of `sys` with `get` or by direct referencing, for example,

```
sys.Ts
sys.inputname
```

Examples

Example 1

Given a zero-pole-gain model with two outputs and one input

```
H = zpk({[0];[-0.5]},{[0.3];[0.1+i 0.1-i]},[1;2],-1)
Zero/pole/gain from input to output...
         z
 #1:  -------
      (z-0.3)

           2 (z+0.5)
 #2:  -------------------
      (z^2 - 0.2z + 1.01)

Sample time: unspecified
```

you can extract the zero/pole/gain data embedded in `H` with

```
[z,p,k] = zpkdata(H)
z =
    [      0]
    [-0.5000]
p =
    [    0.3000]
    [2x1 double]
k =
     1
     2
```

To access the zeros and poles of the second output channel of `H`, get the content of the second cell in `z` and `p` by typing

```
z{2,1}
ans =
   -0.5000
p{2,1}
ans =
   0.1000+ 1.0000i
   0.1000- 1.0000i
```

Example 2

Extract the ZPK matrices and their standard deviations for a 2-input, 1 output identified transfer function.

```
load iddata7
```

transfer function model

```
sys1 = tfest(z7, 2, 1, 'InputDelay',[1 0]);
```

an equivalent process model

```
sys2 = procest(z7, {'P2UZ', 'P2UZ'}, 'InputDelay',[1 0]);

1, p1, k1, ~, dz1, dp1, dk1] = zpkdata(sys1);
[z2, p2, k2, ~, dz2, dp2, dk2] = zpkdata(sys2);
```

Use `iopzplot` to visualize the pole-zero locations and their covariances

```
h = iopzplot(sys1, sys2);
showConfidence(h)
```

See Also

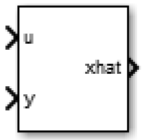
`ssdata` | `tfdata` | `get` | `zpk`

Block Reference

Kalman Filter

Estimate states of discrete-time or continuous-time linear system

Description



Kalman Filter

Use the Kalman Filter block to estimate states of a state-space plant model given process and measurement noise covariance data. The state-space model can be time-varying. A steady-state Kalman filter implementation is used if the state-space model and the noise covariance matrices are all time-invariant. A time-varying Kalman filter is used otherwise.

Kalman filter provides the optimal solution to the following continuous or discrete estimation problems:

Continuous-Time Estimation

Given the continuous plant

$$\dot{x}(t) = A(t)x(t) + B(t)u(t) + G(t)w(t) \quad \text{(state equation)}$$
$$y(t) = C(t)x(t) + D(t)u(t) + H(t)w(t) + v(t) \quad \text{(measurement equation)}$$

with known inputs u, white process noise w, and white measurement noise v satisfying:

$$E\left[w(t)\right] = E\left[v(t)\right] = 0$$
$$E[w(t)w^T(t)] = Q(t)$$
$$E[w(t)v^T(t)] = N(t)$$
$$E[v(t)v(t)^T] = R(t)$$

construct a state estimate $\hat{x}$ that minimizes the state estimation error covariance

$P(t) = E[(x-x)(x-x)^T]$.

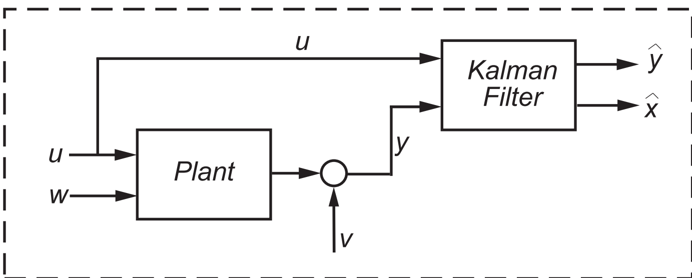
The optimal solution is the Kalman filter with equations

$$\begin{aligned}
L(t) &= (P(t)C^T(t) + \bar{N}), \\
\dot{P}(t) &= A(t)P(t) + P(t)A^T(t) + \bar{Q}(t) - L(t)\bar{R}(t)L^T(t), \\
\dot{x}(t) &= A(t)x(t) + B(t)u(t) + L(t)(y(t) - C(t)x(t) - D(t)u(t)),
\end{aligned}$$

where

$$\begin{aligned}
\bar{Q}(t) &= G(t)Q(t)G^T(t), \\
\bar{R}(t) &= R(t) + H(t)N(t) + N^T(t)H^T(t) + H(t)Q(t)H^T(t), \\
\bar{N}(t) &= G(t)(Q(t)H^T(t) + N(t)).
\end{aligned}$$

The Kalman filter uses the known inputs u and the measurements y to generate the state estimates $\hat{x}$. If you want, the block can also output the estimates of the true plant output $\hat{y}$.



