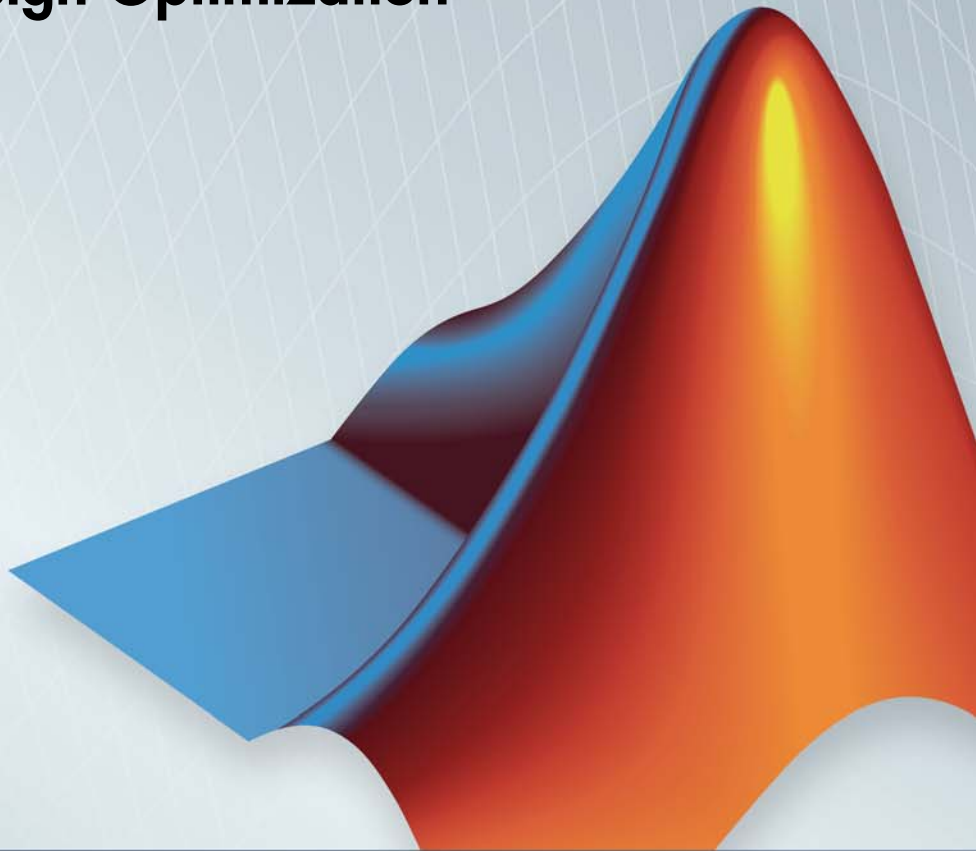


# Simulink® Design Optimization™

## User's Guide

R2014a



MATLAB® & SIMULINK®



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## Response Optimization

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# Data Analysis and Processing

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- “Model Requirements for Importing Data” on page 1-2
- “Import Data (GUI)” on page 1-4
- “Plot and Analyze Data (GUI)” on page 1-11
- “Ways to Preprocess Data” on page 1-14
- “Preprocess Data (GUI)” on page 1-15
- “Add Preprocessed Data Sets to Estimation Project (GUI)” on page 1-30
- “Export Prepared Data to the MATLAB Workspace” on page 1-33

## Model Requirements for Importing Data

Before you can analyze and preprocess the estimation data, you must assign the data to the model's channels. In order to assign the data, the Simulink® model must contain one of the following elements:


- Top-level Inport block

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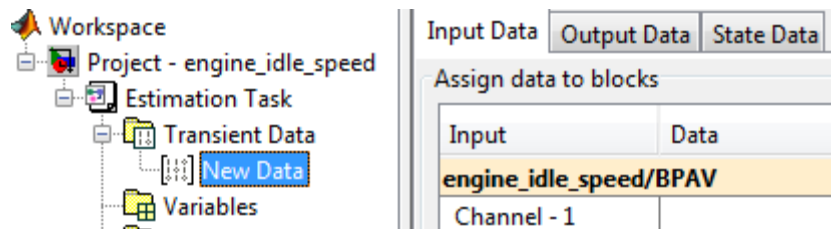
**Note** You do not need an Inport block if your model already contains a fixed input block, such as a Step block.

---

- Top-level Outport block
- Logged signal. The logged signal can be a top-level signal in the model or a signal in the model subsystem.

To enable signal logging for a signal, in the Simulink Editor, select that signal, click the **Record** button arrow  and click **Log/Unlog Selected Signals**. For more information, see “Export Signal Data Using Signal Logging” in the Simulink documentation.

In the Control and Estimation Tools Manager GUI, the rows in the **Input Data** tab correspond to the model's top-level Inport blocks.



Similarly, the rows in the **Output Data** tab correspond to either the top-level Outport blocks or logged signals in the model.

Adding an Inport or Outport block or marking a signal for logging creates a new row in the corresponding **Input Data** or **Output Data** tab. You can use the new row to import estimation data for the corresponding signal. To view

the new row, click **Update Task** in the **Estimation Task** node of the Control and Estimation Tools Manager GUI.

### **More About**

“Supported Data”

## Import Data (GUI)

In this section...
“Creating an Estimation Project” on page 1-4
“Importing Time-Domain Data into the GUI” on page 1-6
“Importing Time-Series Data into the GUI” on page 1-10
“Importing Complex Data into the GUI” on page 1-10

### Creating an Estimation Project

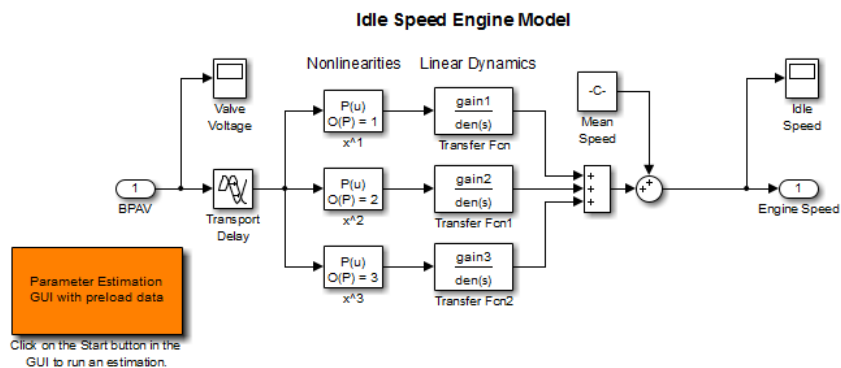
Before you begin data import, you must create and set up an estimation project by configuring the appropriate parameters, solvers, and cost functions. Simulink Design Optimization™ software provides a Graphical User Interface (GUI) that makes setting up the estimation project quick and easy.

To create an estimation project:

- 1 Open the nonlinear idle speed model of an automotive engine by typing :  
`engine_idle_speed`

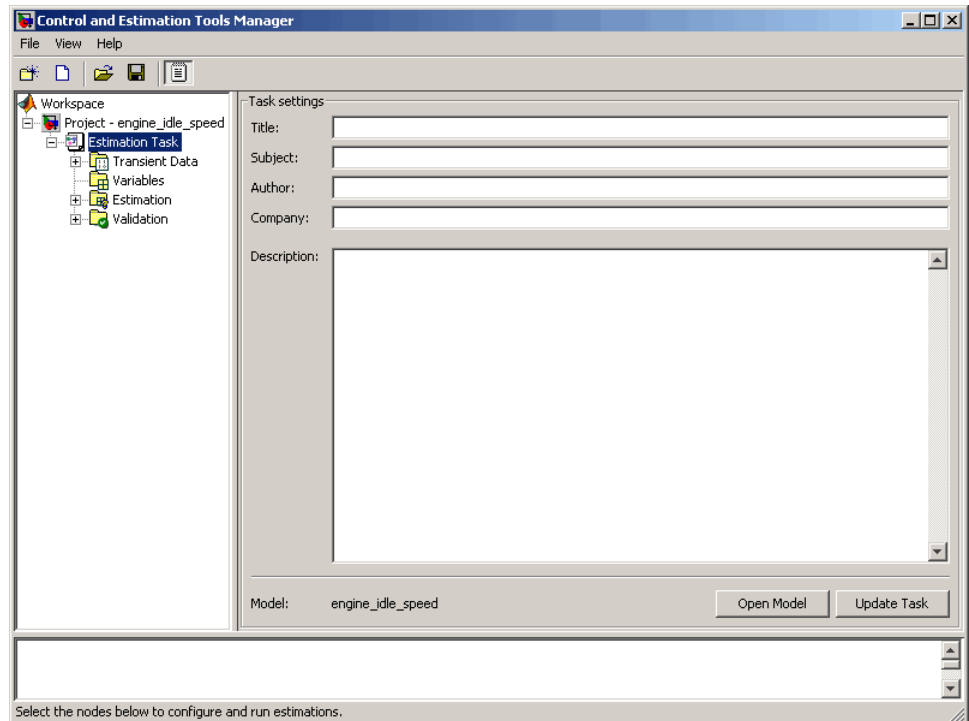
at the MATLAB® prompt.

The model appears as shown next.



The model contains the Inport block BPAV and Outport block Engine Speed for importing input and output data, respectively. To learn more, see “Model Requirements for Importing Data” on page 1-2.

- 2 Open the Control and Estimation Tools Manager GUI by selecting **Analysis > Parameter Estimation** in the Simulink model window.



### Control and Estimation Tools Manager GUI

The project tree displays the project name **Project - engine\_idle\_speed**. Estimation tasks are organized inside the **Estimation Task** node.

---

**Note** The Simulink model must remain open to perform parameter estimation tasks.

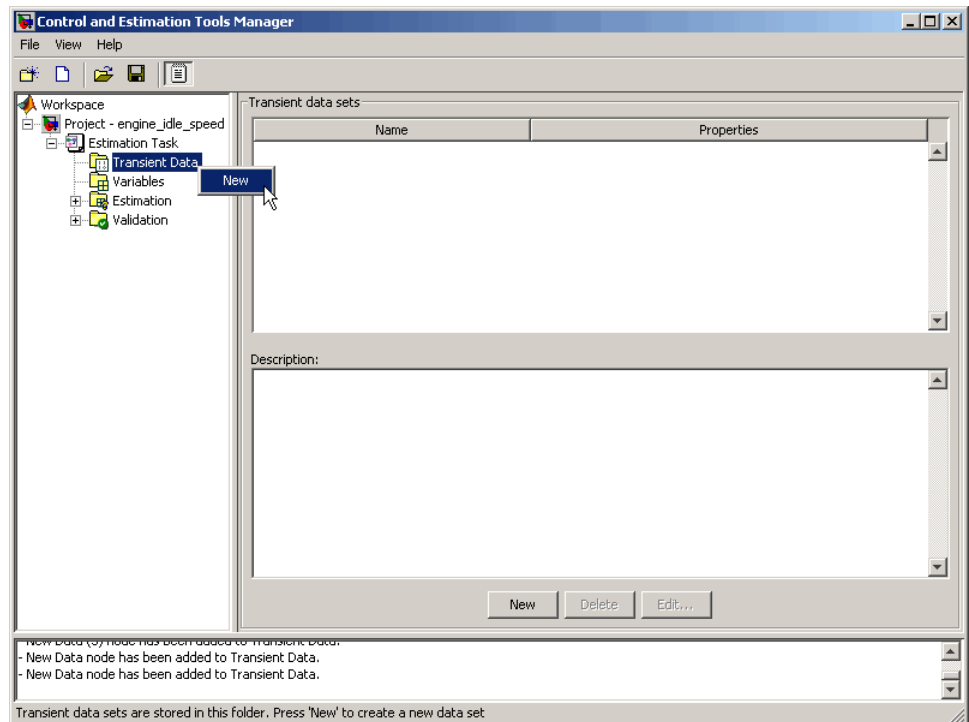
---

## Importing Time-Domain Data into the GUI

After you create an estimation project, as described in “Creating an Estimation Project” on page 1-4, you can import the estimation data into the GUI. To learn more about the types of data for parameter estimation, see “Supported Data”.

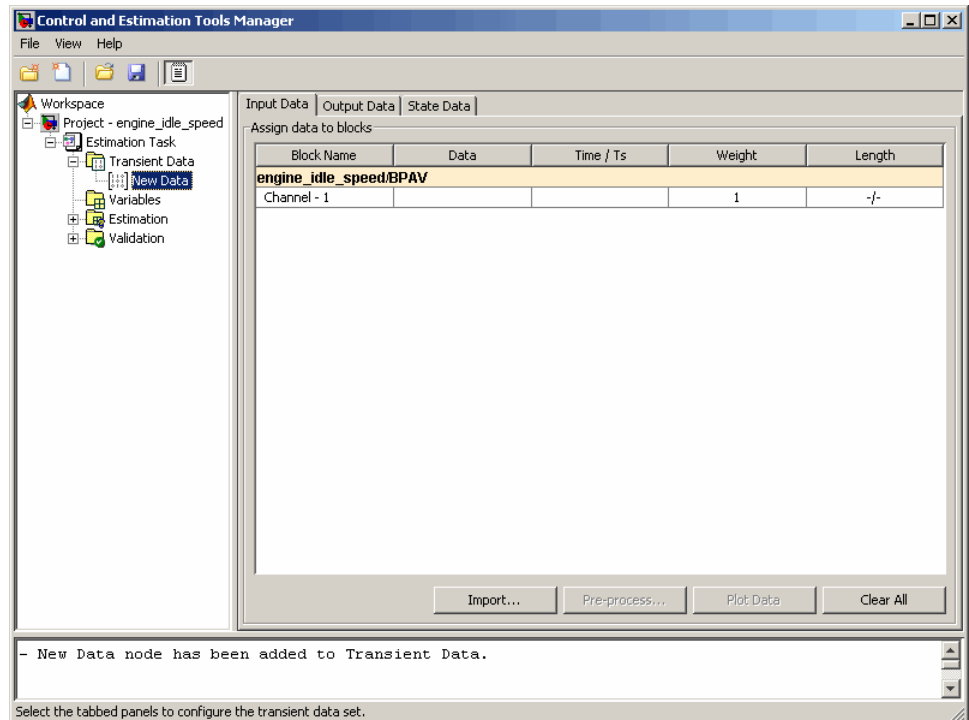
To import *transient* (measured) data for your dynamic system:

- 1 In the Control and Estimation Tools Manager, select **Transient Data** under the **Estimation Task** node of the **Workspace** tree.
- 2 Right-click **Transient Data** and select **New** to create a **New Data** node. Alternatively, you can use the **New** button to create this node.



- 3 Select the **New Data** node under the **Transient Data** node.

The Control and Estimation Tools Manager GUI now resembles the next figure.



### Import Data into the Control and Estimation Tools Manager

The table rows in the **Input Data** tab corresponds to the Inport block BPAV in the `engine_idle_speed` model. Similarly, the rows in the **Output Data** tab corresponds to the Outport block Engine Speed.

---

**Note** The Simulink model must contain an Inport or Outport block or logged signals to enable importing data. For more information, see “Model Requirements for Importing Data” on page 1-2.

---

The idle-speed model of an automotive engine contains the measured data stored in the `iodata` array. The array contains two columns: the first for

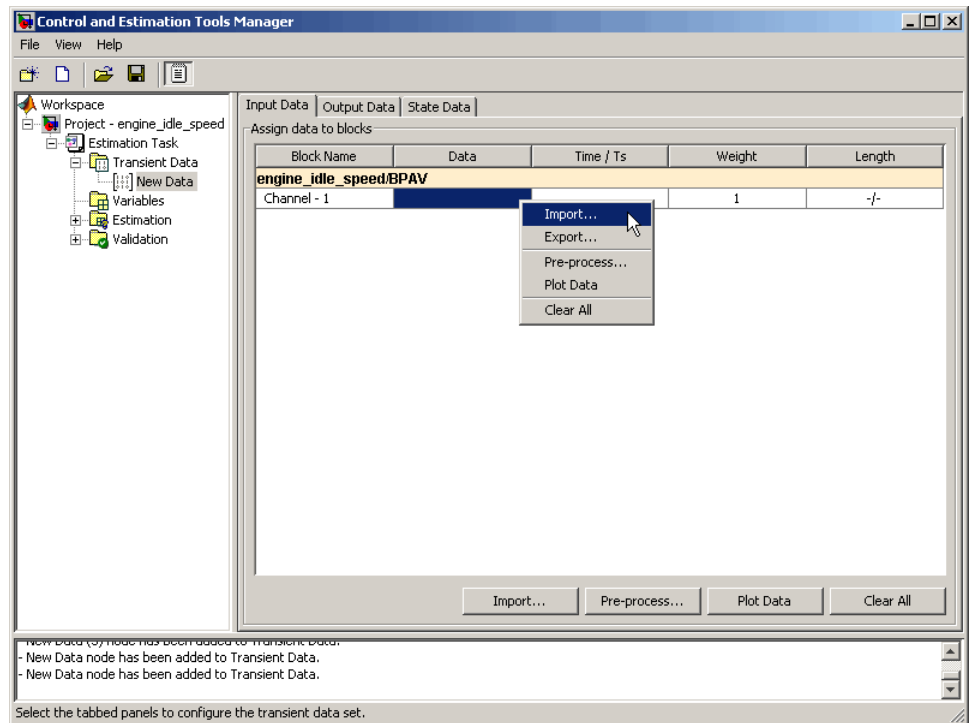
input data, and the second for output data. You must import both the input and the output data, as described in the following sections:

- “Importing Input Data and Time Vector” on page 1-8
- “Importing Output Data and Time Vector” on page 1-9

## Importing Input Data and Time Vector

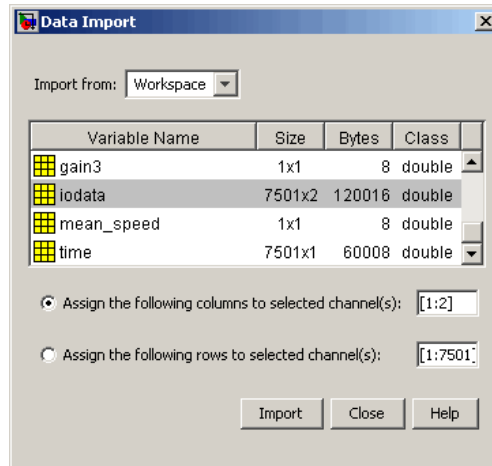
To import the input data for the port BPAV:

- 1 In the **New Data** node, click the **Input Data** tab.
- 2 Right-click the **Data** cell and select **Import** to open the Data Import dialog box. Alternatively, you can use the **Import** button to open this dialog box.



- 3 In the Data Import dialog box, select **iodata** from the list of variables.





- 4** Enter 1 in the **Assign the following columns to selected channel(s)** field, and then click **Import**.
- 5** In the **Input Data** tab, select the **Time/Ts** cell.
- 6** Select `time` in the Data Import dialog box.
- 7** Click **Import** to import the time vector for the input data.
- 8** Click **Close** to close the Data Import dialog box.

### Importing Output Data and Time Vector

To import the output data for the port Engine Speed:

- 1** In the **New Data** node, select the **Output Data** tab.
- 2** Right-click the **Data** cell and select **Import** to open the Data Import dialog box.
- 3** In the Data Import dialog box, select `iodata` from the list of variables.
- 4** Enter 2 in the **Assign the following columns to selected channel(s)** field to use the second column of `iodata`, and then click **Import**.
- 5** In the **Output Data** tab, select the **Time/Ts** cell.