Kalman Estimator

The block implements the steady-state Kalman filter when the system matrices (`A(t)`, `B(t)`, `C(t)`, `D(t)`, `G(t)`, `H(t)`) and noise covariance matrices (`Q(t)`, `R(t)`, `N(t)`) are constant (specified in the Block Parameters dialog box). The steady-state Kalman filter uses a constant matrix `P` that minimizes the steady-state estimation error covariance and solves the associated continuous-time algebraic Riccati equation:

$$P = \lim_{t \to \infty} E[(x - x)(x - x)^T].$$

Discrete-Time Estimation

Given the discrete plant

$$
\begin{aligned}
x[n+1] &= A[n]\,x[n] + B[n]\,u[n] + G[n]\,w[n],\\
y[n] &= C[n]\,x[n] + D[n]\,u[n] + H[n]\,w[n] + v[n],
\end{aligned}
$$

with known inputs u, white process noise w and white measurement noise v satisfying

$$
\begin{aligned}
&E[u[n]] = E[v[n]] = 0,\\
&E[u[n]w^T[n]] = Q[n],\\
&E[v[n]v^T[n]] = R[n],\\
&E[u[n]v^T[n]] = N[n].
\end{aligned}
$$

The estimator has the following state equation

$$
\hat{x}[n+1\,|\,n] = A[n]\hat{x}[n\,|\,n-1] + B[n]u[n] + L[n](y[n] - C[n]\hat{x}[n\,|\,n-1] - D[n]u[n]),
$$

where the gain `L[n]` is calculated through the discrete Riccati equation:

$$
\begin{aligned}
&L[n] = (A[n]P[n]C^T[n] + \bar{N}[n])(C[n]P[n]C^T[n] + \bar{R}[n])^{-1},\\
&M[n] = P[n]C^T[n](C[n]P[n]C^T[n] + \bar{R}[n])^{-1},\\
&Z[n] = (I - M[n]C[n])P[n](I - M[n]C[n])^T + M[n]\bar{R}[n]M^T[n],\\
&P[n+1] = (A[n] - \bar{N}[n]\bar{R}^{-1}[n]C[n])Z(A[n] - \bar{N}[n]\bar{R}^{-1}[n]C[n])^T + \bar{Q}[n] - N[n]\bar{R}^{-1}[n]N^T[n],
\end{aligned}
$$

where I is the identity matrix of appropriate size and

$$
\begin{aligned}
&\bar{Q}[\mathrm{n}] = G[\mathrm{n}]Q[\mathrm{n}]G^T[\mathrm{n}],\\
&\bar{R}[\mathrm{n}] = R[\mathrm{n}] + H[\mathrm{n}]N[\mathrm{n}] + N^T[\mathrm{n}]H^T[\mathrm{n}] + H[\mathrm{n}]Q[\mathrm{n}]H^T[\mathrm{n}],\\
&\bar{N}[\mathrm{n}] = G[\mathrm{n}](Q[\mathrm{n}]H^T[\mathrm{n}] + N[\mathrm{n}]),
\end{aligned}
$$

and

$$
\begin{aligned}
&P[\mathrm{n}] = E[(x - x[n\,|\,n-1])(x - \hat{x}[n\,|\,n-1])^T],\\
&Z[\mathrm{n}] = E[(x - \hat{x}[n\,|\,n])(x - \hat{x}[n\,|\,n])^T],
\end{aligned}
$$

The steady-state Kalman filter uses a constant matrix `P` that minimizes the steady-state estimation error covariance and solves the associated discrete-time algebraic Riccati equation.

There are two variants of discrete-time Kalman filters:

- The current estimator generates the state estimates $\hat{x}[n \mid n]$ using all measurement available, including $y[n]$. The filter updates $\hat{x}[n \mid n-1]$ with $y[n]$ and outputs:

$$\hat{x}[n \mid n] = \hat{x}[n \mid n-1] + M[n](y[n] - C[n]\hat{x}[n \mid n-1] - D[n]u[n]),$$
$$\hat{y}[n \mid n] = C[n]\hat{x}[n \mid n] + D[n]u[n].$$

- The delayed estimator generates the state estimates $\hat{x}[n \mid n-1]$ using measurements up to $y[n-1]$. The filter outputs $\hat{x}[n \mid n-1]$ as defined previously, along with the optional output $\hat{y}[n \mid n-1]$

$$\hat{y}[n \mid n-1] = C[n]\hat{x}[n \mid n-1] + D[n]u[n]$$

The current estimator has better estimation accuracy compared to the delayed estimator, which is important for slow sample times. However, it has higher computational cost, making it harder to implement inside control loops. More specifically, it has direct feedthrough. This leads to an algebraic loop if the Kalman filter is used in a feedback loop that does not contain any delays (the feedback loop itself also has direct feedthrough). The algebraic loop can impact the speed of simulation. You cannot generate code if your model contains algebraic loops.

The Kalman Filter block differs from the `kalman` command in the following ways:

- When calling `kalman(sys,...)`, `sys` includes the `G` and `H` matrices. Specifically, `sys.B` has `[B G]` and `sys.D` has `[D H]`. When you provide a LTI variable to the Kalman Filter block, it does not assume that the LTI variable provided contains `G` and `H`. They are optional and separate.
- The `kalman` command outputs `[yhat;xhat]` by default. The block only outputs `xhat` by default.

Dialog Box and Parameters

The following table summarizes the Kalman Filter block parameters, accessible via the Block Parameter dialog box.

Task	Parameters
Specify filter settings	• **Time domain**

Task	Parameters
	• **Use the current measurement y[n] to improve xhat[n]**
Specify the system model	**Model source** in **Model Parameters** tab
Specify initial state estimates	**Source** in **Model Parameters** tab
Specify noise characteristics	In **Model Parameters** tab: • **Use G and H matrices (default G=I and H=0)** • **Q**, **Time-invariant Q** • **R**, **Time-invariant R** • **N**, **Time-invariant N**
Specify additional inports	In **Options** tab: • **Add input port u** • **Add input port Enable to control measurement updates** • **External reset**
Specify additional outports	In **Options** tab: • **Output estimated model output y** • **Output state estimation error covariance Z**

Time domain

Specify whether to estimate continuous-time or discrete-time states:

- `Discrete-Time` (**Default**) — Block estimates discrete-time states
- `Continuous-Time` — Block estimates continuous-time states

Use the current measurement y[n] to improve xhat[n]

Use the current estimator variant of the discrete-time Kalman filter. When not selected, the delayed estimator (variant) is used.

This option is available only when **Time Domain** is `Discrete-Time`.

Model source

Specify how the A, B, C, D matrices are provided to the block. Must be one of the following:

- `Dialog: LTI State-Space Variable` — Use the values specified in the LTI state-space variable. You must also specify the variable name in **Variable**. The sample time of the model must match the setting in the **Time domain** option, i.e. the model must be discrete-time if the **Time domain** is discrete-time.
- `Dialog: Individual A, B, C, D matrices` — Specify values in the following block parameters:
  - **A** — Specify the A matrix. It must be real and square.
  - **B** — Specify the B matrix. It must be real and have as many rows as the A matrix. This option is available only when **Add input port u** is selected in the **Options** tab.
  - **C** — Specify the C matrix. It must be real and have as many columns as the A matrix.
  - **D** — Specify the D matrix. It must be real. It must have as many rows as the C matrix and as many columns as the B matrix. This option is available only when **Add input port u** is selected in the **Options** tab.
- `External` — Specify the A, B, C, D matrices as input signals to the Kalman Filter block. If you select this option, the block includes additional input ports A, B, C and D. You must also specify the following in the block parameters:
  - `Number of states` — Number of states to be estimated, specified as a positive integer. The default value is 2.
  - `Number of inputs` — Number of known inputs in the model, specified as a positive integer. The default value is 2. This option is only available when **Add input port u** is selected.
  - `Number of outputs` — Number of measured outputs in the model, specified as a positive integer. The default value is 2.

Sample Time

Block sample time, specified as -1 or a positive scalar.

This option is available only when **Time Domain** is `Discrete Time` and **Model Source** is `Dialog: Individual A, B, C, D matrices` or `External`. The sample time is obtained from the LTI state-space variable if the Model Source is `Dialog: LTI State-Space Variable`.

The default value is -1, which implies that the block inherits its sample time based on the context of the block within the model. All block input ports must have the same sample time.

Source

Specify how to enter the initial state estimates and initial state estimation error covariance:

- `Dialog` — Specify the values directly in the dialog box. You must also specify the following parameters:
  - **Initial states x[0]** — Specify the initial state estimate as a real scalar or vector. If you specify a scalar, all initial state estimates are set to this scalar. If you specify a vector, the length of the vector must match with the number of states in the model.
  - **State estimation error covariance P[0]** (only when only when time-varying Kalman filter is used) — Specify the initial state estimation error covariance P[0] for discrete-time Kalman filter or P(0) for continuous-time Kalman filter. Must be specified as one of the following:
    - Real nonnegative scalar. P is an Ns-by-Ns diagonal matrix with the scalar on the diagonals. Ns is the number of states in the model.
    - Vector of real nonnegative scalars. P is an Ns-by-Ns diagonal matrix with the elements of the vector on the diagonals of P.
    - Ns-by-Ns positive semi-definite matrix.
- `External` — Inherit the values from input ports. The block includes an additional input port X0. A second additional input port P0 is added when time-varying Kalman filter is used. X0 and P0 must satisfy the same conditions described previously when you specify them in the dialog box.

Use the Kalman Gain K from the model variable

Specify whether to use the pre-identified Kalman Gain contained in the state-space plant model. This option is available only when:

- **Model Source** is `Dialog: LTI State-Space Variable` and **Variable** is an identified state-space model (`idss`) with a nonzero K matrix.
- **Time Invariant Q**, **Time Invariant R** and **Time Invariant N** options are selected.

If the **Use G and H matrices (default G=I and H=0)** option is selected, **Time Invariant G** and **Time Invariant H** options must also be selected.

Use G and H matrices (default G=I and H=0)

Specify whether to use non-default values for the G and H matrices. If you select this option, you must specify:

- **G** — Specify the G matrix. It must be a real matrix with as many rows as the A matrix. The default value is 1.
- **Time-invariant G** — Specify if the G matrix is time invariant. If you unselect this option, the block includes an additional input port G.
- **H** — Specify the H matrix. It must be a real matrix with as many rows as the C matrix and as many columns as the G matrix. The default value is 0.
- **Time-invariant H** — Specify if the H matrix is time invariant. If you unselect this option, the block includes an additional input port G.
- **Number of process noise inputs** — Specify the number of process noise inputs in the model. The default value is 1.

  This option is available only when **Time-invariant G** and **Time-invariant H** are unselected. Otherwise, this information is inferred from the G or H matrix.

Q

Process noise covariance matrix, specified as one of the following:

- Real nonnegative scalar. Q is an Nw-by-Nw diagonal matrix with the scalar on the diagonals. Nw is the number of process noise inputs in the model.
- Vector of real nonnegative scalars. Q is an Nw-by-Nw diagonal matrix with the elements of the vector on the diagonals of Q.

- Nw-by-Nw positive semi-definite matrix.

Time Invariant Q

Specify if the Q matrix is time invariant. If you unselect this option, the block includes an additional input port Q.

R

Measurement noise covariance matrix, specified as one of the following:

- Real positive scalar. R is an Ny-by-Ny diagonal matrix with the scalar on the diagonals. Ny is the number of measured outputs in the model.
- Vector of real positive scalars. R is an Ny-by-Ny diagonal matrix with the elements of the vector on the diagonals of R.
- Ny-by-Ny positive-definite matrix.