- 6 Select **time** in the Data Import dialog box.
- 7 Click **Import** to import the time vector for the output data.
- 8 Click **Close** to close the Data Import dialog box.

## Importing Time-Series Data into the GUI

*Time-series* data is stored in time-series objects. For more information, see “Time Series Objects” in the MATLAB documentation.

When you import time-series data for parameter estimation, specify the data and time vector as *t.data* and *t.time* in the **Data** and **Time/Ts** columns of the **New Data** node, respectively. For more information on how to import data into the GUI, see “Importing Time-Domain Data into the GUI” on page 1-6.

## Importing Complex Data into the GUI

*Complex-valued* data is data whose value is a complex number. For example, a signal with the value  $1+2j$  is complex. You can use complex data to estimate parameters of electrical systems, such as the magnitude and phase.

---

**Note** You must sample the real and imaginary parts of the data as a function of the same time vector.

---

To use complex data for parameter estimation:

- 1 Split the data into two data sets that contain the real and imaginary parts. To split the data, use the MATLAB functions `real`, and `imag`.
- 2 Import both data sets into the GUI, as described in “Importing Time-Domain Data into the GUI” on page 1-6.
- 3 Specify both the data sets together as estimation data, as described in “Specify Estimation Data” on page 2-3.
- 4 Estimate the parameters, as described in “Run Estimation” on page 2-39.

## Plot and Analyze Data (GUI)

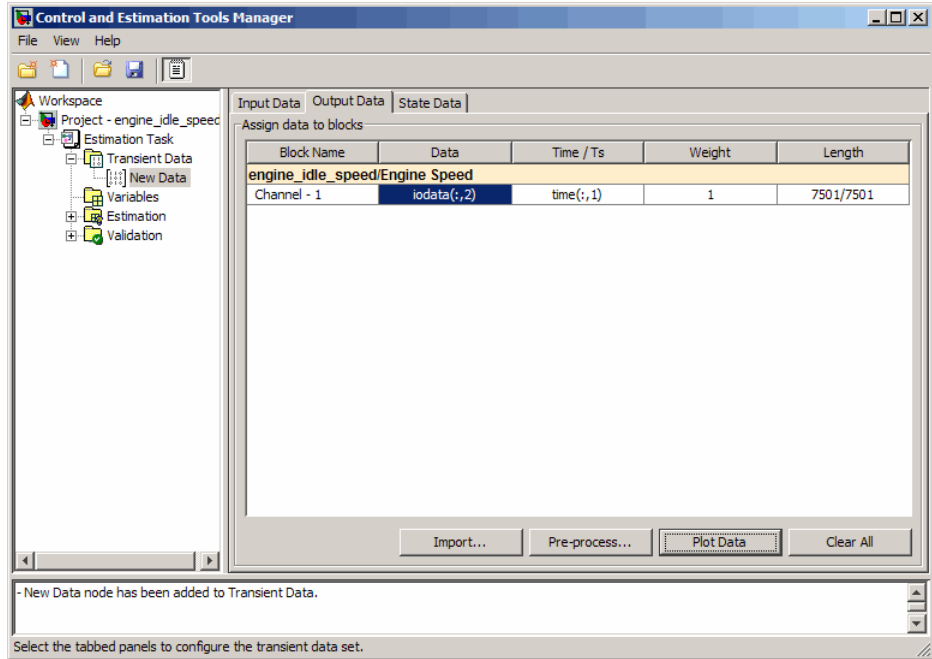
In this section...
“Why Plot the Data Before Parameter Estimation” on page 1-11
“How To Plot Data in the GUI” on page 1-11

### Why Plot the Data Before Parameter Estimation

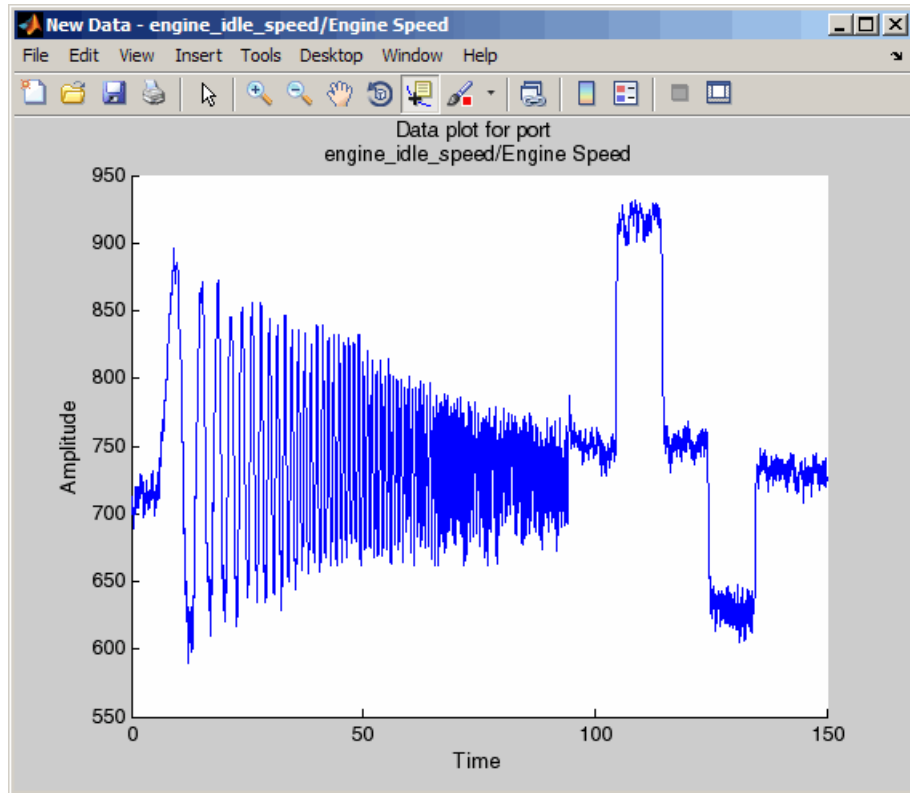
After you import the estimation data, as described in “Import Data (GUI)” on page 1-4, it is useful to remove outliers, smooth, detrend, or otherwise treat the data to make it more tractable for analysis and estimation purposes. To view and analyze the data characteristics, you must plot the data on a time plot.

### How To Plot Data in the GUI

To plot a data set, select the **Data** cell that you want to plot in the **Transient Data** node of the Control and Estimation Tools Manager GUI, and click **Plot Data**.



The data is plotted on a time plot, as shown in the next figure.



Using the time plot, you can examine the data characteristics such as noise, outliers and portions of the data to use for estimating parameters. After you analyze the data, you preprocess the data as described in “Preprocess Data (GUI)” on page 1-15.

## Ways to Preprocess Data

After you import the estimation data, as described in “Import Data (GUI)” on page 1-4, you can perform the following preprocessing operations using the Data Preprocessing Tool in Simulink Design Optimization software:

- Exclusion — Exclude a portion of the data from the estimation process. You can exclude data by:
  - Selecting it with your mouse.
  - Graphically by selecting regions on a plot.
  - Using rules, such as upper or lower bounds.
- Handle missing data — Remove missing data, or compute missing data using interpolation.
- Handle outliers — Remove outliers.
- Detrend — Remove mean values or a straight line trend.
- Filter — Smooth data using a first-order filter, an arbitrary transfer function, or an ideal filter.

## Preprocess Data (GUI)

### In this section...

“Opening the Data Preprocessing Tool” on page 1-15

“Handling Missing Data” on page 1-17

“Handling Outliers” on page 1-19

“Detrending Data” on page 1-19

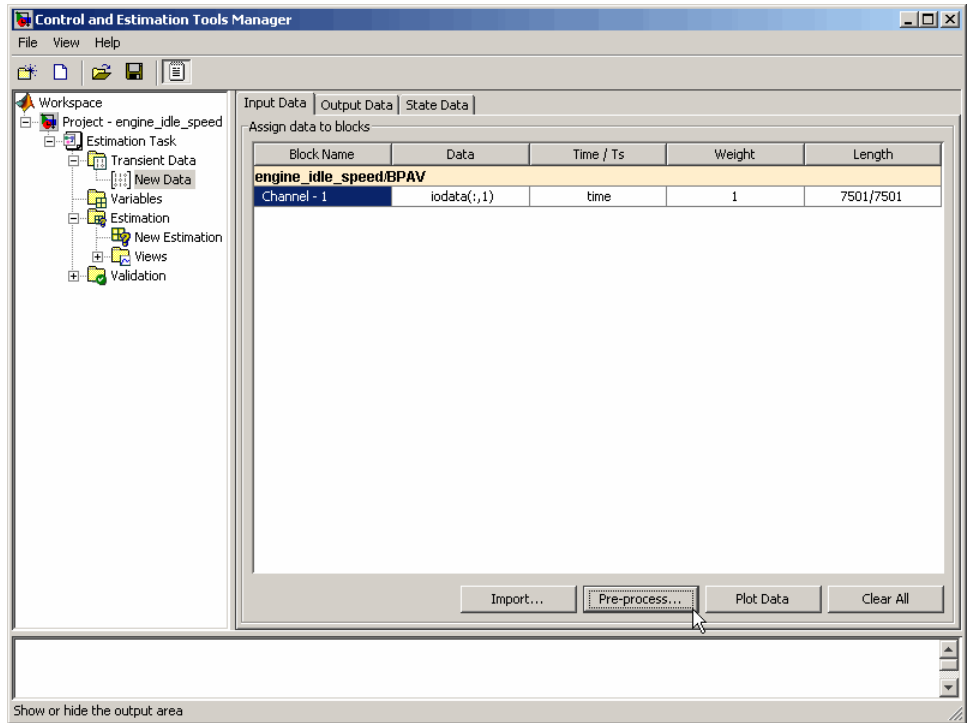
“Filtering Data” on page 1-19

“Selecting Data” on page 1-21

### Opening the Data Preprocessing Tool

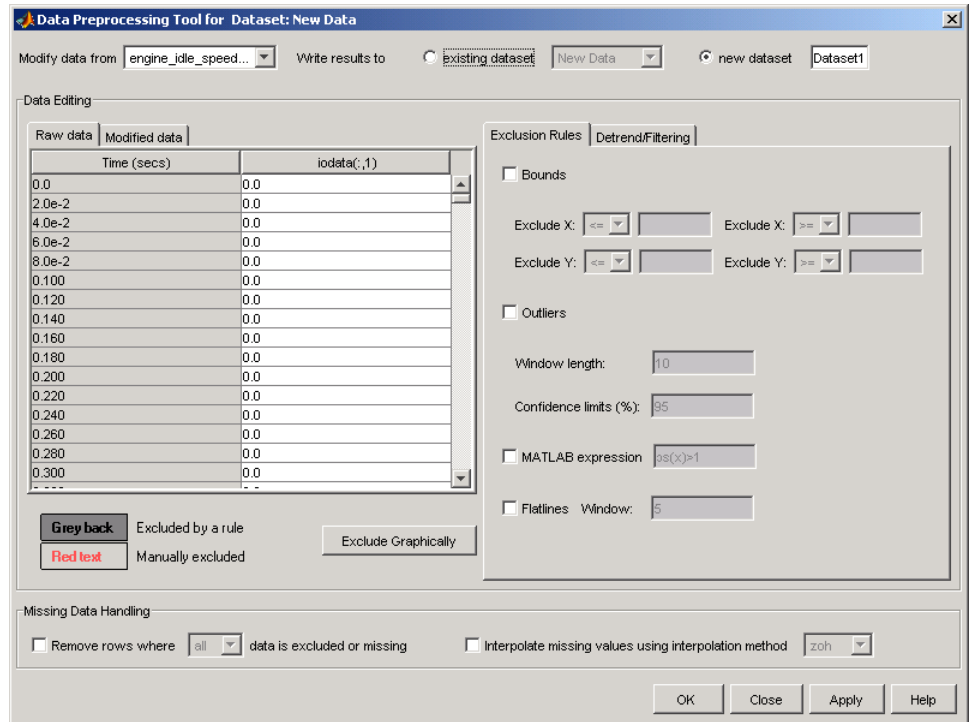
To open the Data Preprocessing Tool:

- 1 In the Control and Estimation Tools Manager GUI, select the **Transient Data** node under the **Estimation Task** node, and then choose the data you want to preprocess either in the **Input Data**, or **Output Data** tab. This enables the **Pre-process** button.



**2** Click **Pre-process** to open the Data Preprocessing Tool.





**Tip** When you have multiple data sets, select the data set that you want to preprocess from the **Modify data from** drop-down list in the Data Preprocessing Tool.

In this section, the sample data set imported for preprocessing is the same as used in the `engine_idle_speed` Simulink model. For an overview of creating estimation projects and importing data sets, see “Model Requirements for Importing Data” on page 1-2, and “Creating an Estimation Project” on page 1-4.

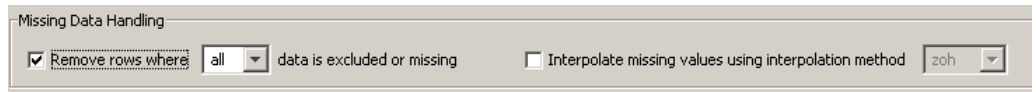
## Handling Missing Data

- “Removing Missing Data” on page 1-18

- “Interpolating Missing Data” on page 1-18

## Removing Missing Data

Rows of missing or excluded data are represented by NaNs. To remove the rows containing missing or excluded data, select the **Remove rows where** check box in the **Missing Data Handling** area of the Data Preprocessing Tool GUI.



When the data set contains multiple columns of data, select **all** to remove rows in which all the data is excluded. Select **any** to remove any excluded cell. In the case of one-column data, **any** and **all** are equivalent.

---

**Tip** You can view the modified data in the **Modified data** tab of the Data Preprocessing Tool GUI.

---

## Interpolating Missing Data

The interpolation operation computes the missing data values using known data values. When you select the **Interpolate missing values using interpolation method** check box in the **Missing Data Handling** area of the Data Preprocessing Tool GUI, the software interpolates the missing data values.



You can compute the missing data values using one of the following interpolation methods:

- Zero-order hold (zoh) — Fills the missing data sample with the data value immediately preceding it.
- Linear interpolation (Linear) — Fills the missing data sample with the average of the data values immediately preceding and following it.

By default, the interpolation method is set to zoh. You can select the Linear interpolation method from the **Interpolate missing values using interpolation method** drop-down list.

---

**Tip** You can view the results of interpolation in the **Modified data** tab of the Data Preprocessing Tool GUI.

---

## Handling Outliers

Outliers are data values that deviate from the mean by more than three standard deviations. When estimating parameters from data containing outliers, the results may not be accurate.

To remove outliers, select the **Outliers** check box to activate outlier exclusion. You can set the **Window length** to any positive integer, and use confidence limits from 0 to 100%. The window length specifies the number of data points used when calculating outliers.

Removing outliers replaces the data samples containing outliers with NaNs, which you can interpolate in a subsequent operation. To learn more, see “Interpolating Missing Data” on page 1-18.

## Detrending Data

To detrend, select the **Detrending** check box. You can choose constant or straight line detrending. Constant detrending removes the mean of the data to create zero-mean data. Straight line detrending finds linear trends (in the least-squares sense) and then removes them.

## Filtering Data

- “Types of Filters” on page 1-19
- “How to Filter Data” on page 1-20

### Types of Filters

You have these choices for filtering your data:

- **First order** — A filter of the type  $\frac{1}{\tau s + 1}$  where  $\tau$  is the time constant that you specify in the associated field.

- **Transfer function** — A filter of the type

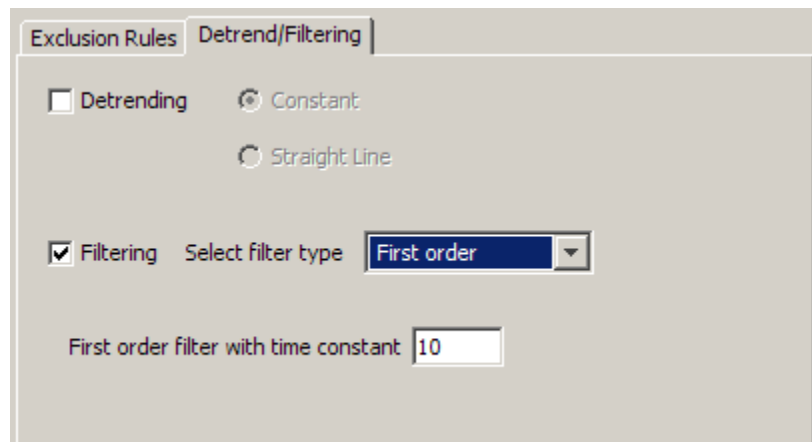
$$\frac{a_n s^n + a_{n-1} s^{n-1} + \dots + a_0}{b_m s^m + b_{m-1} s^{m-1} + \dots + b_0}$$

where you specify the coefficients as vectors in the associated **A coefficients** and **B coefficients** fields.

- **Ideal** — An idealized (noncausal) filter, either stop or pass band. Specify either filter as a two-element vector in the **Range (Hz)** field. These filters are ideal in the sense that there is no finite rolloff or ripple; the ends of the ranges are perfectly horizontal in the frequency domain.

## How to Filter Data

To filter the data to remove noise, select the **Detrend/Filtering** tab in the Data Preprocessing Tool GUI. Select the **Filtering** check box, and choose the type of filter from the **Select filter type** drop-down list.



## Selecting Data

- “Techniques for Excluding Data in the Data Preprocessing Tool” on page 1-21
- “Graphically Selecting Data” on page 1-21
- “Using Rules to Select Data Samples” on page 1-24
- “Using the Data Table to Select Data Samples” on page 1-26

## Techniques for Excluding Data in the Data Preprocessing Tool

You can use the Data Preprocessing Tool to select a portion of the data to be excluded from the estimation process. You can choose one of the following techniques:

- Selecting data from the Data Editing Table.
- Selecting data from a plot of the data.
- Specifying a rule.

You accomplish the first two manually, and for the last you specify a rule. When you exclude data using manual selection, the excluded data is shown as red. When you exclude data using a rule, the background color of the cell becomes gray. When a portion of the data is excluded both manually and by a rule, the data is red, and the background is gray.

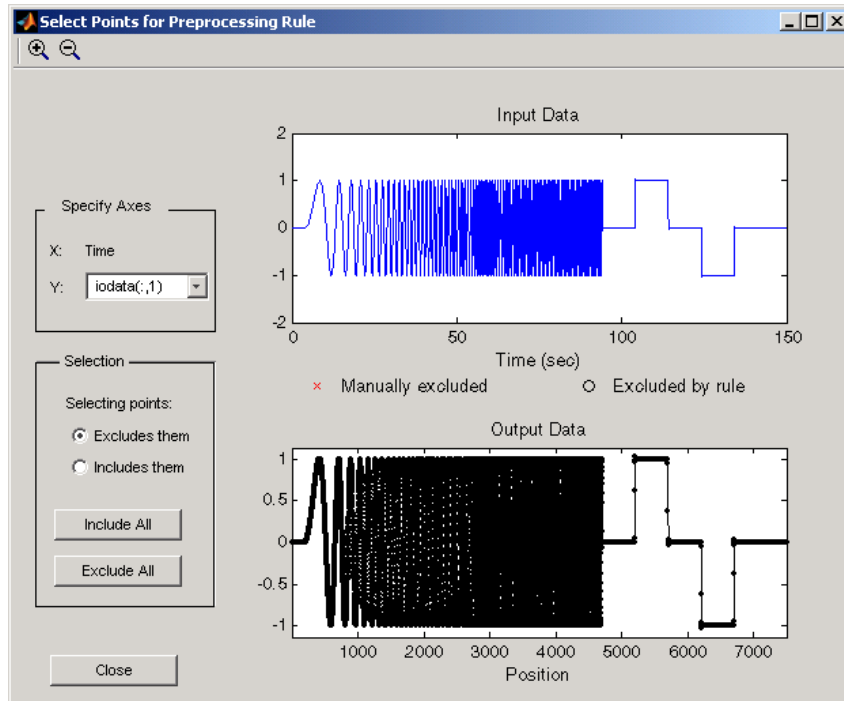
---

**Note** Changes in data are visible everywhere. When you use the **Data Editing** table, you can view the results in the data plot.

---

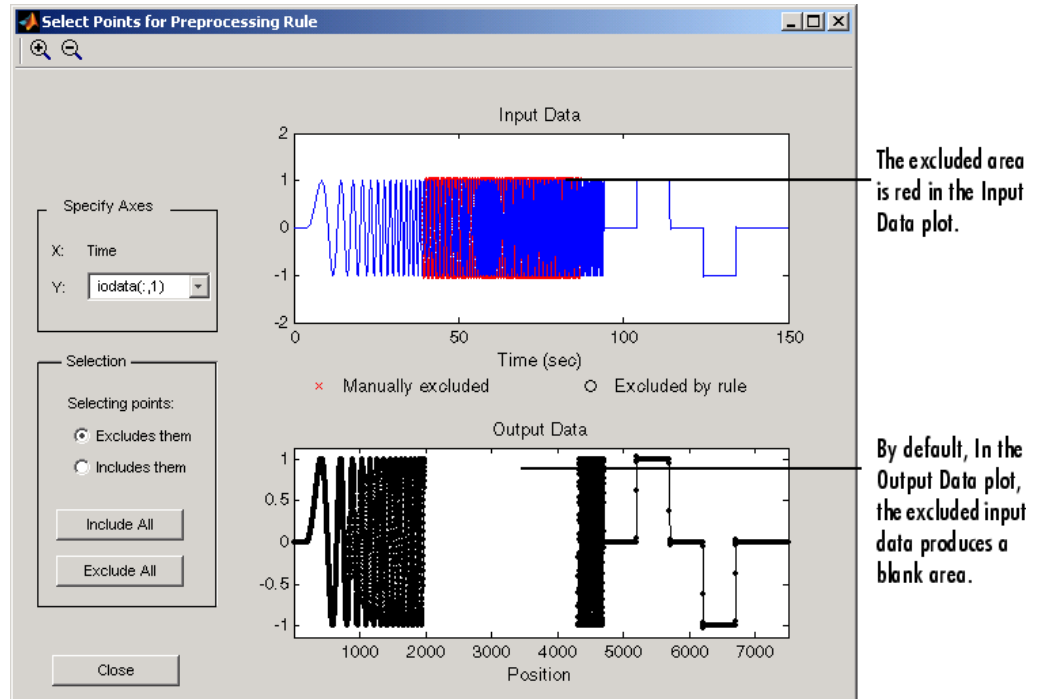
## Graphically Selecting Data

You can exclude data graphically. Click **Exclude Graphically** to open the Select Points for Preprocessing Rule window.



The way you exclude data is similar to the way you select a region for zooming: place your cursor in the **Input Data** plot and drag the mouse to draw a region of exclusion.

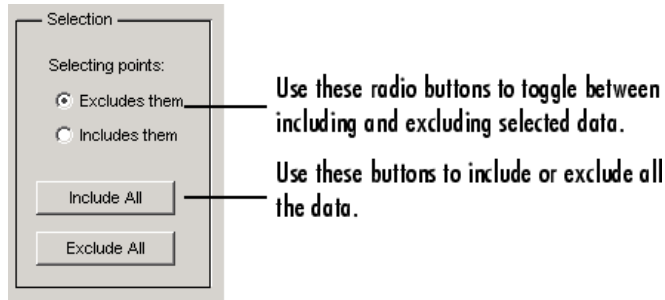
This figure shows an example of resulting data exclusion in the input data.



In the **Output Data** plot, the excluded input data produces a blank area by default. This corresponds to the NaNs that now represent excluded data. If you choose to interpolate or remove the excluded data, the output data shows the interpolated points.

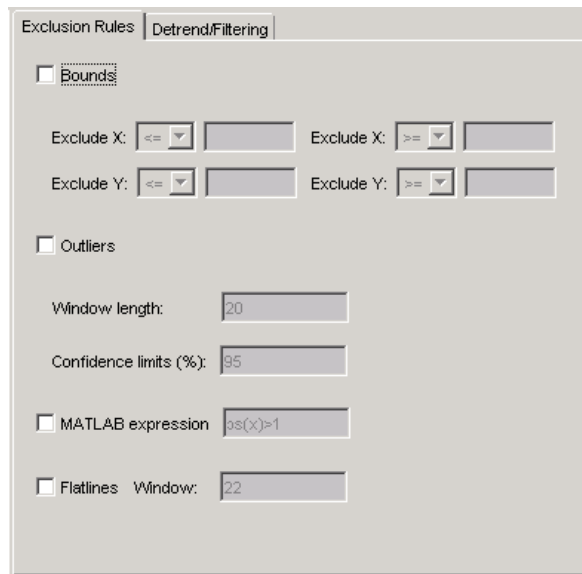
When you make changes in the Select Points for Preprocessing Rule window, they immediately appear in the **Data Editing** pane, and vice versa.

**Selection Pane.** By default, any box that you draw with your mouse selects data for exclusion, but you can toggle between exclusion and inclusion using the **Selection** pane on the left side of the Select Points for Preprocessing Rule window.



## Using Rules to Select Data Samples

A more precise way to exclude data is to use mathematical rules. The **Exclusion Rules** pane in the Data Preprocessing Tool allows you to enter customized rules for excluding data.



These are the rules you can use to exclude data:

- “Upper and Lower Bounds” on page 1-25
- “MATLAB Expressions” on page 1-25



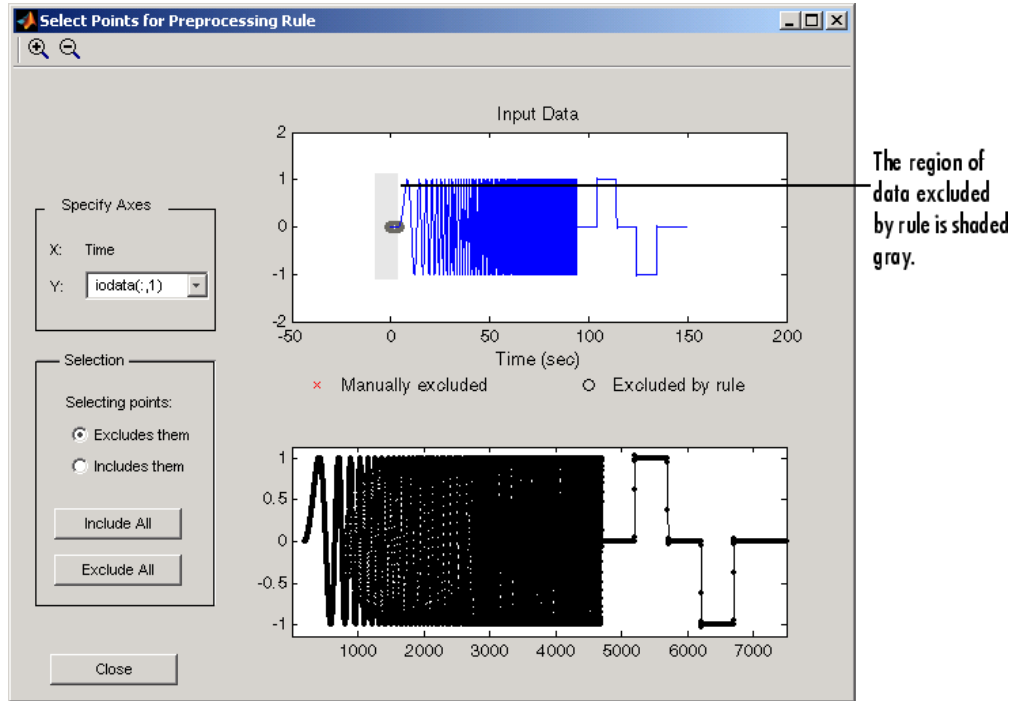
- “Flatlines” on page 1-25

**Upper and Lower Bounds.** Select the **Bounds** check box to activate upper and lower bound exclusion. Enter numbers in the **Exclude X** and **Exclude Y** fields for upper and lower bound exclusion. By default, the exclusion rule is to include the boundary values, but you can use the menu to exclude the boundaries as well.

**MATLAB Expressions.** Use the **MATLAB expression** field to enter any mathematical expression using MATLAB code. Use *x* as the variable name in your expression for the data being tested.

**Flatlines.** If you have areas of your data set where the data is constant, providing no new information, then you can choose to exclude those data points as flatlines. The **Window length** field sets the minimum number of constant data points required to define the area as a flatline.

**Example of Rule Exclusion.** This figure shows data with a region of the  $x$ -axis excluded.



### Using the Data Table to Select Data Samples

The **Data Editing** table lists both the raw data set and the modified data that you create.

The screenshot shows the 'Data Editing' window with two tabs: 'Raw data' and 'Modified data'. The 'Raw data' tab is active, displaying a table with two columns: 'Time (secs)' and 'iodata(:,1)'. The data is as follows:

Time (secs)	iodata(:,1)
21.680	-0.472
21.700	-0.515
21.720	-0.557
21.740	-0.598
21.760	-0.638
21.780	-0.676
21.800	-0.712
21.820	-0.746
21.840	-0.779
21.860	-0.809
21.880	-0.838
21.900	-0.865
21.920	-0.889
21.940	-0.911
21.960	-0.931
21.980	-0.948

Annotations in the image:

- An arrow points to the blue-highlighted rows with the text: "Use your mouse to select groups of cells for exclusion. Selected cells become blue. Right-click and select Exclude. The background becomes white, but the numbers are now red."
- An arrow points to the 'Exclude Graphically' button with the text: "Click this button to view the data graphically."

At the bottom of the window, there are three buttons:

- Grey back**: Excluded by a rule
- Red text**: Manually excluded
- Exclude Graphically**

There are two tabs in the **Data Editing** pane: **Raw data** and **Modified data**. The **Raw Data** pane shows the working copy of the data. For example, if you exclude rows of data in the **Raw data** pane, the corresponding rows of numbers become red in this table. By default the **Modified data** pane represents the rows you removed by inserting NaNs.

The screenshot shows a 'Data Editing' window with two tabs: 'Raw data' and 'Modified data'. The 'Modified data' tab is selected. The table has two columns: 'Time (secs)' and 'iodata(:,1)\*'. The data is as follows:

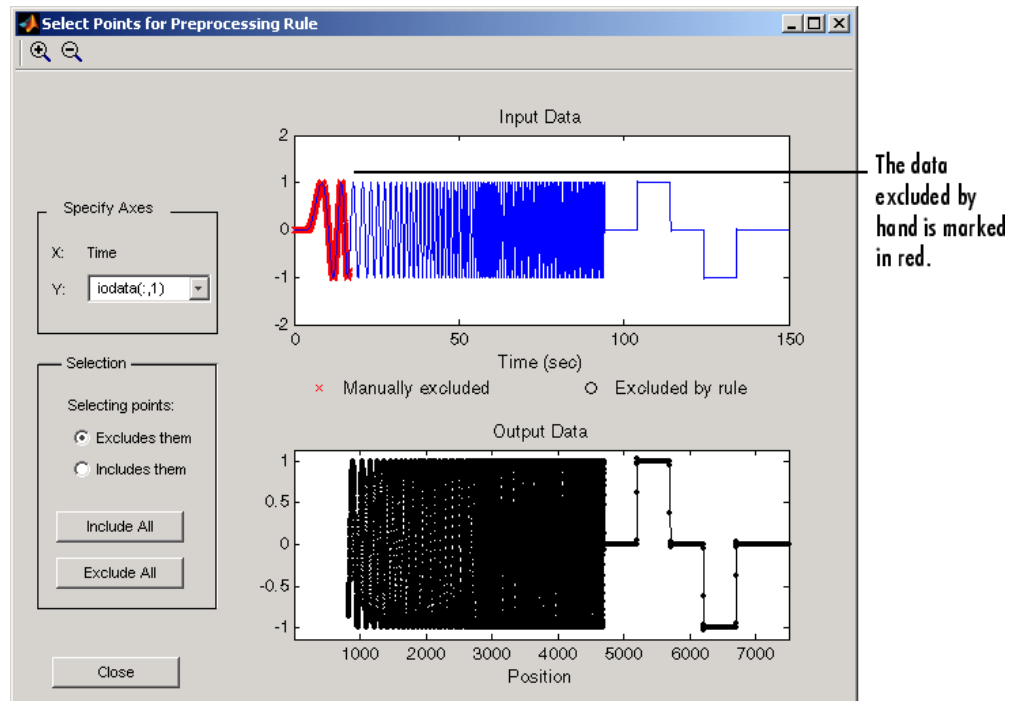
Time (secs)	iodata(:,1)*
8.760	0.979
8.780	0.976
8.800	0.972
8.820	0.969
8.840	NaN
8.860	NaN
8.880	NaN
8.900	NaN
8.920	NaN
8.940	NaN
8.960	NaN
8.980	NaN
9.0	NaN
9.20	NaN
9.40	NaN
9.60	NaN

Below the table, there are three buttons: 'Grey back' (labeled 'Excluded by a rule'), 'Red text' (labeled 'Manually excluded'), and 'Exclude Graphically'.

By default, data that you excluded from the **Raw Data** table is represented by NaNs in the **Modified Data** table. If you choose to interpolate or remove missing data, the results of that action are shown in the **Modified Data** table.

In the **Modified data** pane, you can choose to remove the excluded data completely or interpolate it. See “Handling Missing Data” on page 1-17 for more information.

After you select data for exclusion, you can view it graphically by clicking **Exclude Graphically**.



As you make changes in the **Data Editing** pane, they immediately appear in the Select Points for Preprocessing Rule window, and vice versa.

## Add Preprocessed Data Sets to Estimation Project (GUI)

After you preprocess the data using the techniques described in “Ways to Preprocess Data” on page 1-14, you can add the data set to an estimation project either by overwriting an existing data set or creating a new data set.

### In this section...

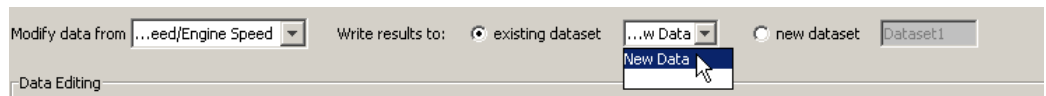
“Overwriting an Existing Data Set” on page 1-30

“Creating a New Data Set” on page 1-31

### Overwriting an Existing Data Set

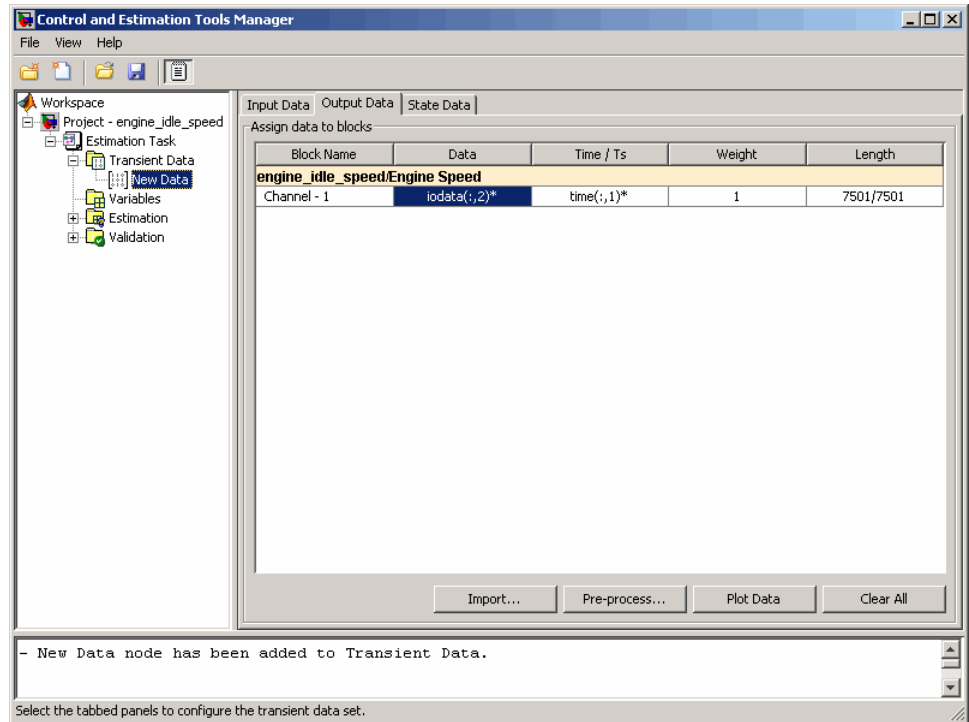
To overwrite an existing data set with the preprocessed data:

- 1 In the **Write results to** area of the Data Preprocessing Tool GUI, select the **existing dataset** option.
- 2 Choose the data set you want to overwrite from the drop-down list.



- 3 Click **Add**.

This action overwrites the selected data set with the modified data in the Control and Estimation Tools Manager GUI.



**Tip** You can export the preprocessed data to the MATLAB Workspace, as described in “Export Prepared Data to the MATLAB Workspace” on page 1-33.

## Creating a New Data Set

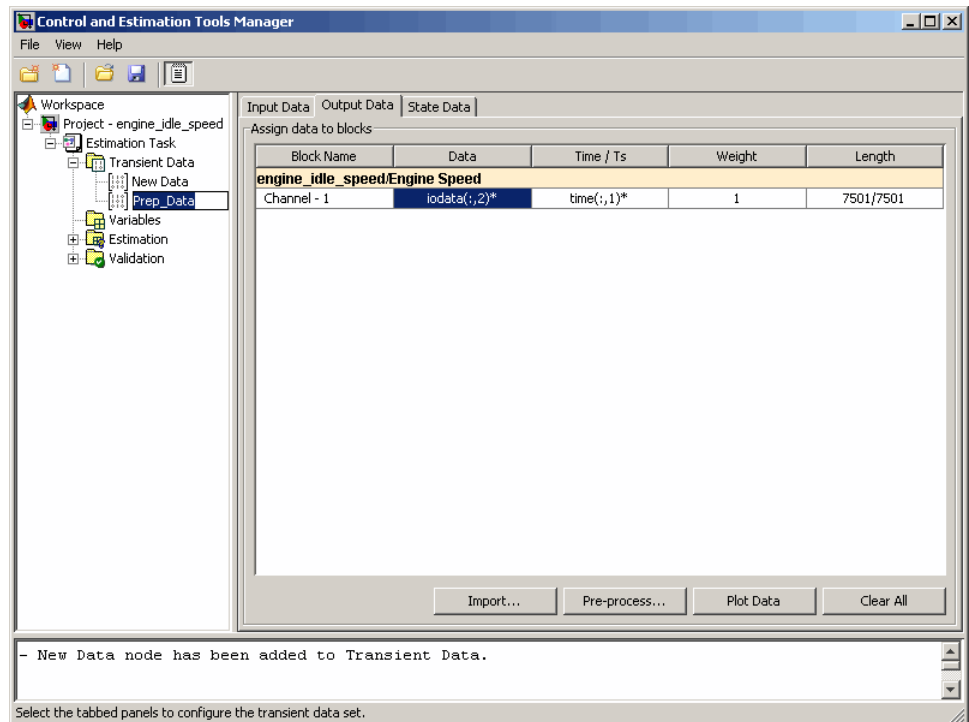
If you do not want to overwrite an existing data set with the preprocessed data, as described in “Overwriting an Existing Data Set” on page 1-30, you can create a new data set for the preprocessed data:

- 1 In the **Write results to** area of the Data Preprocessing Tool GUI, select the **new dataset** option.
- 2 Specify the name of the data set in the adjacent field.