Time Invariant R

Specify if the R matrix is time invariant. If you unselect this option, the block includes an additional input port R.

N

Process and measurement noise cross-covariance matrix. Specify it as a Nw-by-Ny matrix. The matrix [Q N; N^T R] must be positive definite.

Time Invariant N

Specify if the N matrix is time invariant. If you unselect this option, the block includes an additional input port N.

Add input port u

Select this option if your model contains known inputs `u(t)` or `u[k]`. The option is selected by default. Unselecting this option removes the input port `u` from the block and removes the **B**, **D** and **Number of inputs** parameters from the block dialog box.

Add input port Enable to control measurement updates

Select this option if you want to control the measurement updates. The block includes an additional inport `Enable`. The `Enable` input port takes a scalar signal. This option is unselected by default.

By default the block does measurement updates at each time step to improve the state and output estimates $\hat{x}$ and $\hat{y}$ based on measured outputs. The measurement update is skipped for the current sample time when the signal in the Enable port is 0. Concretely, the equation for state estimates become $\dot{\hat{x}}(t) = A(t)\hat{x}(t) + B(t)u(t)$ for continuous-time Kalman filter and $\hat{x}[n+1 \mid n] = A[n]\hat{x}[n \mid n-1] + B[n]u[n]$ for discrete-time.

External Reset

Option to reset estimated states and parameter covariance matrix using specified initial values.

Suppose you reset the block at a time step, `t`. If the block is enabled at `t`, the software uses the initial parameter values specified either in the block dialog or the input ports P0 and X0 to estimate the states. In other words, at `t`, the block performs a time update and if it is enabled, a measurement update after the reset. The block outputs these updated estimates.

Specify one of the following:

- `None` (Default) — Estimated states $\hat{x}$ and state estimation error covariance matrix P values are not reset.
- `Rising` — Triggers a reset when the control signal rises from a negative or zero value to a positive value. If the initial value is negative, rising to zero triggers a reset.
- `Falling` — Triggers a reset when the control signal falls from a positive or a zero value to a negative value. If the initial value is positive, falling to zero triggers a reset.
- `Either` — Triggers a reset when the control signal is either rising or falling.
- `Level` — Triggers a reset in either of these cases:
  - The control signal is nonzero at the current time step.
  - The control signal changes from nonzero at the previous time step to zero at the current time step.

- `Level hold` — Triggers reset when the control signal is nonzero at the current time step.

When you choose an option other than `None`, a `Reset` input port is added to the block to provide the reset control input signal.

Output estimated model output y

Add $\hat{y}$ output port to the block to output the estimated model outputs. The option is unselected by default.

Output estimated model output P or Z

Add P output port or Z output port to the block. The Z matrix is provided only when **Time Domain** is `Discrete Time` and the **Use the current measurement y[n] to improve xhat[n]** is selected. Otherwise, the P matrix, as described in the "Description" on page 2-2 section previously, is provided.

The option is unselected by default.

Ports

Port Name	Port Type (In/ Out)	Description
u (Optional)	In	Known inputs, specified as a real scalar or vector.
y	In	Measured outputs, specified as a real scalar or vector.
xhat	Out	Estimated states, returned as a real scalar or vector.
yhat (Optional)	Out	Estimated outputs, returned as a real scalar or vector.
P or Z (Optional)	Out	State estimation error covariance, returned as a matrix.
A (Optional)	In	A matrix, specified as a real matrix.

Port Name	Port Type (In/ Out)	Description
B (Optional)	In	B matrix, specified as a real matrix.
C (Optional)	In	C matrix, specified as a real matrix.
D (Optional)	In	D matrix, specified as a real matrix.
G (Optional)	In	G matrix, specified as a real matrix.
H (Optional)	In	H matrix, specified as a real matrix.
Q (Optional)	In	Q matrix, specified as a real scalar, vector or matrix.
R (Optional)	In	R matrix, specified as a real scalar, vector or matrix.
N (Optional)	In	N matrix, specified as a real matrix.
P0 (Optional)	In	P matrix at initial time, specified as a real scalar, vector, or matrix.
X0 (Optional)	In	Initial state estimates, specified as a real scalar or vector.
Enable (Optional)	In	Control signal to enable measurement updates, specified as a real scalar.
Reset (Optional)	In	Control signal to reset state estimates, specified as a real scalar.

Supported Data Types

- Double-precision floating point
- Single-precision floating point (for discrete-time Kalman filter only)

Note:

- All input ports except **Enable** and **Reset** must have the same data type (single or double).

- **Enable** and **Reset** ports support `single`, `double`, `int8`, `uint8`, `int16`, `uint16`, `int32`, `uint32`, and boolean data types.

Limitations

- The plant and noise data must satisfy:
  - (C,A) detectable
  - $\bar{R} > 0$ and $\bar{Q} - \bar{N}\bar{R}^{-1}\bar{N}^T \geq 0$
  - $(A - \bar{N}\bar{R}^{-1}C, \bar{Q} - \bar{N}\bar{R}^{-1}\bar{N}^T)$ has no uncontrollable mode on the imaginary axis (or unit circle in discrete time) with the notation

$$\bar{Q} = GQG^T$$
$$\bar{R} = R + HN + N^T H^T + HQH^T$$
$$\bar{N} = G(QH^T + N)$$

- The continuous-time Kalman filter cannot be used in Function-Call Subsystems or Triggered Subsystems.