### 3 Click Add.

This action adds a new data node in the Control and Estimation Tools Manager GUI containing the modified data.



**Tip** You can export the preprocessed data to the MATLAB Workspace, as described in “Export Prepared Data to the MATLAB Workspace” on page 1-33.



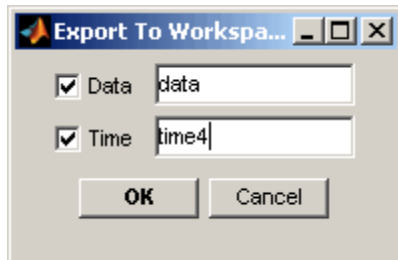
## Export Prepared Data to the MATLAB Workspace

After you add the preprocessed data to an estimation project, as described in “Add Preprocessed Data Sets to Estimation Project (GUI)” on page 1-30, you can export the data set to the MATLAB Workspace. You can use the data to further prepare it or estimate parameters using the data.

- 1** In the **Transient Data** node of the Control and Estimation Tools Manager GUI, select the node containing the prepared data set.
- 2** Right-click the table **Data** cell containing the data that you want to export, and select **Export**.

The Export to Workspace dialog box opens.

- 3** Specify the MATLAB variable names for the prepared data and the corresponding time vector in the **Data** and **Time** fields, respectively.



- 4** Click **OK**.

The resulting MATLAB variables `data` and `time4` appear in the MATLAB Workspace browser.



# Parameter Estimation

---

- “Specify Estimation Data” on page 2-3
- “Specify Parameters to Estimate” on page 2-7
- “Specify Independent Parameters to Estimate” on page 2-15
- “Specify Known Initial States” on page 2-19
- “Progress Plots” on page 2-22
- “Estimation and Simulation Options” on page 2-26
- “Progress Display Options” on page 2-38
- “Run Estimation” on page 2-39
- “Model Validation” on page 2-43
- “Load and Import Validation Data” on page 2-44
- “Compare Measured and Simulated Responses” on page 2-47
- “Compare Residuals” on page 2-51
- “Accelerating Model Simulations During Estimation” on page 2-53
- “Speedup Using Parallel Computing” on page 2-55
- “How to Use Parallel Computing” on page 2-59
- “Estimating Initial Conditions for Blocks with External Initial Conditions” on page 2-68
- “Estimate Model Parameters and Initial States (GUI)” on page 2-69
- “Estimation Projects” on page 2-80
- “How the Software Formulates Parameter Estimation as an Optimization Problem” on page 2-85

- “Writing a Cost Function” on page 2-95
- “Gradient Computations” on page 2-103
- “Estimate Model Parameter Values (Code)” on page 2-104
- “Estimate Model Parameters and Initial States (Code)” on page 2-115
- “Estimate Model Parameters using Multiple Experiments (Code)” on page 2-124
- “Estimate Model Parameters Per Experiment (Code)” on page 2-136
- “Estimate Model Parameters with Parameter Constraints (Code)” on page 2-148
- “Estimate Model Parameter Values (GUI)” on page 2-157

## Specify Estimation Data

In this section...
“Creating an Estimation Task” on page 2-3
“How to Specify Data” on page 2-4

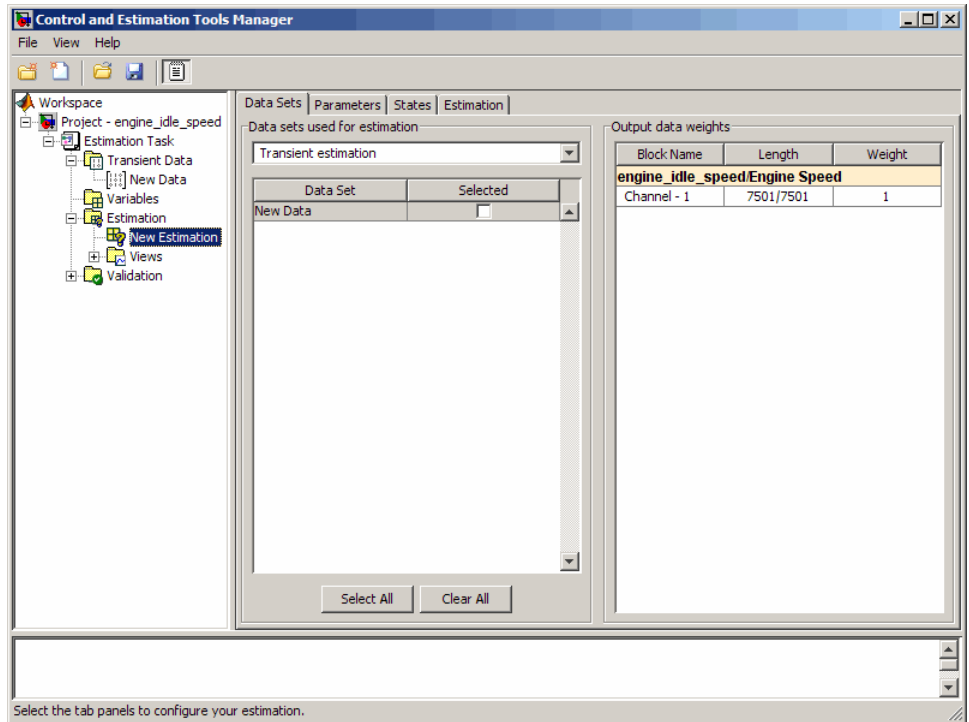
### Creating an Estimation Task

After you import the transient data, as described in “Import Data (GUI)” on page 1-4, you must create an estimation task and configure the estimation settings. If your data contains noise or outliers, you must also preprocess the data, as described in “Preprocess Data (GUI)” on page 1-15.

To create a container that stores the estimation settings:

- 1** In the Control and Estimation Tools Manager, right-click the **Estimation** node in the **Workspace** tree and select **New**.
- 2** Select the **New Estimation** node.

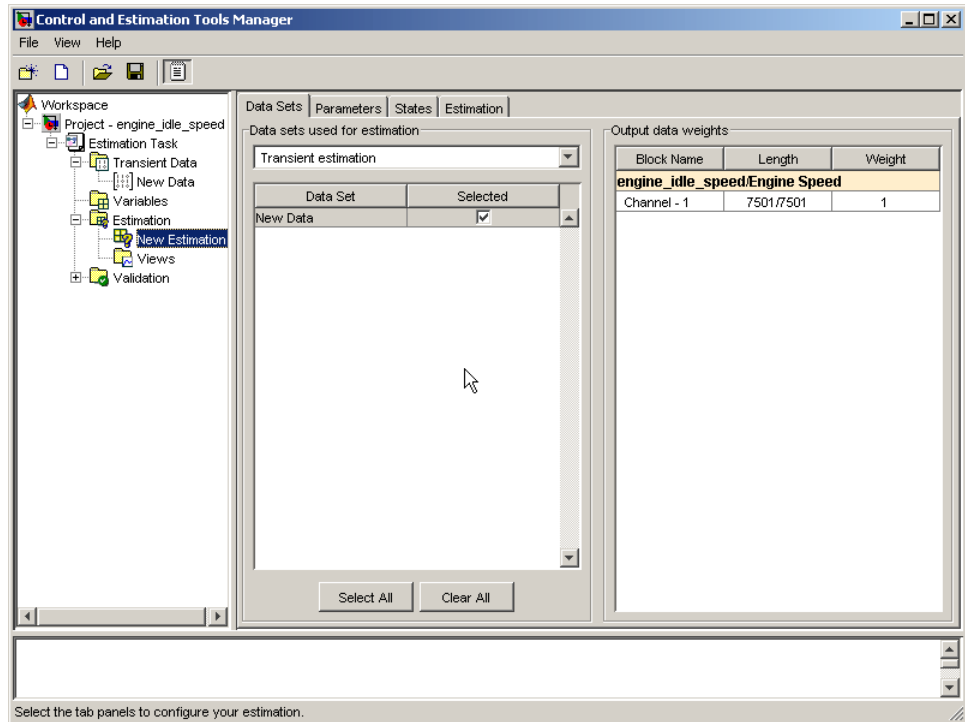
The Control and Estimation Tools Manager now resembles the next figure.



### How to Specify Data

After you select the **New Estimation** node, the **Data Sets** tab appears. Here you select the data set that you want to use in the estimation.

Select the **Selected** check box to the right of the **New Data** data set.



**Note** If you imported multiple data sets, you can select them for estimation by selecting the check box to the right of each desired data set. When using several data sets, you increase the estimation precision. However, you also increase the number of required simulations: for  $N$  parameters and  $M$  data sets, there are  $M \cdot (2N+1)$  simulations per iteration.

Then, specify the weight of each output from this model by setting the **Weight** column in the **Output data weights** table.

The relative weights are used to place more or less emphasis on specific output variables. The following are a few guidelines for specifying weights:

- Use less weight when an output is noisy.
- Use more weight when an output strongly affects parameters.

- Use more weight when it is more important to accurately match this model output to the data.



## Specify Parameters to Estimate

### In this section...

“Choosing Which Parameters to Estimate First” on page 2-7

“How to Specify Parameters for Estimation” on page 2-7

“Specifying Initial Guesses and Upper/Lower Bounds” on page 2-12

### Choosing Which Parameters to Estimate First

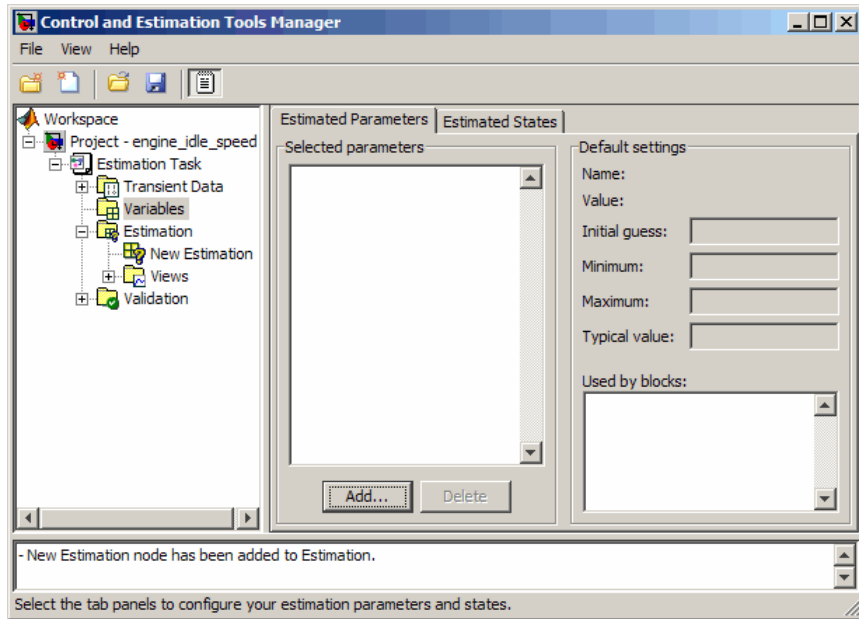
Simulink Design Optimization software lets you estimate scalar, vector and matrix parameters. Estimating model parameters is an iterative process. Often, it is more practical to estimate a small group of parameters and use the final estimated values as a starting point for further estimation of parameters that are trickier. When you have a large number of parameters to estimate, select the parameters that influence the output the most to be estimated first. Making these sorts of choices involves experience, intuition, and a solid understanding of the strengths and limitations of your Simulink model.

After you estimate a subset of parameters and validate the estimated parameters, select the remaining parameters for estimation.

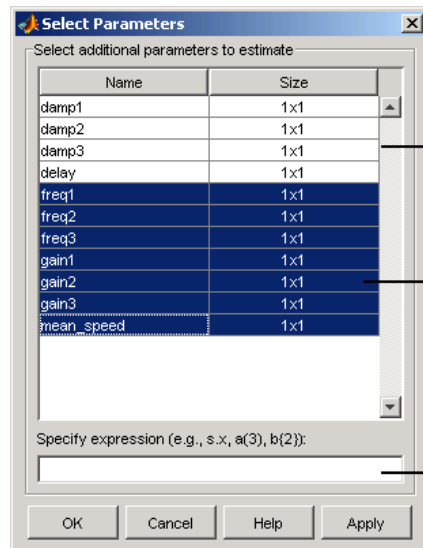
### How to Specify Parameters for Estimation

To select parameters for estimation:

- 1 In the Control and Estimation Tools Manager, select the **Variables** node in the **Workspace** tree to open the **Estimated Parameters** pane.



- 2 In the **Estimated Parameters** pane, click **Add** to open the Select Parameters dialog box.



By default, the Select Parameters dialog box looks at all variables in the model workspace and the MATLAB workspace that are used by the model.

List of parameters

Use your mouse to select data. To select adjacent parameters, hold down the Shift key while clicking the first and last parameter in the selection. To select nonadjacent parameters, hold down the Ctrl key while clicking each parameter.

Use the text field to get the parameters contained in either a Simulink parameter object, MATLAB array, structure, or cell array. Note that you cannot use mathematical expressions such as  $x + 5$ .

The dialog box lists all the variables in the model workspace and the MATLAB workspace that the model uses. You can use the mouse to select the parameters to estimate.

You can also enter parameters, separated by commas, in the **Specify expression** field of the Select Parameters dialog box. The parameters can be stored in one of the following:

- Simulink software parameter object

Example: For a Simulink parameter object *k*, type *k.value*.

- Structure

Example: For a structure *S*, type *S.fieldname* (where *fieldname* represents the name of the field that contains the parameter).

- Cell array

Example: Type *C{1}* to select the first element of the *C* cell array.

- MATLAB array

Example: Type *a(1:2)* to select the first column of a 2-by-2 array called *a*.

Sometimes, models have parameters that are not explicitly defined in the model itself. For example, a gain  $k$  could be defined in the MATLAB workspace as  $k=a+b$ , where  $a$  and  $b$  are not defined in the model but  $k$  is used. To add these independent parameters to the Select Parameters dialog box, see “Specify Independent Parameters to Estimate” on page 2-15.

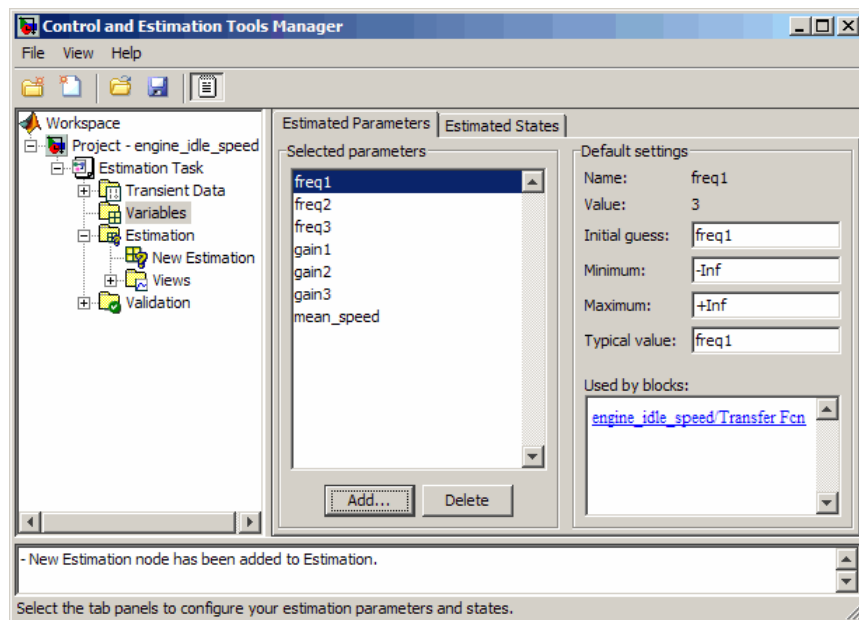
- 3 Select the last seven parameters: `freq1`, `freq2`, `freq3`, `gain1`, `gain2`, `gain3`, and `mean_speed`, and then click **OK**.

---

**Note** You need not estimate the parameters selected here all at once. You can first select all the parameters that you are interested in, and then later select the ones to estimate as described in the next step.

---

The Control and Estimation Tools Manager now resembles the next figure.



To learn how to specify the settings in the **Default settings** area of the pane, see “Specifying Initial Guesses and Upper/Lower Bounds” on page 2-12.

- 4 In the **New Estimation** node of the Control and Estimation Tools Manager GUI, select the **Parameters** tab . In this pane, you select which parameters to estimate and the range of values for the estimation.
  - a Select the parameters you want to estimate by selecting the check box in the **Estimate** column.
  - b Enter initial values for your parameters in the **Initial Guess** column.

The default values in the **Minimum** and **Maximum** columns are -Inf and +Inf, respectively, but you can select any range you want. For more information, see “Specifying Initial Guesses and Upper/Lower Bounds” on page 2-12.

---

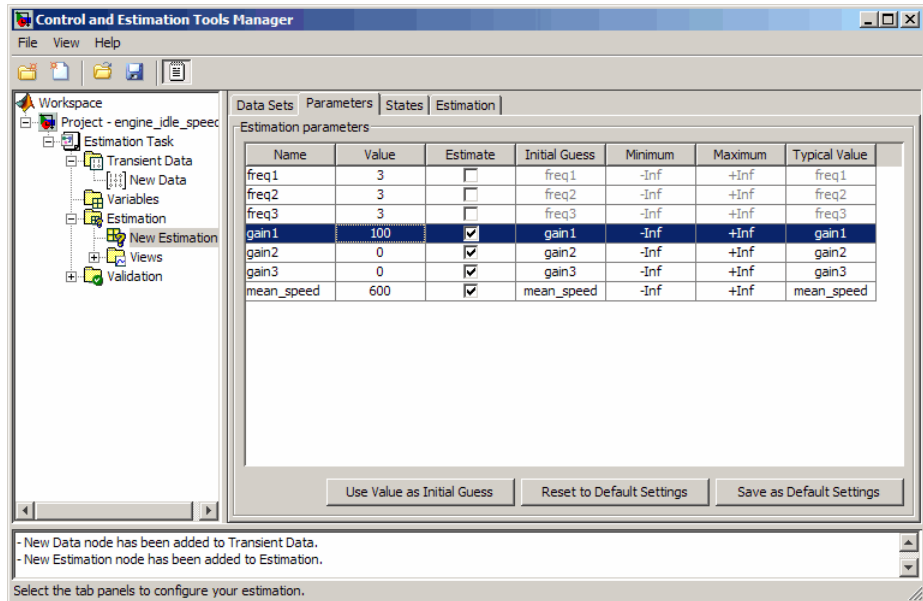
**Note** When you specify the **Minimum** and **Maximum** values for the parameters here, it does not affect your settings in the **Variables** node. You make these choices on a per estimation basis. You can move data to and from the **Variables** node into the **Estimation** node.

---

For this example, select `gain1`, `gain2`, `gain3` and `mean_speed` for estimation and set `gain1` to 10, `gain2` to 100, `gain3` to 50, and `mean_speed` to 500. Alternatively, use any initial values you like.

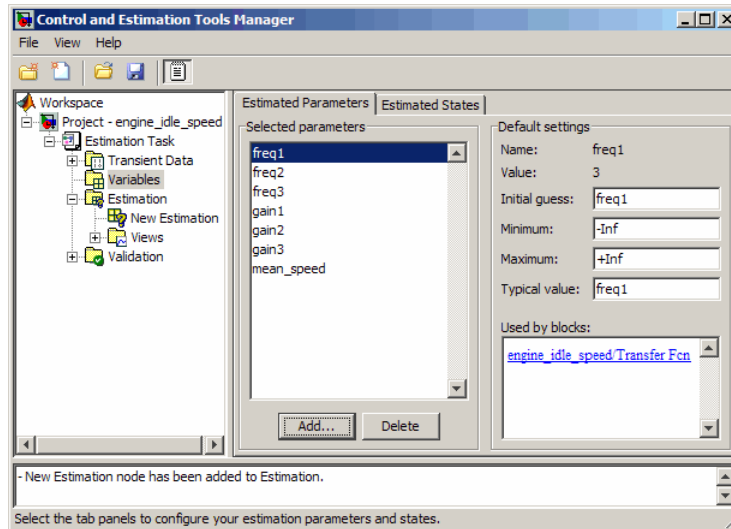
If you have good reason to believe a parameter lies within a finite range, it is usually best not to use the default minimum and maximum values. Often, there are computational advantages in specifying finite bounds if you can. It can be very important to specify lower and upper bounds. For example, if a parameter specifies the weight of a part, be sure to specify 0 as the absolute lower bound if better knowledge is unavailable.

The Control and Estimation Tools Manager now resembles the next figure.



### Specifying Initial Guesses and Upper/Lower Bounds

After you select parameters for estimation in the **Variables** node of the Control and Estimation Tools Manager GUI, the **Estimated Parameters** tab in the Control and Estimation Tools Manager looks like the following figure.



For each parameter, use the **Default settings** pane to specify the following:

- **Initial guess** — The value the estimation uses to start the process.
- **Minimum** — The smallest allowable parameter value. The default is  $-\text{Inf}$ .
- **Maximum** — The largest allowable parameter value. The default is  $+\text{Inf}$ .
- **Typical value** — The average order of magnitude. If you expect your parameter to vary over several orders of magnitude, enter the number that specified the average order of magnitude you expect. For example, if your initial guess is 10, but you expect the parameter to vary between 10 and 1000, enter 100 (the average of the order of magnitudes) for the typical value.

You use the typical value in two ways:

- To scale parameters with radically different orders of magnitude for equal emphasis during the estimation. For example, try to select the typical values so that

$$\frac{\text{anticipated value}}{\text{typical value}} \cong 1$$

or

$$\frac{\text{initial value}}{\text{typical value}} \cong 1$$

- To put more or less emphasis on specific parameters. Use a larger typical value to put more emphasis on a parameter during estimation.

### **Related Examples**

- “Specify Independent Parameters to Estimate” on page 2-15
- “Specify Known Initial States” on page 2-19



## Specify Independent Parameters to Estimate

This example shows how to specify independent parameters, that do not appear explicitly in the model, as estimation parameters.

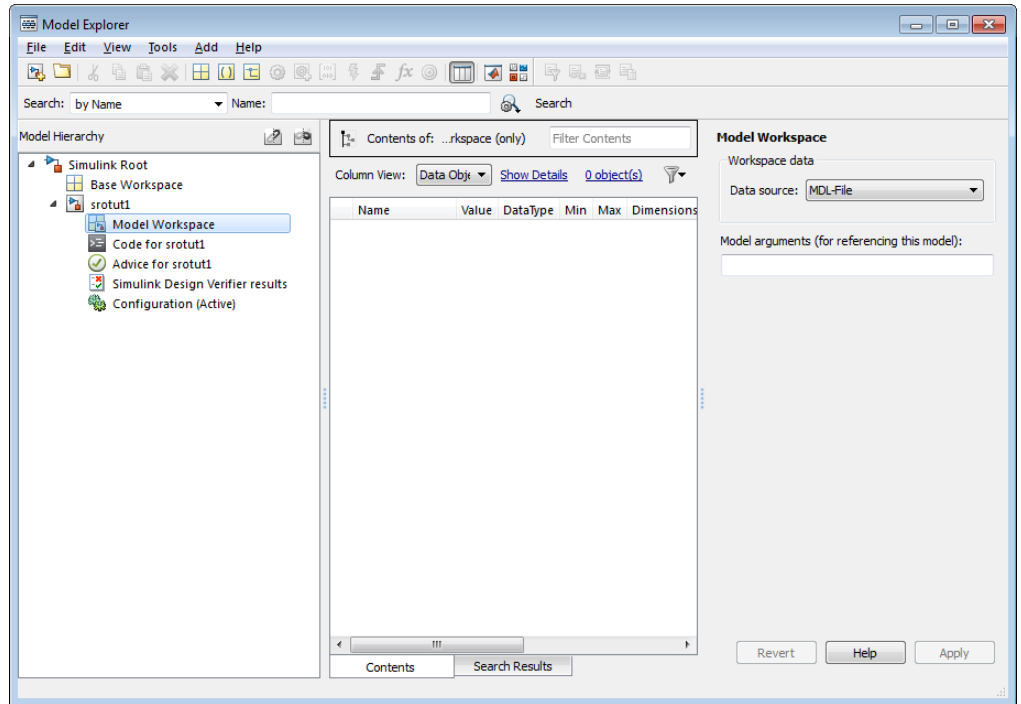
Assume that the parameter `Kint` in the model `srotut1` is related to the parameters `x` and `y` according to the relationship  $Kint=x+y$ . Also assume that the initial values of `x` and `y` are 1 and -0.7 respectively. To estimate `x` and `y` instead of `Kint`, first define these parameters in the model workspace. To do this:

- 1 At the MATLAB prompt, type

```
srotut1
```

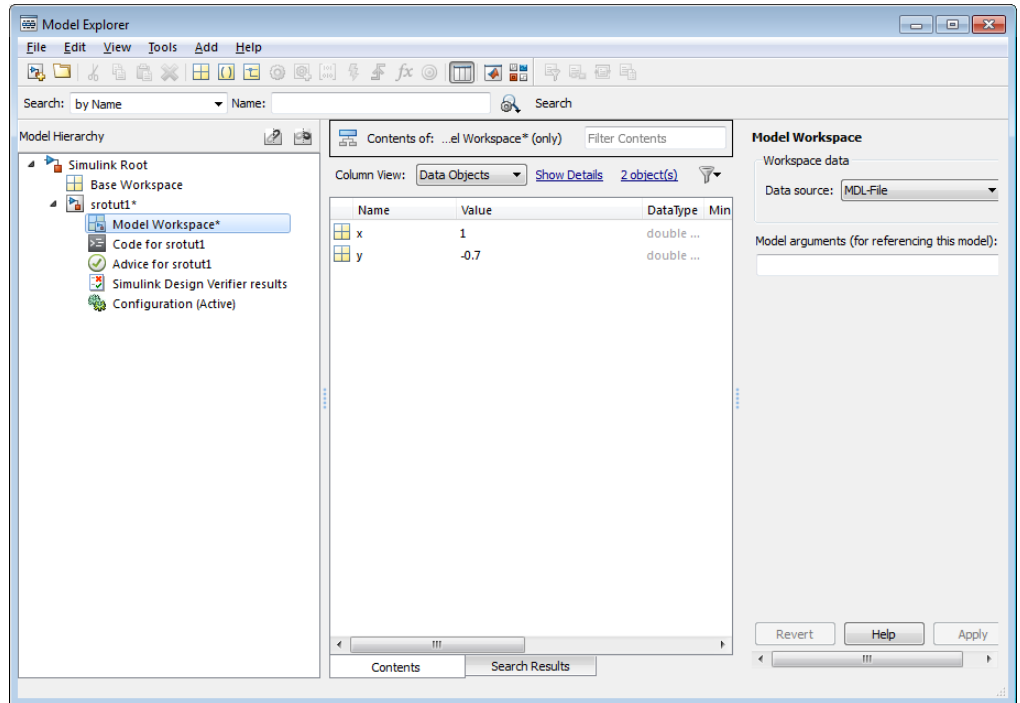
This opens the `srotut1` model window.

- 2 Select **View > Model Explorer** from the `srotut1` window to open the Model Explorer window.
- 3 In the Model Hierarchy tree, select **srotut1 > Model Workspace**.



- 4 Select **Add > MATLAB Variable** to add a new variable to the model workspace. A new variable with a default name **Var** appears in the **Name** column.
- 5 Double-click **Var** to make it editable and change the variable name to **x**. Edit the initial **Value** to 1.
- 6 Repeat steps 4 and 5 to add a variable **y** with an initial value of -0.7.

The Model Explorer window resembles the following figure.



- 7 To add the Simulation Start function that defines the relationship between  $K_{int}$  and the independent parameters  $x$  and  $y$ , select **File > Model Properties** in the `srotut1` model window.
- 8 In the Model Properties window, click the **Callbacks** tab.
- 9 To enter a Simulation start function, select **StartFcn\***, and type the name of a new function. For example, `srotut1_start` in the **Simulation start function** panel. Then, click **OK**.
- 10 Create a MATLAB file named `srotut1_start`. The content of the file defines the relationship between the parameters in the model and the parameters in the workspace. For this example, the content resembles the following:

```
wks = get_param(gcs, 'ModelWorkspace')
x = wks.evalin('x')
y = wks.evalin('y')
```

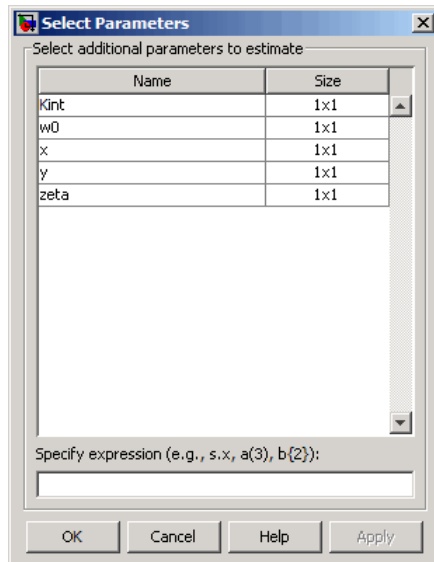
`Kint = x+y;`

---

**Note** You must first use the `get_param` function to get the variables `x` and `y` from the model workspace before you can use them to define `Kint`.

---

When you select parameters for estimation in the **Variables** node of Control and Estimation Tools Manager, `x` and `y` appear in the Select Parameters dialog box.



---

**Caution** Avoid adding independent parameters together with their corresponding dependent parameters to the lists of parameters to be estimated. Otherwise, the estimation could give incorrect results. For example, when a parameter `c` depends on the parameters `a` and `b` avoid adding all three parameters to the list.

---

### Concepts

- “Choosing Which Parameters to Estimate First” on page 2-7

## Specify Known Initial States

### In this section...

“When to Specify Initial States Versus Estimate Initial States” on page 2-19

“How to Specify Initial States in the GUI” on page 2-19

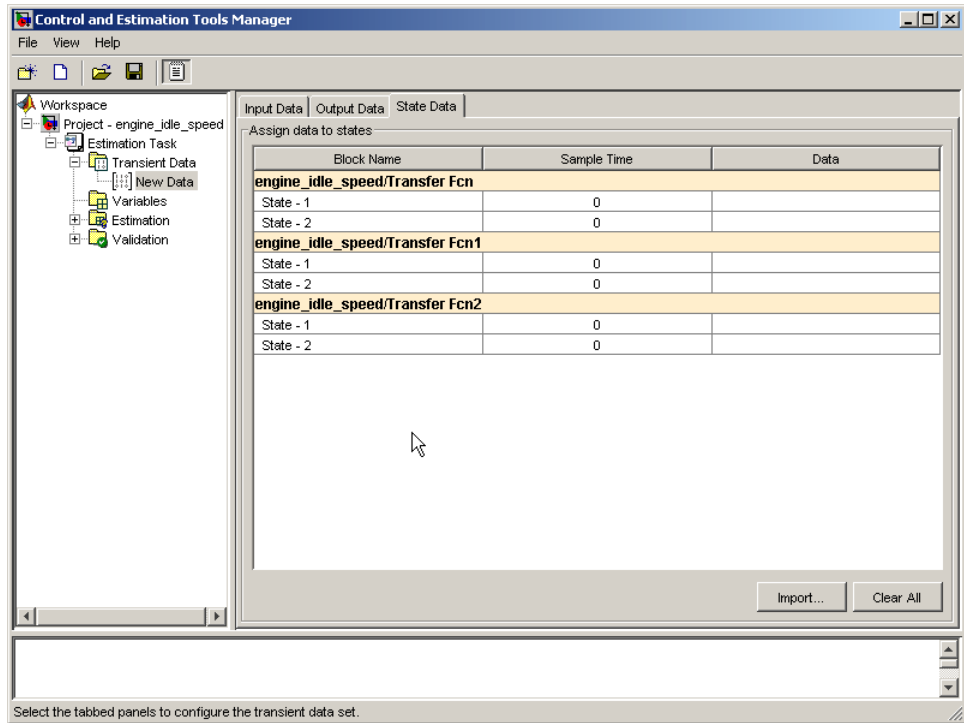
### When to Specify Initial States Versus Estimate Initial States

Often, sets of measured data are collected at various times and under different initial conditions. When you estimate model parameters using one data set and subsequently run another estimation with a second data set, your parameter values may not match. Given that the Simulink Design Optimization software attempts to find constant values for parameters, this is clearly a problem.

You can estimate the initial conditions using procedures that are similar to those you use to estimate parameters. You can then use these initial condition estimates as a basis for estimating parameters for your Simulink model. The Control and Estimation Tools Manager has an **Estimated States** pane that lists the states available for initial condition estimation.

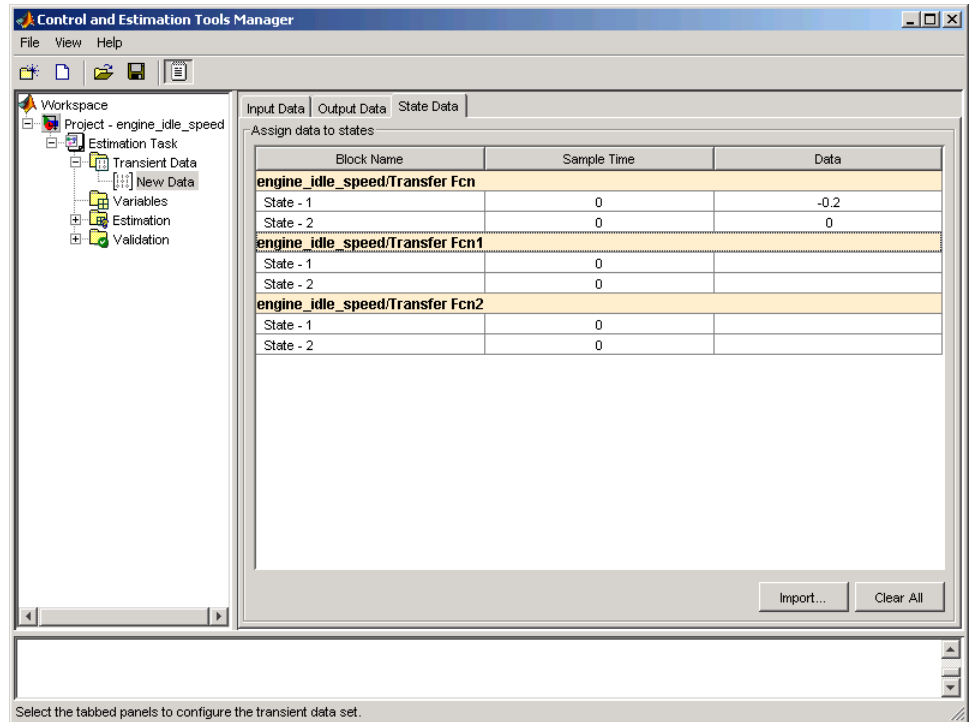
### How to Specify Initial States in the GUI

After you select parameters for estimation, as described in “Specify Parameters to Estimate” on page 2-7, you can specify initial conditions of states in your model. By default, the estimation uses initial conditions specified in the Simulink model. If you want to specify initial conditions other than the defaults, use the **State Data** tab. You can select the **State Data** tab in the **New Data** node under the **Transient Data** node in the **Workspace** tree.



To specify the initial condition of a state for the `engine_idle_speed` model:

- 1 Select the **Data** cell associated with the state.
- 2 Enter the initial conditions. In this example, enter `-0.2` for **State - 1** of the `engine_idle_speed/Transfer Fcn`. For **State - 2**, enter `0`.



## Progress Plots

In this section...
“Types of Plots” on page 2-22
“Basic Steps for Creating Plots” on page 2-22

### Types of Plots

You can choose the plot type from the **Plot Type** drop-down list. The following types of plots are available for viewing and evaluating the estimation:

- **Cost function** — Plot the cost function values.
- **Measured and simulated** — Plot empirical data against simulated data.
- **Parameter sensitivity** — Plot the rate of change of the cost function as a function of the change in the parameter. That is, plot the derivative of the cost function with respect to the parameter being varied.
- **Parameter trajectory** — Plot the parameter values as they change.
- **Residuals** — Plot the error between the experimental data and the simulated output.

### Basic Steps for Creating Plots

Before you begin estimating the parameters, you must create the plots for viewing the progress of the estimation.

---

**Note** An estimation must be created before creating views. Otherwise, the **Options** table will be empty. To learn more, see “Creating an Estimation Task” on page 2-3.