References

[1] Franklin, G.F., J.D. Powell, and M.L. Workman, *Digital Control of Dynamic Systems*, Second Edition, Addison-Wesley, 1990.

[2] Lewis, F., *Optimal Estimation*, John Wiley & Sons, Inc, 1986.

See Also

`kalman`

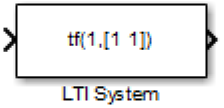
Related Examples

- “State Estimation Using Time-Varying Kalman Filter”

LTI System

Use linear system model object in Simulink

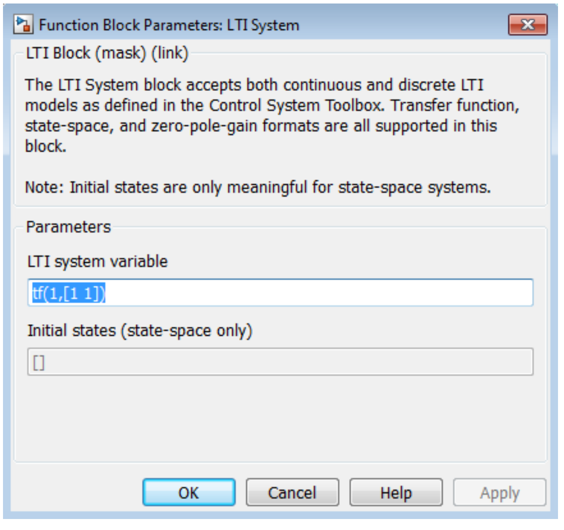
Description



The LTI System block imports linear system model objects into the Simulink environment.

The imported system must be proper. State-space models are always proper. SISO transfer functions or zero-pole-gain models are proper if the degree of their numerator is less than or equal to the degree of their denominator. MIMO transfer functions are proper if all their SISO entries are proper.

Dialog Box



LTI system variable

Enter your LTI model. This block supports state-space, zero/pole/gain, and transfer function formats. Your model can be discrete- or continuous-time.

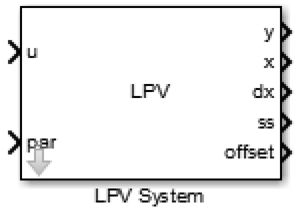
Initial states (state-space only)

If your model is in state-space format, you can specify the initial states in vector format. The default is zero for all states.

LPV System

Simulate Linear Parameter-Varying (LPV) systems

Description



Represent and simulate Linear Parameter-Varying (LPV) systems in Simulink. The block also supports code generation.

A *linear parameter-varying* (LPV) system is a linear state-space model whose dynamics vary as a function of certain time-varying parameters called *scheduling parameters*. In MATLAB, an LPV model is represented in a state-space form using coefficients that are parameter dependent.

Mathematically, an LPV system is represented as:

$$dx(t) = A(p)x(t) + B(p)u(t)$$
$$y(t) = C(p)x(t) + D(p)u(t)$$
$$x(0) = x_0$$

where

- `u(t)` are the inputs
- `y(t)` the outputs
- `x(t)` are the model states with initial value `x0`
- $dx(t)$ is the state derivative vector $\dot{x}$ for continuous-time systems and the state update vector $x(t+\Delta T)$ for discrete-time systems. ΔT is the sample time.

- `A(p)`, `B(p)`, `C(p)` and `D(p)` are the state-space matrices parameterized by the scheduling parameter vector `p`.
- The parameters `p = p(t)` are measurable functions of the inputs and the states of the model. They can be a scalar quantity or a vector of several parameters. The set of scheduling parameters define the *scheduling space* over which the LPV model is defined.

The block implements a grid-based representation of the LPV system. You pick a grid of values for the scheduling parameters. At each value `p = p*`, you specify the corresponding linear system as a state-space (`ss` or `idss`) model object. You use the generated array of state-space models to configure the LPV System block.

The block accepts an array of state-space models with operating point information. The information on the scheduling variables is extracted from the `SamplingGrid` property of the LTI array. The scheduling variables define the grid of the LPV models. They are scalar-valued quantities that can be functions of time, inputs and states, or constants. They are used to pick the local dynamics in the operating space. The software interpolates the values of these variables. The block uses this array with data interpolation and extrapolation techniques for simulation.

The LPV system representation can be extended to allow offsets in `dx`, `x`, `u` and `y` variables. This form is known as *affine form* of the LPV model. Mathematically, the following represents an LPV system:

$$\begin{aligned} dx(t) &= A(p)x(t) + B(p)u(t) + \left(\overline{dx}(p) - A(p)\bar{x}(p) - B(p)\bar{u}(p)\right) \\ y(t) &= C(p)x(t) + D(p)u(t) + \left(\bar{y}(p) - C(p)\bar{x}(p) - D(p)\bar{u}(p)\right) \\ x(0) &= x_0 \end{aligned}$$

$\overline{dx}(p)$, $\bar{x}(p)$, $\bar{u}(p)$, $\bar{y}(p)$ are the offsets in the values of `dx(t)`, `x(t)`, `u(t)` and `y(t)` at a given parameter value `p = p(t)`.

You obtain such representations of the linear system array by linearizing a Simulink model over a batch of operating points (see “Batch Linearization” in Simulink Control Design documentation.) The offsets then correspond to the operating points at which you linearized the model.

The following limitations apply to the LPV System block:

- Internal delays cannot be extrapolated to be less than their minimum value in the state-space model array.
- When using an irregular grid of linear models to define the LPV system, only the nearest neighbor interpolation scheme is used. This may reduce the accuracy of simulation results. It is recommended to work with regular grids. To learn more about regular and irregular grids, see “Regular vs. Irregular Grids”.