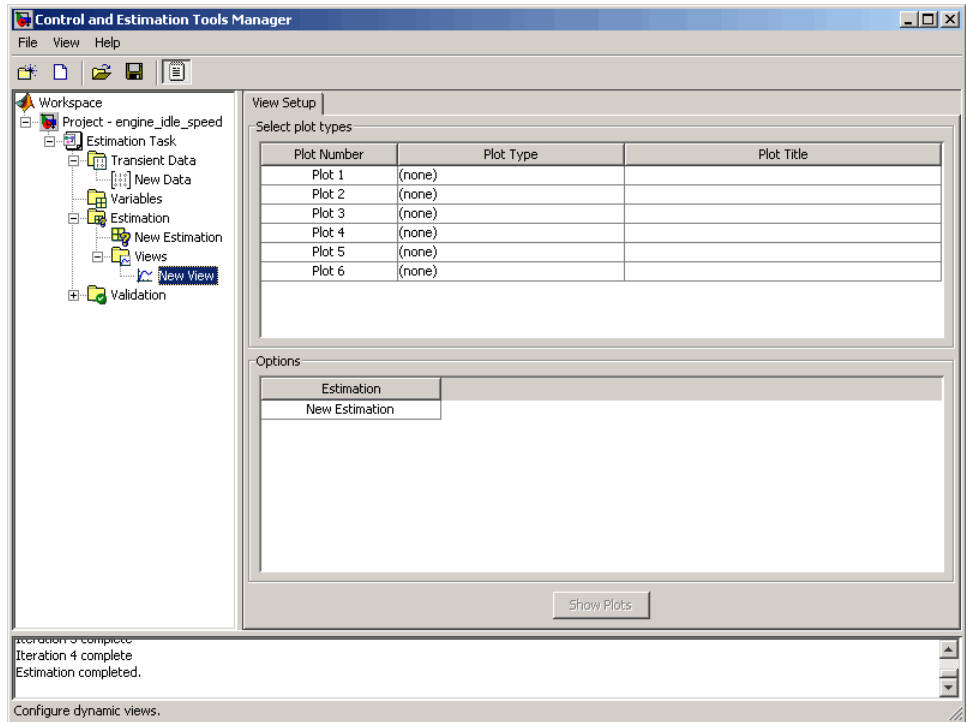
---

To create plots for viewing the estimation progress, follow the steps below:

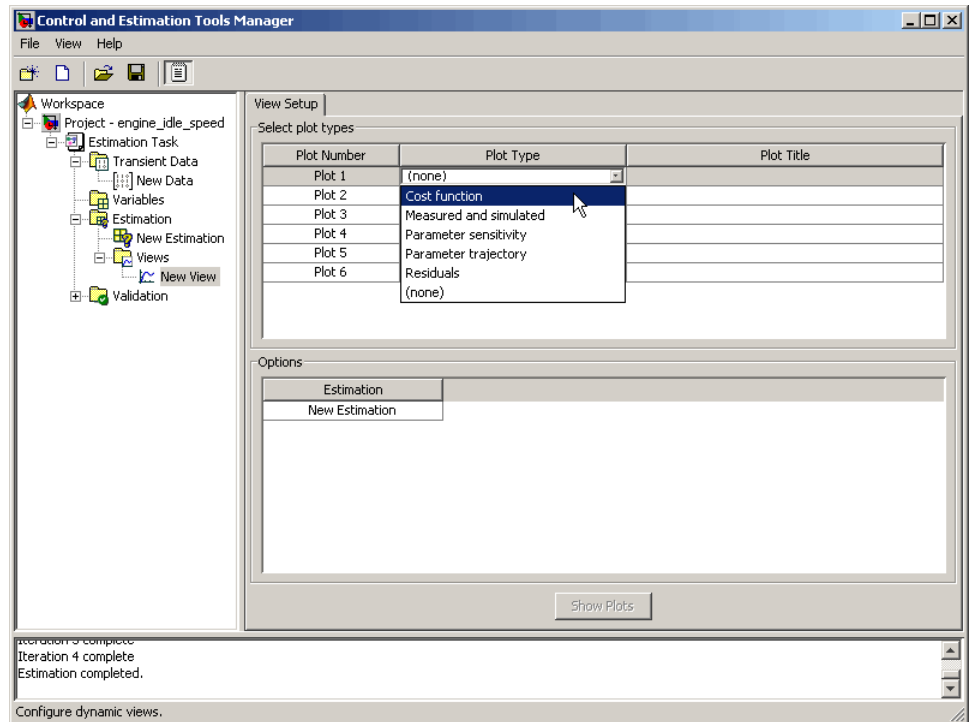
- 1 Right-click the **Views** node in the Control and Estimation Tools Manager and select **New**.



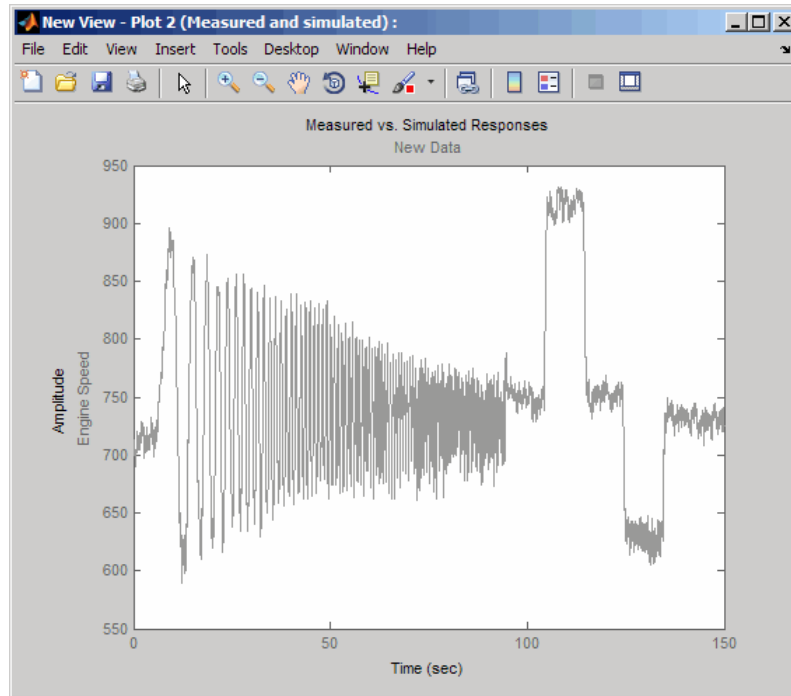
**2** In the **Workspace** tree, select **New View** to open the **View Setup** pane.



- 3 In the **Select plot types** table, select the **Plot Type** from the drop-down list. In this example, select **Cost function**.



- 4 Select **Measured and simulated** as the **Plot Type** for **Plot 2**. Use this plot to validate the estimated parameters.
- 5 In the **Options** area, select the check-box for both **Plot 1** and **Plot 2**.
- 6 Click **Show Plots**. This displays an empty cost function plot and a plot of the measured data.



When you perform the estimation, the plot updates automatically.

## Estimation and Simulation Options

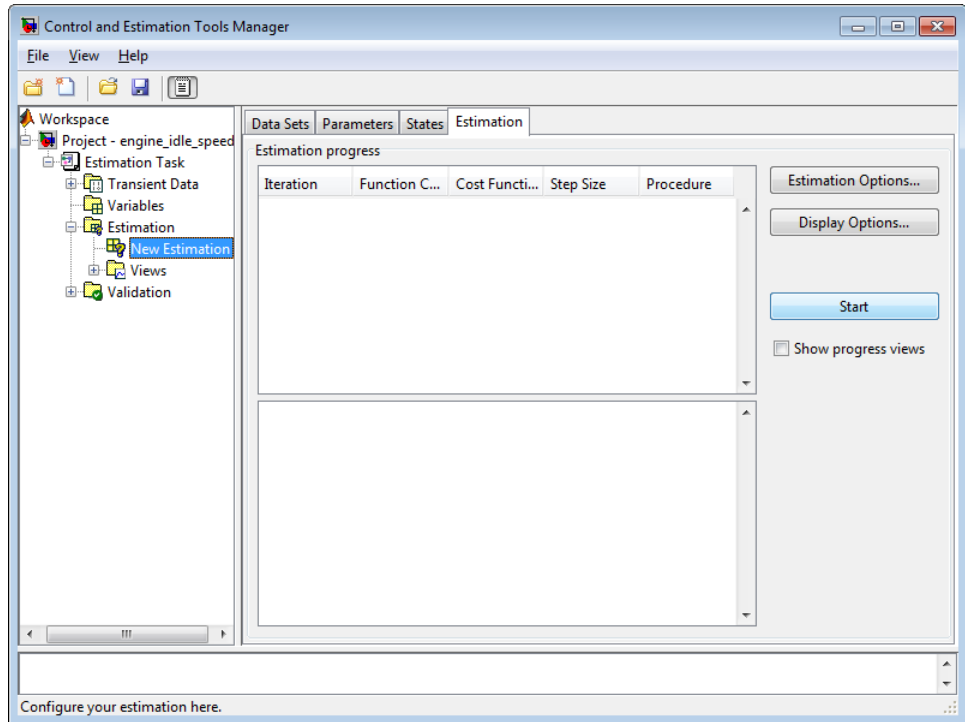
In this section...
“Estimation Options” on page 2-26
“Simulation Options” on page 2-32

### Estimation Options

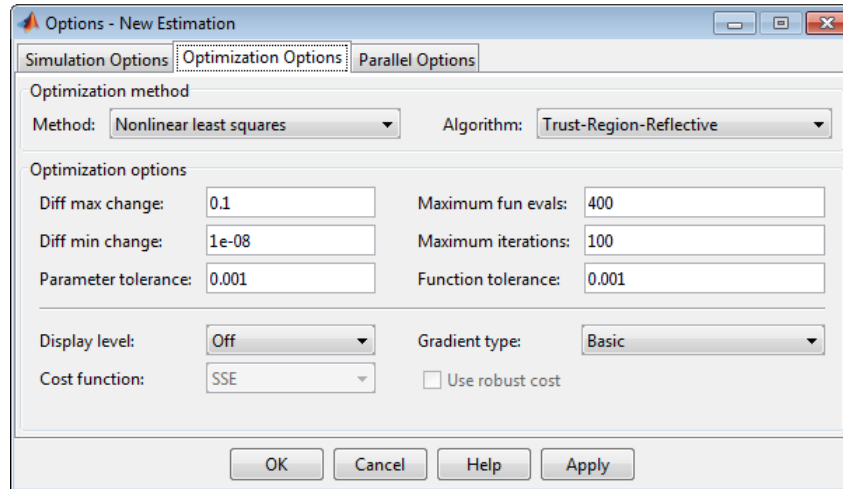
- “Accessing Estimation Options” on page 2-26
- “Supported Estimation Methods” on page 2-28
- “Selecting Optimization Termination Options” on page 2-30
- “Selecting Additional Optimization Options” on page 2-30
- “Specifying Goodness of Fit Criteria (Cost Function)” on page 2-31
- “How to Specify Estimation Options in the GUI” on page 2-31

### Accessing Estimation Options

In the **New Estimation** node in the **Workspace** tree, click the **Estimation** tab.



Click **Estimation Options**. This action opens the Options- New Estimation dialog box where you can specify the estimation method, algorithm options and cost function for the estimation.

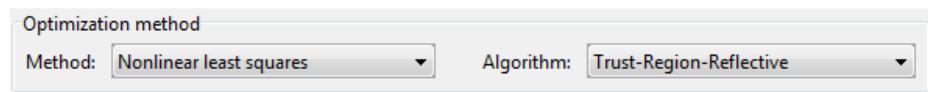


The following sections describe the estimation method settings and cost function:

- “Supported Estimation Methods” on page 2-28
- “Selecting Optimization Termination Options” on page 2-30
- “Selecting Additional Optimization Options” on page 2-30
- “Specifying Goodness of Fit Criteria (Cost Function)” on page 2-31

### Supported Estimation Methods

Both the **Method** and **Algorithm** options define the optimization method. Use the **Optimization method** area of the Options dialog box to set the estimation method and its algorithm.



For the **Method** option, the four choices are:

- **Nonlinear least squares** (default) — Uses the Optimization Toolbox™ nonlinear least squares function `lsqnonlin`.
- **Gradient descent** — Uses the Optimization Toolbox function `fmincon`.

- **Pattern search** — Uses the pattern search method `patternsearch`. This option requires Global Optimization Toolbox software.
- **Simplex search** — Uses the Optimization Toolbox function `fminsearch`, which is a direct search method. **Simplex search** is most useful for simple problems and is sometimes faster than `fmincon` for models that contain discontinuities.

The following table summarizes the **Algorithm** options for the Nonlinear least squares and Gradient descent estimation methods:

Method	Algorithm Option	Learn More
Nonlinear least squares	<ul style="list-style-type: none"> <li>• Trust-Region-Reflective (default)</li> <li>• Levenberg-Marquardt</li> </ul>	In the Optimization Toolbox documentation, see: <ul style="list-style-type: none"> <li>• “Trust-Region-Reflective Least Squares Algorithm”</li> <li>• “Levenberg-Marquardt Method”</li> </ul>
Gradient descent	<ul style="list-style-type: none"> <li>• Active-Set (default)</li> <li>• Interior-Point</li> <li>• Trust-Region-Reflective</li> <li>• Sequential Quadratic Programming</li> </ul>	In the Optimization Toolbox documentation, see: <ul style="list-style-type: none"> <li>• “fmincon Active Set Algorithm”</li> <li>• “fmincon Interior Point Algorithm”</li> <li>• “fmincon Trust Region Reflective Algorithm”</li> <li>• “fmincon SQP Algorithm”</li> </ul>

## Selecting Optimization Termination Options

Specify termination options in the **Optimization options** area.

Optimization options			
Diff max change:	0.1	Maximum fun evals:	400
Diff min change:	1e-08	Maximum iterations:	100
Parameter tolerance:	0.001	Function tolerance:	0.001

Several options define when the optimization terminates:

- **Diff max change** — The maximum allowable change in variables for finite-difference derivatives. See `fmincon` in the Optimization Toolbox documentation for details.
- **Diff min change** — The minimum allowable change in variables for finite-difference derivatives. See `fmincon` in the Optimization Toolbox documentation for details.
- **Parameter tolerance** — Optimization terminates when successive parameter values change by less than this number.
- **Maximum fun evals** — The maximum number of cost function evaluations allowed. The optimization terminates when the number of function evaluations exceeds this value.
- **Maximum iterations** — The maximum number of iterations allowed. The optimization terminates when the number of iterations exceeds this value.
- **Function tolerance** — The optimization terminates when successive function values are less than this value.

By varying these parameters, you can force the optimization to continue searching for a solution or to continue searching for a more accurate solution.

## Selecting Additional Optimization Options

At the bottom of the **Optimization options** pane is a group of additional optimization options.

Display level:	Off	Gradient type:	Basic
----------------	-----	----------------	-------



Additional options for optimization include:

- **Display level** — Specifies the form of the output that appears in the MATLAB command window. The options are *Iteration*, which displays information after each iteration, *None*, which turns off all output, *Notify*, which displays output only if the function does not converge, and *Final*, which only displays the final output. Refer to the Optimization Toolbox documentation for more information on what type of iterative output each method displays.
- **Gradient type** — When using Gradient Descent or Nonlinear least squares as the **Method**, the gradients are calculated based on finite difference methods. The *Refined* method offers a more robust and less noisy gradient calculation method than *Basic*, although it does take longer to run optimizations using the *Refined* method.

For information about how the software computes the gradients, see “Gradient Computations” on page 2-103.

### Specifying Goodness of Fit Criteria (Cost Function)

The *cost function* is a function that estimation methods attempt to minimize. You can specify the cost function at the bottom of the **Optimization options** area.



You have the following options when selecting a cost function:

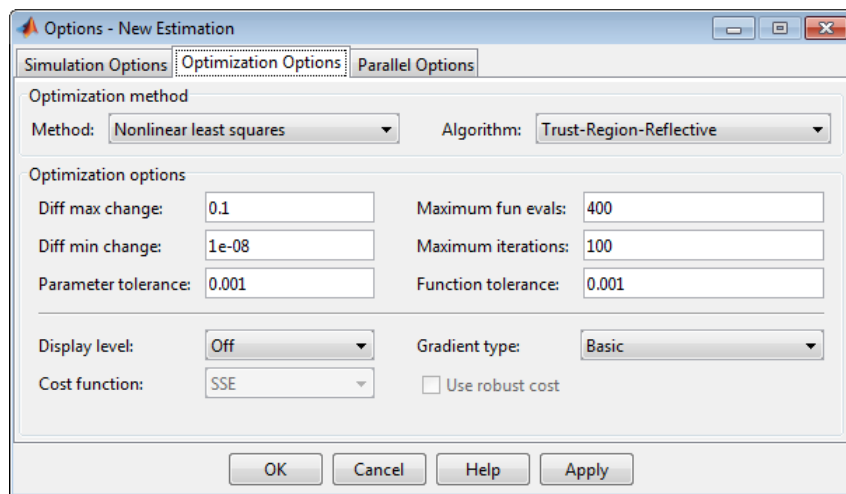
- **Cost function** — The default is SSE (sum of squared errors), which uses a least-squares approach. You can also use SAE, the sum of absolute errors.
- **Use robust cost** — Makes the optimizer use a robust cost function instead of the default least-squares cost. This is useful if the experimental data has many outliers, or if your data is noisy.

### How to Specify Estimation Options in the GUI

You can set several options to tune the results of the estimation. These options include the optimization methods and their tolerances.

To set options for estimation:

- 1 Select the **New Estimation** node in the **Workspace** tree.
- 2 Click the **Estimation** tab.
- 3 Click **Estimation Options** to open the Options dialog box.
- 4 Click the **Optimization Options** tab and specify the options.



## Simulation Options

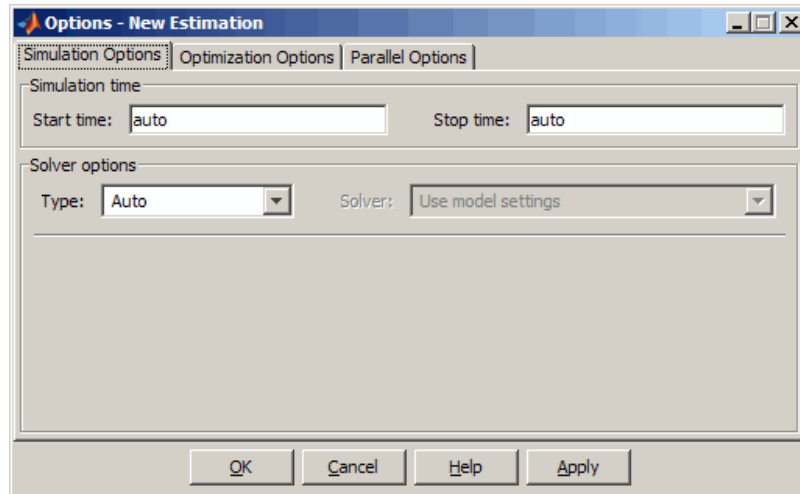
- “Accessing Simulation Options” on page 2-32
- “Selecting Simulation Time” on page 2-33
- “Selecting Solvers” on page 2-35

## Accessing Simulation Options

To estimate parameters of a model, Simulink Design Optimization software runs simulations of the model.

To set options for simulation:

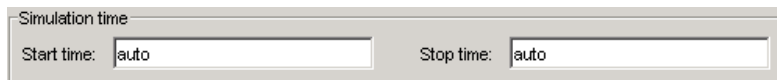
- 1 Select the **New Estimation** node in the **Workspace** tree.
- 2 Click the **Estimation** tab.
- 3 Click **Estimation Options** to open the Options dialog box.



- 4 Click the **Simulation Options** tab and specify the options, as described in the following sections:
  - “Selecting Simulation Time” on page 2-33
  - “Selecting Solvers” on page 2-35

### Selecting Simulation Time

You can specify the simulation start and stop times in the **Simulation time** area of the **Simulation Options** tab.

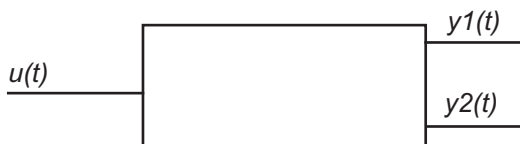


By default, **Start time** and **Stop time** are automatically computed based on the start and stop times specified in the Simulink model.

To set alternative start and stop times for the optimization, enter the new times under **Simulation time**. This action overwrites the simulation start and stop times specified in the Simulink model.

**Simulation Time for Data Sets with Different Time Lengths.** Simulink Design Optimization software can simulate models containing empirical data sets of different time lengths. You can use experimental data sets for estimation that contain I/O samples collected at different time points.

The following example shows a single-input, two-output model for which you want to estimate the parameters.



The model uses two output data sets containing transient data samples for parameter estimation:

- Output  $y1(t)$  at time points  $t1 = \{t_1^1, t_2^1, \dots, t_n^1\}$ .
- Output  $y2(t)$  at time points  $t2 = \{t_1^2, t_2^2, \dots, t_m^2\}$ .

The simulation time  $t$  is computed as:

$$t = t1 \cup t2 = \{t_1^1, t_1^2, t_2^1, t_2^2, \dots, t_n^1, t_m^2\}$$

This new set ranges from  $tmin$  to  $tmax$ . The values  $tmin$  and  $tmax$  represent the minimum and maximum time points in  $t$  respectively.

When you run the estimation, the model is simulated over the time range  $t$ . Simulink extracts the simulated data for each output based on the following criteria:

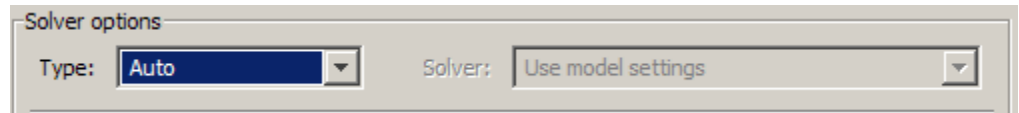
- **Start time** — Typically, the start time in the Simulink model is set to 0. For a nonzero start time, the simulated data corresponding to time points before  $t_1^1$  for  $y1(t)$  and  $t_1^2$  for  $y2(t)$  are discarded.
- **Stop time** — If the stop time  $t_{stop} \geq t_{max}$ , the simulated data corresponding to time points in  $t1$  are extracted for  $y1(t)$ . Similarly, the simulated data for time points in  $t2$  are extracted for  $y2(t)$ .

If the stop time  $t_{stop} < t_{max}$ , the data spanning time points  $> t_{stop}$  are discarded for both  $y1(t)$  and  $y2(t)$ .

## Selecting Solvers

When running the estimation, the software solves the dynamic system using one of several Simulink solvers.

Specify the solver type and its options in the **Solver options** area of the **Simulation Options** tab of the Options dialog box.



The solver can be one of the following **Type**:

- **Auto (default)** — Uses the simulation settings specified in the Simulink model.
- **Variable-step** — Variable-step solvers keep the error within specified tolerances by adjusting the step size the solver uses. For example, if the states of your model are likely to vary rapidly, you can use a variable-step solver for faster simulation. For more information on the variable-step solver options, see “Variable-Step Solver Options” on page 2-36.
- **Fixed-step** — Fixed-step solvers use a constant step-size. For more information on the fixed-step solver options, see “Fixed-Step Solver Options” on page 2-37.

See “Choose a Solver” in the Simulink documentation for information about solvers.

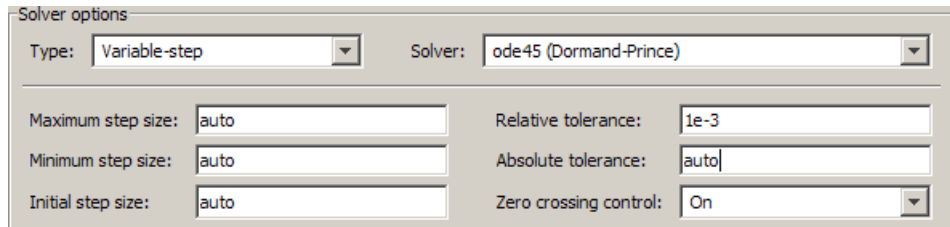
---

**Note** To obtain faster simulations during estimation, you can change the solver **Type** to **Variable-step** or **Fixed-step**. However, the estimated parameter values apply only for the chosen solver type, and may differ from values you obtain using settings specified in the Simulink model.

---

**Variable-Step Solver Options.** When you select **Variable-step** as the solver **Type**, you can choose one of the following as the **Solver**:

- Discrete (no continuous states)
- ode45 (Dormand-Prince)
- ode23 (Bogacki-Shampine)
- ode113 (Adams)
- ode15s (stiff/NDF)
- ode23s (stiff/Mod. Rosenbrock)
- ode23t (Mod. stiff/Trapezoidal)
- ode23tb (stiff/TR-BDF2)



Solver options

Type: Variable-step Solver: ode45 (Dormand-Prince)

Maximum step size: auto Relative tolerance: 1e-3

Minimum step size: auto Absolute tolerance: auto

Initial step size: auto Zero crossing control: On

You can also specify the following parameters that affect the step-size of the simulation:

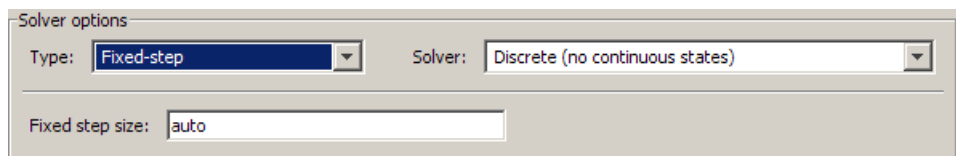
- **Maximum step size** — The largest step-size the solver can use during a simulation.
- **Minimum step size** — The smallest step-size the solver can use during a simulation.
- **Initial step size** — The step-size the solver uses to begin the simulation.

- **Relative tolerance** — The largest allowable relative error at any step in the simulation.
- **Absolute tolerance** — The largest allowable absolute error at any step in the simulation.
- **Zero crossing control** — Set to on for the solver to compute exactly where the signal crosses the  $x$ -axis. This option is useful when using functions that are nonsmooth and the output depends on when a signal crosses the  $x$ -axis, such as absolute values.

By default, the software automatically chooses the values for these options. To specify your own values, enter them in the appropriate fields. For more information, see “Solver Pane” in the Simulink documentation.

**Fixed-Step Solver Options.** When you select **Fixed-step** as the solver **Type**, you can choose one of the following as the **Solver**:

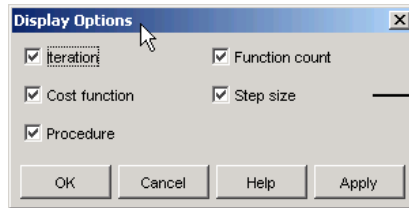
- Discrete (no continuous states)
- ode5 (Dormand-Prince)
- ode4 (Runge-Kutta)
- ode3 (Bogacki-Shampine)
- ode2 (Heun)
- ode1 (Euler)



You can also specify the **Fixed step size** value, which determines the step size the solver uses during the simulation. By default, the software automatically chooses a value for this option. For more information, see “Fixed-step size (fundamental sample time)” in the Simulink documentation.

## Progress Display Options

You can specify the display options by clicking **Display Options** in the **Estimation** tab in the Control and Estimation tools Manager. This opens the following dialog box.



By default, all boxes are checked. Uncheck any feature that you don't want to view during the estimation process.

Clearing a check box implies that feature will not appear in the display table as the estimation progresses. To learn more about the display table, see “Iterative Display” in the Optimization Toolbox documentation.

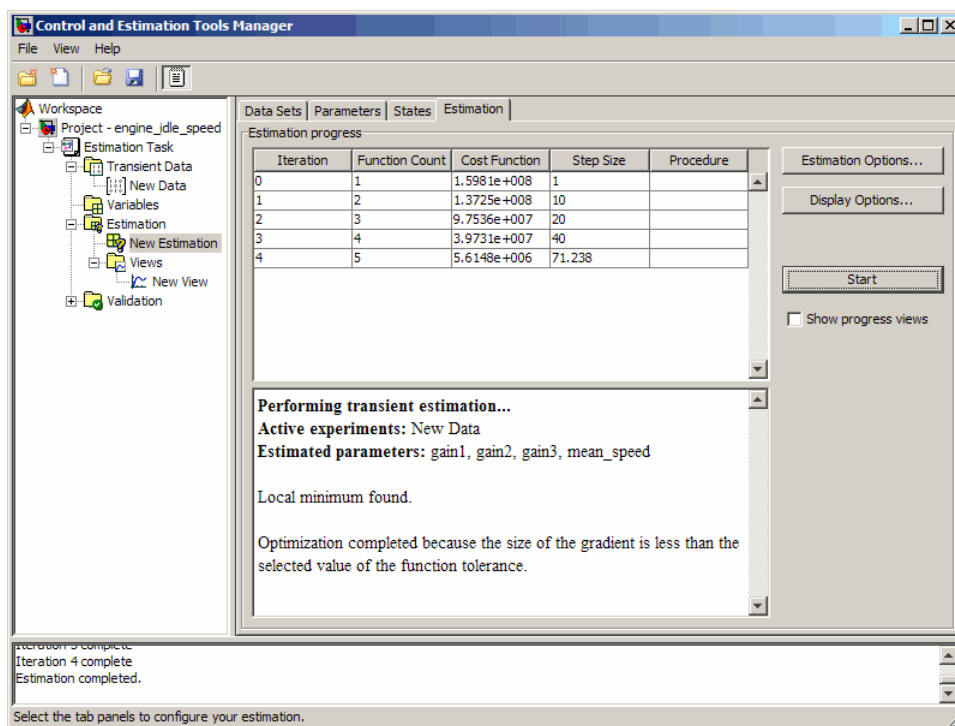


## Run Estimation

Before you begin estimating the parameters, you must have configured the estimation data and parameters, and specified estimation and simulation options, as described in “Specify Estimation Data” on page 2-3 and “Specify Parameters to Estimate” on page 2-7.

To start the estimation, select the **New Estimation** node in the Control and Estimation Tools Manager and select the **Estimation** tab.

Click **Start** to begin the estimation process. At the end of the iterations, the window should resemble the following:

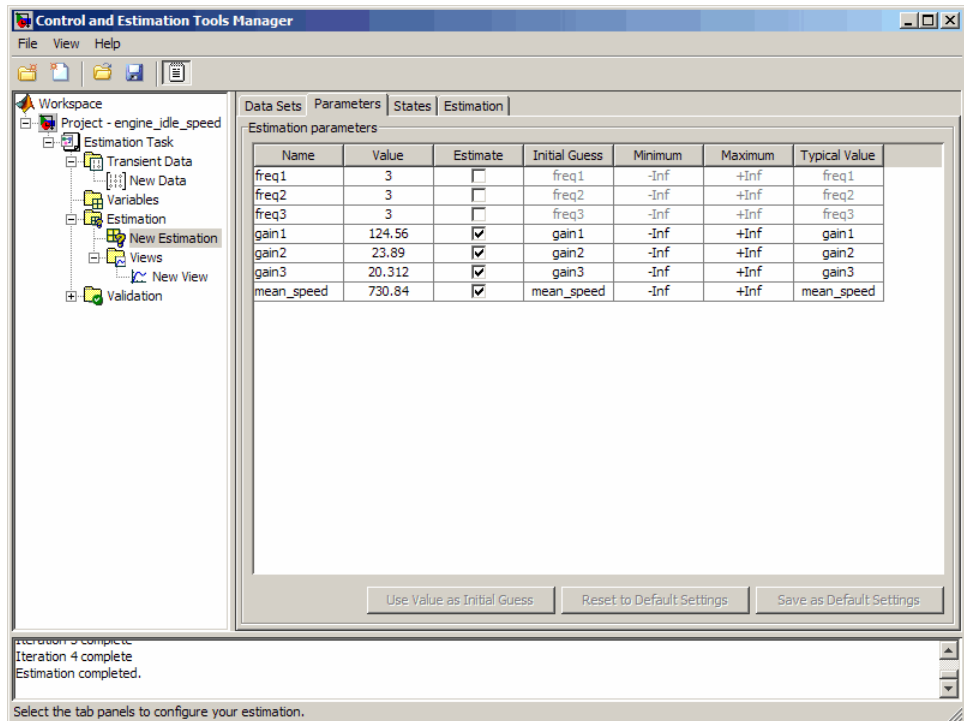


Usually, a lower cost function value indicates a successful estimation, meaning that the experimental data matches the model simulation with the estimated parameters.

For information on types of problems you may encounter using optimization solvers, see the following topics in the Optimization Toolbox documentation:

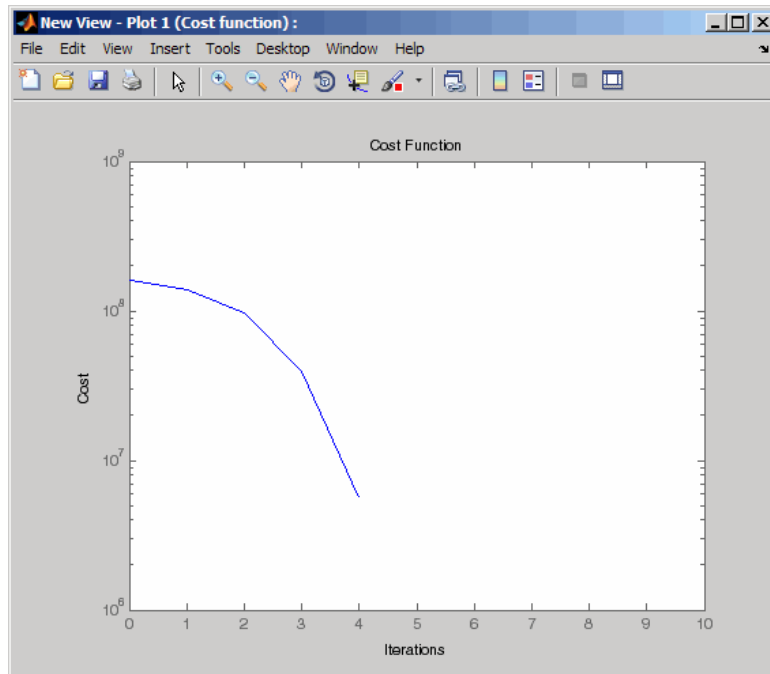
- “When the Solver Fails”
- “When the Solver Might Have Succeeded”
- “When the Solver Succeeds”

The **Estimation** pane displays each iteration of the optimization methods. To see the final values for the parameters, click the **Parameters** tab.



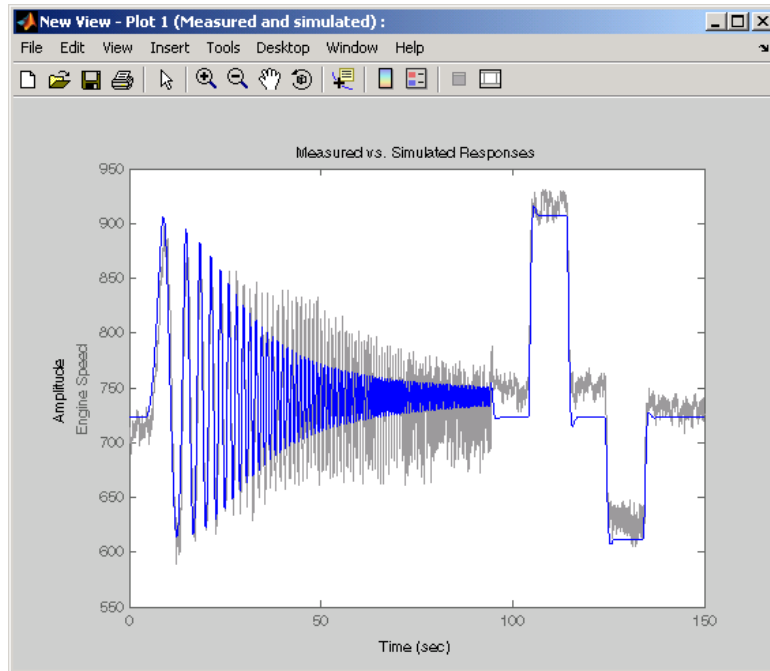
The values of these parameters are also updated in the MATLAB workspace. If you specify the variable name in the **Initial Guess** column, you can restart the estimation from where you left off at the end of a previous estimation.

After the estimation process completes, the cost function minimization plot appears as shown in the following figure.



If the optimization went well, you should see your cost function converge on a minimum value. The lower the cost, the more successful is the estimation.

You can also examine the measured versus simulated data plot to see how closely the simulated data matches the measured estimation data. The next figure shows the measured versus simulated data plot generated by running the estimation of the `engine_idle_speed` model.



## Model Validation

After you complete estimating the parameters, as described in “Run Estimation” on page 2-39, you must validate the results against another set of data.

The steps to validate a model using the Control and Estimation Tools Manager are:

- 1 Import the validation data set to the **Transient Data** node.
- 2 Add a new validation task in the **Validation** node in the **Workspace** tree.
- 3 Configure the validation settings by selecting the plot types and the validation data set from the **Validation Setup** pane.
- 4 Click **Show Plots** in the **Validation Setup** pane and view the results in the plot window.
- 5 Compare the validation plots to the corresponding view plots to see if they match.

The basic difference between the validation and views features is that you can run validation after the estimation is complete. All views should be set up before an estimation, and you can watch the views update in real time. Validations can use other validation data sets for comparison with the model response. Also, validations appear after you have completed an estimation and do not update.

You can validate your data by comparing measured vs. simulated data for your estimation data and validation data sets. Also, it is often useful to compare residuals in the same way.

### Related Examples

- “Load and Import Validation Data” on page 2-44
- “Compare Measured and Simulated Responses” on page 2-47
- “Compare Residuals” on page 2-51

## Load and Import Validation Data

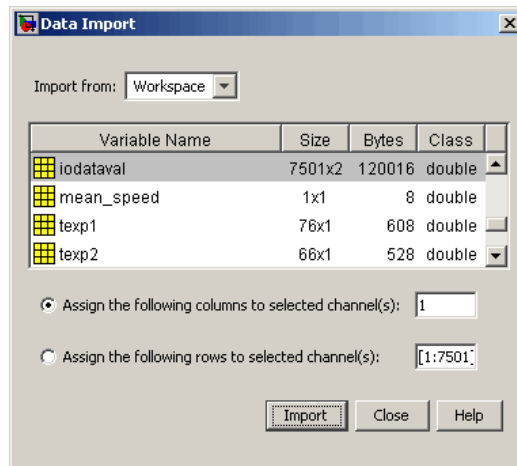
To validate the estimated parameters computed in “Run Estimation” on page 2-39, you must first import the data into the Control and Estimation Tools Manager GUI.