Data Type Support

Single and double data. You must convert any other data type for input signals or model properties to these data types.

Parameters

The LPV System Block Parameter dialog box contains four tabs for specifying the system data, scheduling algorithm and output ports. The following table summarizes the block parameters.

Task	Parameters
Specify an array of state-space models and initial states	In **LPV Model** tab: • **State-space array** • **Initial state**
Specify operating point offsets	In **LPV Model** tab: • **Input offset** • **Output offset** • **State offset**
Specify offsets in state derivative or update variable	in the **LPV Model** tab: • **State derivative/update offset**
Specify which model matrices are fixed and their nominal values to override entries in model data.	In the **Fixed Entries** tab: • **Nominal Model** • **Fixed Coefficient Indices**

Task	Parameters
In some situations, you may want to replace a parameter-dependent matrix such as `A(p)` with a fixed value `A*` for simulation. For example, `A*` may represent an average value over the scheduling range.	
Specify options for interpolation and extrapolation	In the **Scheduling** tab: • **Interpolation method** • **Extrapolation method** • **Index search method** • **Begin index search using previous index result**
Specify additional outputs for the block	In the **Outputs** tab: • **Output states** • **Output state derivatives (continuous-time) or updates (discrete-time)** • **Output interpolated state-space data** • **Output interpolated offsets**
Specify code generation settings	In the **Code Generation** tab: • **Block data type (discrete-time case only)** • **Initial buffer size for delays** • **Use fixed buffer size**

State-space array

An array of state-space (`ss` or `idss`) models. All the models in the array must use the same definition of states. Use the `SamplingGrid` property of the state-space object to specify scheduling parameters for the model. See the `ss` or `idss` model reference page for more information on the `SamplingGrid` property.

Initial state

Initial conditions to use with the local model to start the simulation, specified one of the following:

- 0 (**Default**)
- Double vector of length equal to the number of model states

Input offset

Offsets in input `u(t)`, specified as one of the following:

- 0 (**Default**) — Use when there are no input offsets ($\bar{u}(p) = 0 \forall p$).
- Double vector of length equal to the number of inputs — Use when input offset is the same across the scheduling space.
- Double array of size [`nu` 1 `sysArraySize`] — Use when offsets are present and they vary across the scheduling space. Here, `nu` = number of inputs, `sysArraySize` = array size of state-space array. Use `size` to determine the array size.

Output offset

Offsets in output `y(t)`, specified as one of the following:

- 0 (**Default**) — Use when there are no output offsets $\bar{y}(p) = 0 \forall p$.
- Double vector of length equal to the number of outputs. Use when output offsets are the same across the scheduling space.
- Double array of size [`ny` 1 `sysArraySize`]. Use when offsets are present and they vary across the scheduling space. Here, `ny` = number of outputs, `sysArraySize` = array size of state-space array. Use `size` to determine the array size.

State offset

Offsets in states `x(t)`, specified as one of the following:

- 0 (**Default**) — Use when there are no state offsets $\bar{x}(p) = 0 \forall p$.

- Double vector of length equal to the number of states. Use when the state offsets are the same across the scheduling space.
- Double array of size `[nx 1 sysArraySize]`, where `nx` = number of states, `sysArraySize` = array size of state-space array. Use when offsets are present and they vary across the scheduling space. Here, `nx` = number of states, `sysArraySize` = array size of state-space array. Use `size` to determine the array size.

State derivative/update offset

Offsets in state derivative or update variable `dx(t)`, specified as one of the following:

- If you obtained the linear system array by linearization under equilibrium conditions, select the **Assume equilibrium conditions** option. This corresponds to an offset of $\overline{dx}(p)=0$ for a continuous-time system and $\overline{dx}(p)=\overline{x}(p)$ for a discrete-time system. This option is selected by default.
- If the linear system contains at least one system that you obtained under non-equilibrium conditions, uncheck the **Assume equilibrium conditions** option. Specify one of the following in the **Offset value** field:

  - If the `dx` offset values are the same across the scheduling space, specify as a double vector of length equal to the number of states.
  - If the `dx` offsets are present and they vary across the scheduling space, specify as a double array of size [`nx` 1 `sysArraySize`], where `nx` = number of states, and `sysArraySize` = array size of state-space array.

Nominal Model

State-space model that provides the values of the fixed coefficients, specified as one of the following:

- `Use the first model in state-space array` (**Default:**) — The first model in the state-space array is used to represent the LPV model. In the following example, the state-space array is specified by object `sys` and the fixed coefficients are taken from model `sys(:,:,1)`.

  ```
  % Specify a 4-by-5 array of state-space models.
  sys = rss(4,2,3,4,5);
  a = 1:4;
  b = 10:50;
  ```

```
[av,bv] = ndgrid(a,b);
% Use “alpha” and “beta” variables as scheduling parameters.
sys.SamplingGrid = struct('alpha',av,'beta',bv);
```

Fixed coefficients are taken from the model `sysFixed = sys(:,:,1)`. If the (2,1) entry of `A` matrix is forced to be fixed, its value used during the simulation is `sysFixed.a(2,1)`.

- `Custom value` — Specify a different state-space model for fixed entries. Specify a variable for the fixed model in the **State space model** field. The fixed model must use the same state basis as the state-space array in the LPV model.

Fixed Coefficient Indices

Specify which coefficients of the state-space matrices and delay vectors are fixed.

Specify one of the following:

- Scalar Boolean (`true` or `false`) if all entries of a matrix are to be treated the same way.
  - The default values for **A matrix**, **B matrix**, **C matrix**, and **D matrix** are `false`. This means that all entries are free for `A`, `B`, `C`, and `D` matrices of state-space array.
  - The default values for **Input delay**, **Output delay**, and **Internal delay** are `true`. This means that all entries are fixed for the model delays.
- Logical matrix of a size compatible with the size of the corresponding matrix:

State-space matrix	Size of fixed entry matrix
A matrix	`nx`-by-`nx`
B matrix	`nx`-by-`nu`
C matrix	`ny`-by-`nx`
D matrix	`ny`-by-`nu`
Input delay	`nu`-by-1
Output delay	`ny`-by-1
Internal delay	`ni`-by-1

where, `nu` = number of inputs, `ny` = number of outputs, `nx` = number of states, `ni` = length of internal delay vector.

- Numerical indices to specify the location of fixed entries. See `sub2ind` reference page for more information on how to generate numerical indices corresponding to a given subscript `(i,j)` for an element of a matrix.

Interpolation method

Interpolation method. Defines how the state-space data must be computed for scheduling parameter values that are located away from their grid locations.

Specify one of the following options:

- `Flat` — Choose the state-space data at the grid point closest, but not larger than, the current point. The *current point* is the value of the scheduling parameters at current time.
- `Nearest` — Choose the state-space data at the closest grid point in the scheduling space.
- `Linear` — Obtain state-space data by linear interpolation of the nearest 2d neighbors in the scheduling space, where d = number of scheduling parameters.

The default interpolation scheme is `Linear` for regular grids of scheduling parameter values. For irregular grids, the `Nearest` interpolation scheme is always used regardless of the choice made. to learn more about regular and irregular grids, see "Regular vs. Irregular Grids".

The `Linear` method provides the highest accuracy but takes longer to compute. The `Flat` and `Nearest` methods are good for models that have mode-switching dynamics.

Extrapolation method

Extrapolation method. Defines how to compute the state-space data for scheduling parameter values that fall outside the range over which the state-space array has been provided (as specified in the `SamplingGrid` property).

Specify one of the following options:

- `Clip` (**Default:**) — Disables extrapolation and returns the data corresponding to the last available scheduling grid point that is closest to the current point.
- `Linear` — Fits a line between the first or last pair of values for each scheduling parameter, depending upon whether the current value is less than the first or greater

than the last grid point value, respectively. This method returns the point on that line corresponding to the current value. Linear extrapolation requires that the interpolation scheme be linear too.

Index search method

The location of the current scheduling parameter values in the scheduling space is determined by a prelookup algorithm. Select `Linear search` or `Binary search`. Each search method has speed advantages in different situations. For more information on this parameter, see the Prelookup block reference page in Simulink documentation.

Begin index search using previous index result

Select this check box when you want the block to start its search using the index found at the previous time step. For more information on this parameter. see the Prelookup block reference page in Simulink documentation.

Output states

Add `x` port to the block to output state values. This option is selected by default.

Output state derivatives (continuous-time) or updates (discrete-time)

Add `dx` port to the block to output state derivative values or update the values. This option is selected by default.

Output interpolated state-space data

Add `ss` port to the block to output state-space data as a structure. This option is selected by default.

The fields of the generated structure are:

- State-space matrices `A`, `B`, `C`, `D`.
- Delays `InputDelay`, `OutputDelay`, and `InternalDelay`. The `InternalDelay` field is available only when the model has internal delay.

Output interpolated offsets

Add `offset` port to the block to output LPV model offsets $\left(\bar{u}(p), \bar{y}(p), \bar{x}(p), \overline{dx}(p)\right)$.

The fields of the structure are:

- `InputOffset`, `OutputOffset`, `StateOffset`, and `StateDerivativeOffset` in continuous-time.
- `InputOffset`, `OutputOffset`, `StateOffset`, and `StateUpdateOffset` in discrete-time.

Block data type (discrete-time case only)

Supported data type. Use this option only for discrete-time state-space models. Specify `double` or `single`.

Initial buffer size for delays

Initial memory allocation for the number of input points to store for models that contain delays. If the number of input points exceeds the initial buffer size, the block allocates additional memory. The default size is 1024.

When you run the model in Accelerator mode or build the model, make sure the initial buffer size is large enough to handle maximum anticipated delay in the model.

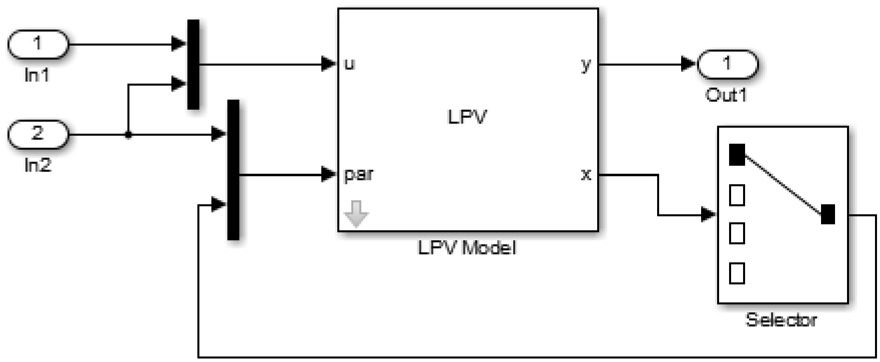
Use fixed buffer size

Specify whether to use a fixed buffer size to save delayed input and output data from previous time steps. Use this option for continuous-time LPV systems that contain input or output delays. If the buffer is full, new data replaces data already in the buffer. The software uses linear extrapolation to estimate output values that are not in the buffer.

Examples

Configure the Scheduling Parameter Input Port

Consider a 2-input, 3 output, 4-state LPV model. Use input `u(2)` and state `x(1)` as scheduling parameters. Configure the Simulink model as shown in the following figure.



Simulate a Linear Parameter-Varying System

Consider a linear mass-spring-damper system whose mass changes as a function of an external load command. The governing equation is:

$$m(u)\ddot{y} + c\dot{y} + k(y)y = F(t)$$

where `m(u)` is the mass dependent upon the external command `u`, `c` is the damping ratio, `k` is the stiffness of the spring and `F(t)` is the forcing input. `y(t)` is position of the mass at a given time `t`. For a fixed value of `u`, the system is linear and expressed as:

$$A = \begin{bmatrix} 0 & 1 \\ -\frac{k}{m} & -\frac{c}{m} \end{bmatrix}, B = \begin{bmatrix} 0 \\ \frac{1}{m} \end{bmatrix}, C = \begin{bmatrix} 1 & 0 \end{bmatrix}$$

$$\dot{x} = Ax + Bu, \; y = Cx$$

where $x = \begin{bmatrix} y \\ \dot{y} \end{bmatrix}$ is the state vector and `m` is the value of the mass for a given value of `u`.

In this example, you want to study the model behavior over a range of input values from 1 to 10 Volts. For each value of `u`, measure the mass and compute the linear representation of the system. Suppose, mass is related to the input by the relationship:

$m(u) = 10u + 0.1u^2$. For values of u ranging from 1:10 results in the following array of linear systems.

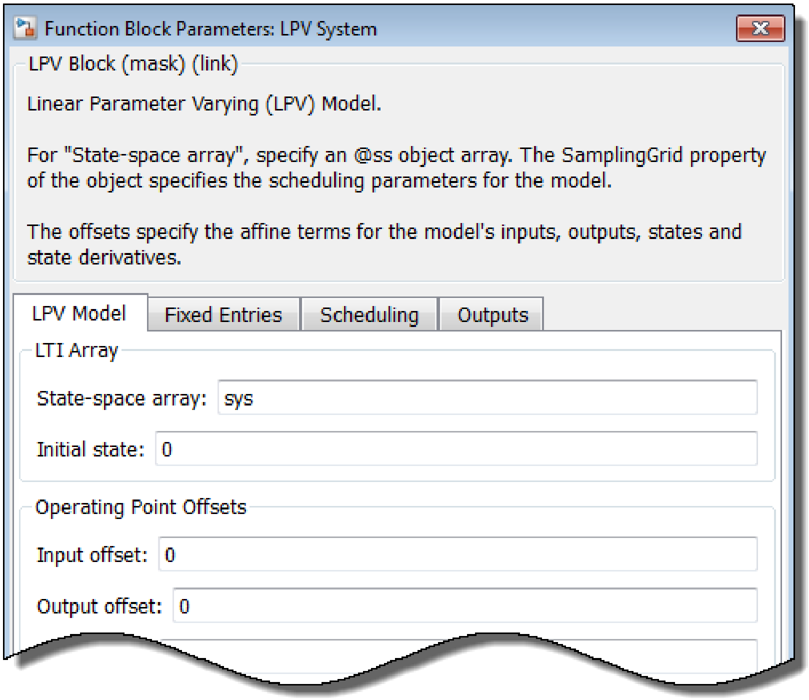
```
% Specify damping coefficient.
c = 5;
% Specify stiffness.
k = 300;
% Specify load command.
u = 1:10;
% Specify mass.
m = 10*u + 0.1*u.^2;
% Compute linear system at a given mass value.
for i = 1:length(u)
   A = [0 1; -k/m(i), -c/m(i)];
   B = [0; -1/m(i)];
   C = [1 0];
   sys(:,:,i) = ss(A,B,C,0);
end
```

The variable u is the scheduling input. Add this information to the model.

```
sys.SamplingGrid = struct('LoadCommand',u);
```

Configure the LPV System block:

- Type sys in the **State-space array** field.
- Connect the input port par to a one-dimensional source signal that generates the values of the load command. If the source provides values between 1 and 10, interpolation is used to compute the linear model at a given time instance. Otherwise, extrapolation is used.



Ports

Port Name	Port Type (In/ Out)	Description
u	In	Input signal u(t) in Equation 2-2 described previously. In multi-input case, this port accepts a signal of the dimension of the input.
par	In	Provides the signals for variables defining the scheduling space ("sampling grid" variables). The scheduling variables can be functions of time, inputs and states, or constants. The required dependence can be achieved by preparing a scheduling signal

Port Name	Port Type (In/Out)	Description
		using clock input (for time), input signal (`u`), and the outputs signals (`x`, `dx/dt`, `y`) of the LPV block, as required.
y	Out	Model output
x	Out	Values of the model states
xdot	Out	Values of the state derivatives. The state derivatives are sometimes used to define the scheduling parameters.
ss	Out	Local state-space model at the major simulation time steps
offset	Out	LPV model offsets

Related Examples

- "Using LTI Arrays for Simulating Multi-Mode Dynamics"
- "Approximating Nonlinear Behavior using an Array of LTI Systems"
- "LPV Approximation of a Boost Converter Model"

More About

- "Linear Parameter-Varying Models"