To load the validation data, type

```
load iodataval
```

at the MATLAB prompt. This loads the data into the MATLAB workspace. The next step is to import this data into the Control and Estimation Tools Manager. See “Import Data (GUI)” on page 1-4 for information on importing data, but the quickest way is to follow these steps:

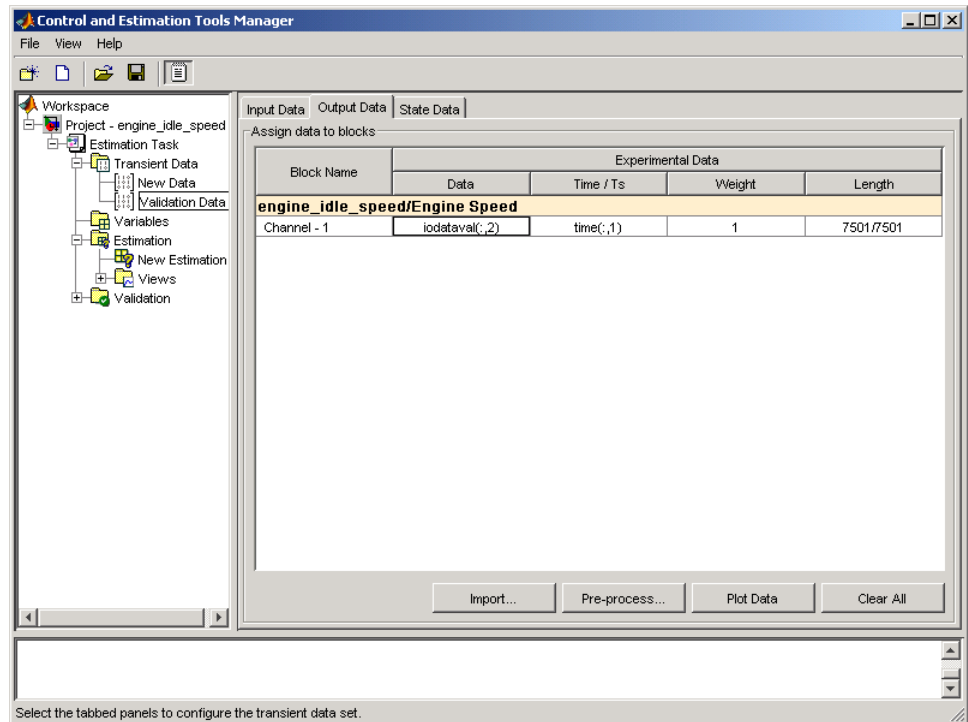
- 1** Right-click the **Transient Data** node in the **Workspace** tree in the Control and Estimation Tools Manager and select **New**.
- 2** Select **New Data (2)** from the **Transient Data** pane.
- 3** Right-click the **New Data (2)** node in the **Workspace** tree and select **Rename**. Change the name of the data to **Validation Data**.
- 4** In the **Input Data** pane, select the **Data** cell associated with Channel - 1 and click **Import**. In the Data Import dialog box, select `iodataval` and assign column 1 to the selected channel by entering 1 in the **Assign columns** field. Click **Import** to import the input data.



- 5** Select the **Time/Ts** cell and import time using the Data Import dialog box.
- 6** Similarly, in the **Output Data** pane, select **Time/Ts** and import time.
- 7** In the **Output Data** pane, select the **Data** cell associated with Channel 1 - 1 and click **Import**. Import the second column of data in **iodataval** by

selecting it from the list in the Import Data dialog box and entering 2 in the **Assign columns** field. Click **Import** to import the output data.

The Control and Estimation Tools Manager should resemble the next figure.



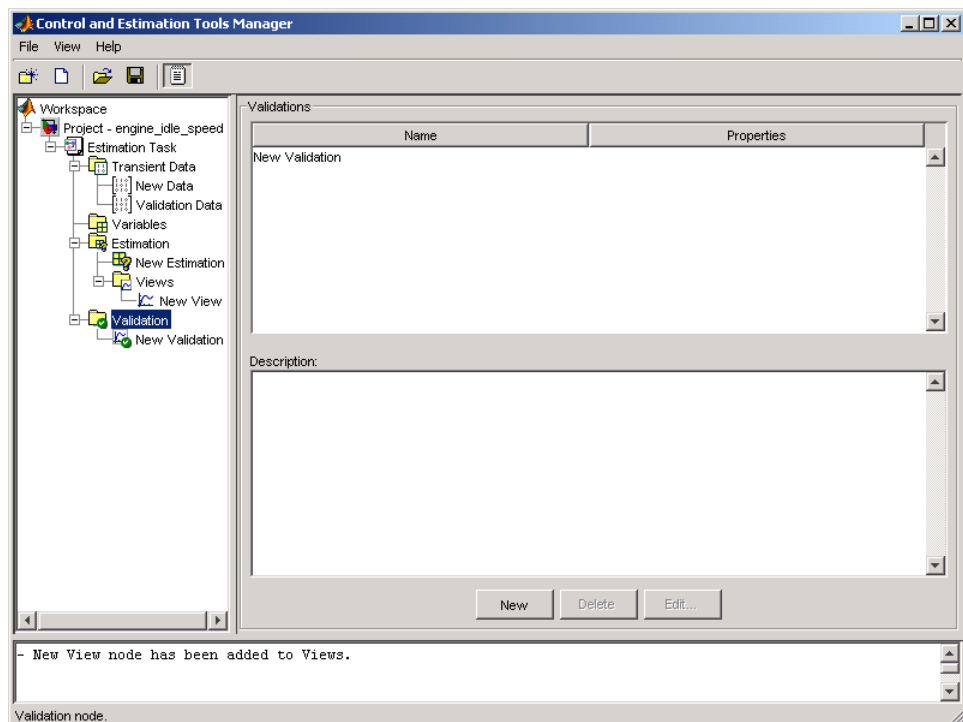
### Related Examples

- “Compare Measured and Simulated Responses” on page 2-47
- “Compare Residuals” on page 2-51



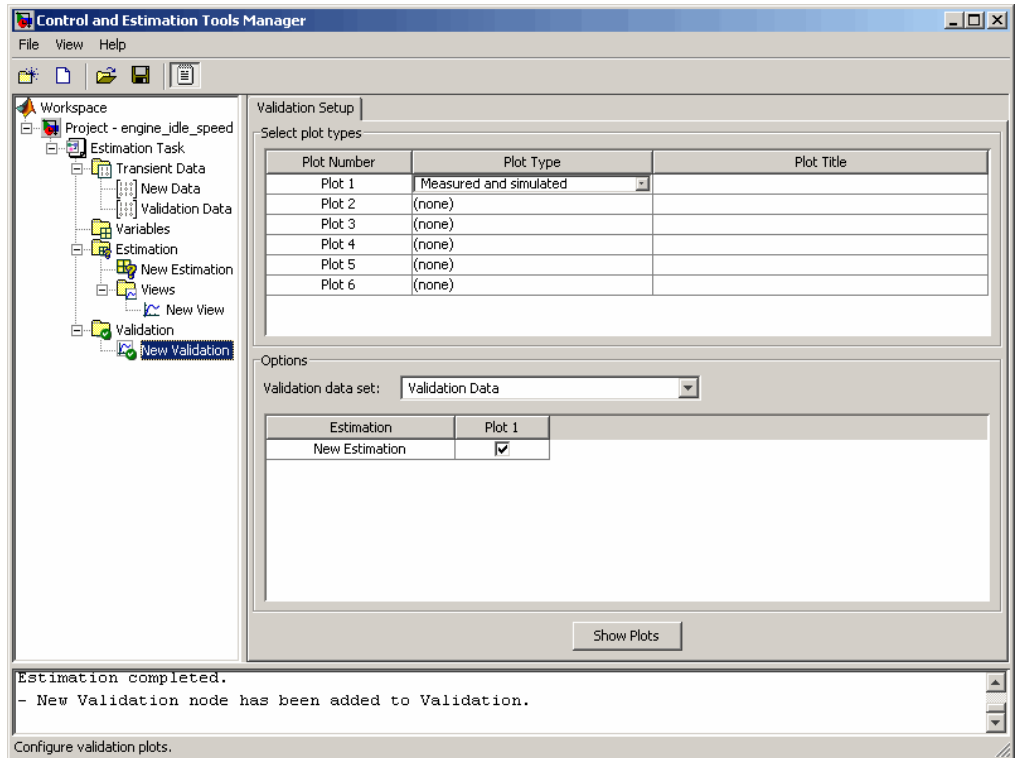
## Compare Measured and Simulated Responses

After you import the validation data, as described in “Load and Import Validation Data” on page 2-44, right-click the **Validation** node and select **New**. This creates a **New Validation** node in the Control and Estimation Tools Manager.

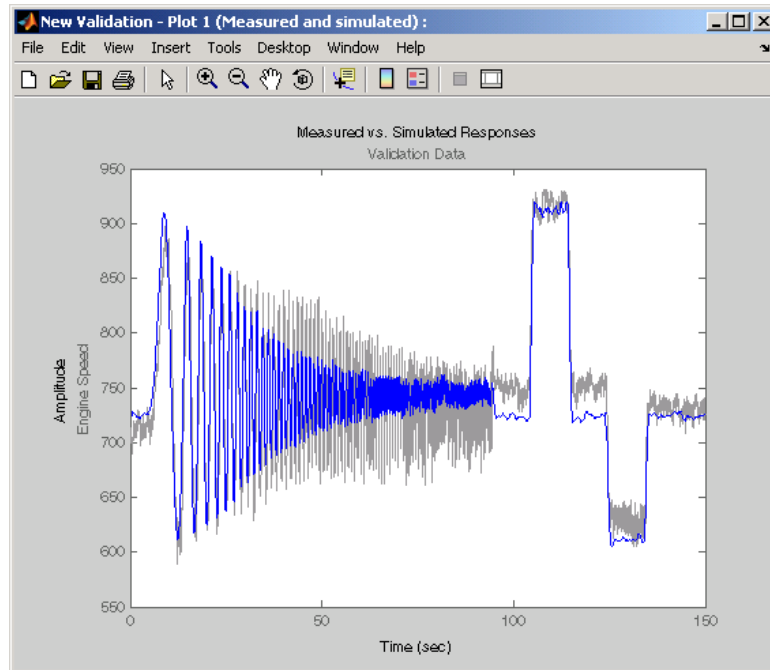


To perform the validation:

- 1 Select the **New Validation** node in the **Workspace** tree to open the **Validation Setup** pane.

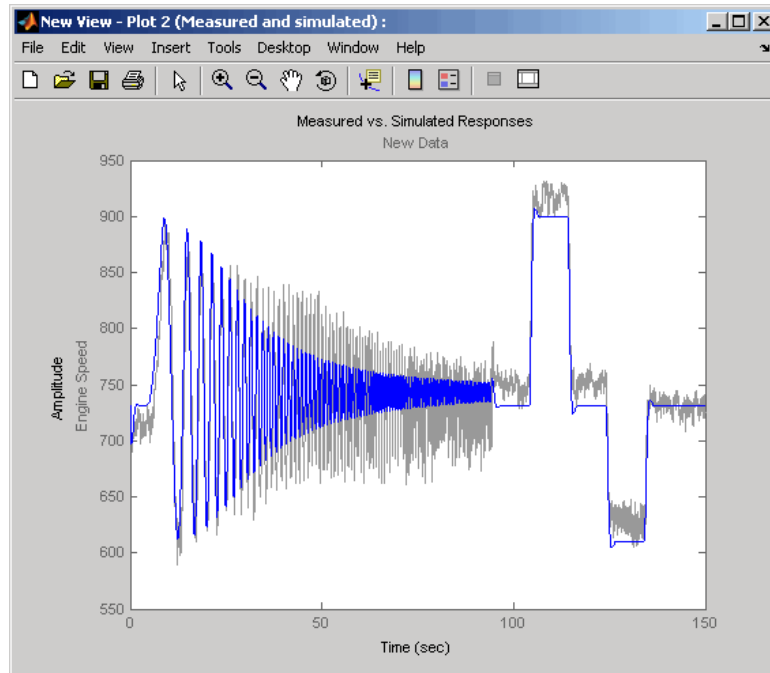


- 2 Click the **Plot Type** cell for Plot 1 and select Measured and simulated from the drop-down menu.
- 3 In the **Options** area, select Validation Data in the **Validation data set** drop-down list.
- 4 Click **Show Plots** to open a plot figure window as shown next.



### Measured Versus Simulated Data Plot for Validation Data

- 5 Compare this plot with the plot of Measured and simulated data for the validation data. For more information on how to create this plot, see “Progress Plots” on page 2-22.



**Measured and Simulated Data Views Plot**

---

**Tip** Examine the residuals compare the difference between the simulated response and measured data, as described in “Compare Residuals” on page 2-51.

---

### Related Examples

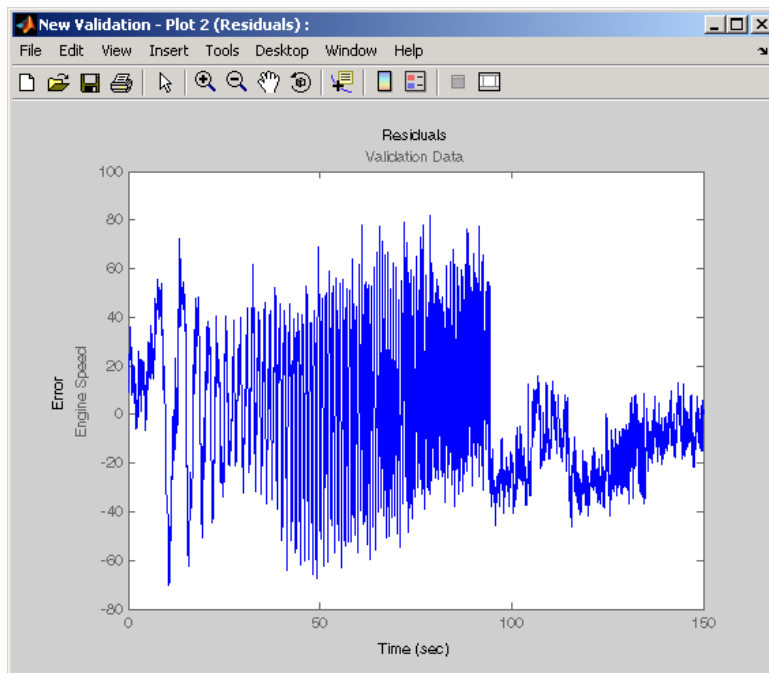
- “Load and Import Validation Data” on page 2-44
- “Compare Residuals” on page 2-51

## Compare Residuals

The residuals plot shows the difference between the simulated response and measured data. To indicate a good fit between the simulated output and measured data, the residuals:

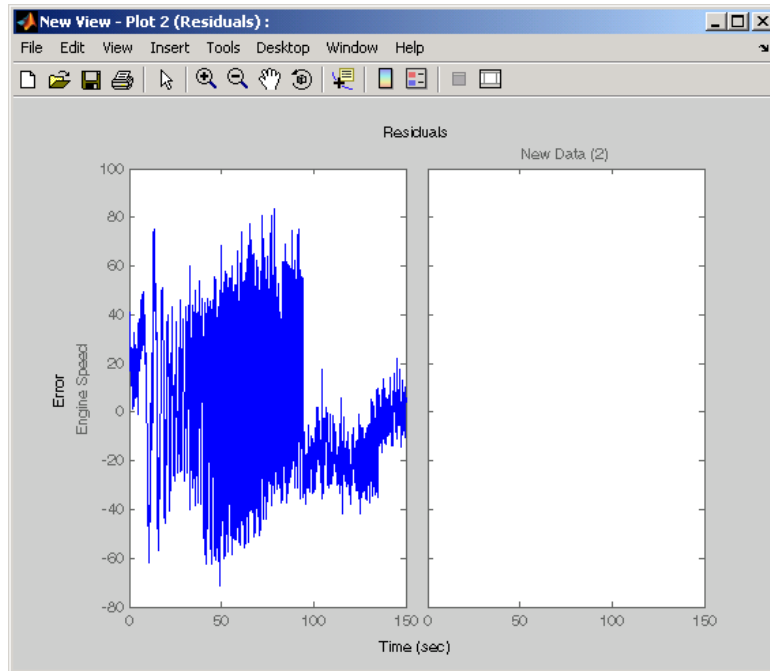
- Should lie within a small percent of the maximum output variation
- Should not display any systematic patterns

After you have compared the measured and simulated responses for an estimation, as described in “Compare Measured and Simulated Responses” on page 2-47, examine the residuals. Select **Residuals** as the **Plot Type** for **Plot 2** in the **New Validation** pane. In the **Options** area, select the **Plot 2** check box and click **Show Plots**. The following figure shows the resulting residuals plot.



**Plot of Residuals Using the Validation Data**

Compare the validation data residuals with the original data set residuals from the **Views** node in the **Workspace** tree. To create the plot of residuals for the original data set, select the **New View** node and choose **Residuals** as the **Plot Type**.



### Plot of Residuals Using the Test Data

The plot on the left agrees with the plot of the residuals for the validation data. The right side has no plot because residuals were not calculated for the validation data during the original estimation process.

### Related Examples

- “Load and Import Validation Data” on page 2-44
- “Compare Measured and Simulated Responses” on page 2-47

## Accelerating Model Simulations During Estimation

### In this section...

“About Accelerating Model Simulations During Estimation” on page 2-53

“Limitations” on page 2-53

“Setting the Accelerator Mode for Parameter Estimation” on page 2-53

### About Accelerating Model Simulations During Estimation

You can accelerate the parameter estimation computations by changing the simulation mode of your Simulink model. Simulink Design Optimization software supports `Normal` and `Accelerator` simulation modes. For more information about these modes, see “How Acceleration Modes Work” in the Simulink documentation.

The default simulation mode is `Normal`. In this mode, Simulink software uses interpreted code, rather than compiled C code during simulations.

In the `Accelerator` mode, Simulink Design Optimization software runs simulations during estimation with compiled C code. Using compiled C code speeds up the simulations and reduces the time to estimate parameters.

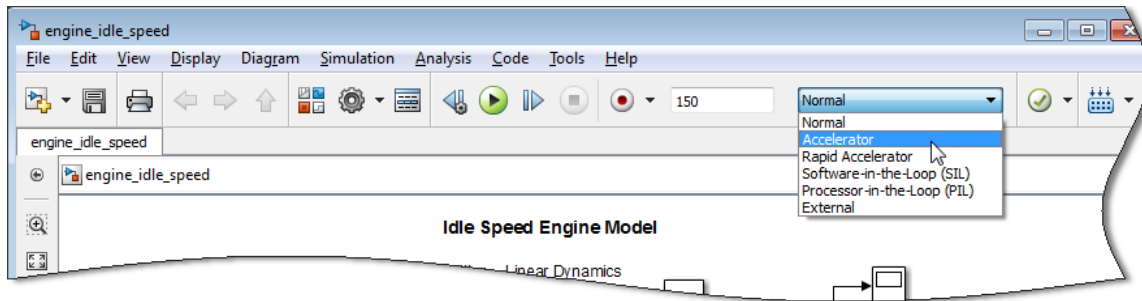
### Limitations

You cannot use the `Accelerator` mode if your model contains algebraic loops. If the model contains MATLAB function blocks, you must either remove them or replace them with Fcn blocks.

### Setting the Accelerator Mode for Parameter Estimation

To set the simulation mode to `Accelerator`, open the Simulink model window and perform one of the following actions:

- Select **Simulation > Mode > Accelerator**.
- Choose `Accelerator` from the drop-down list as shown in the next figure.



---

**Tip** To obtain the maximum performance from the Accelerator mode, close all Scope blocks in your model.

---



## Speedup Using Parallel Computing

### In this section...

“When to Use Parallel Computing for Parameter Estimation” on page 2-55

“How Parallel Computing Speeds Up Estimation” on page 2-55

### When to Use Parallel Computing for Parameter Estimation

You can use Simulink Design Optimization software with Parallel Computing Toolbox™ software to speed up parameter estimation of Simulink models. Using parallel computing may reduce the estimation time in the following cases:

- The model contains a large number parameters to estimate, and the estimation method is specified as either Nonlinear least squares or Gradient descent.
- The Pattern search method is selected as the estimation method.
- The model is complex and takes a long time to simulate.

When you use parallel computing, the software distributes independent simulations to run them in parallel on multiple MATLAB sessions, also known as *workers*. The time required to simulate the model dominates the total estimation time. Therefore, distributing the simulations significantly reduces the estimation time.

For information on how the software distributes the simulations and the expected speedup, see “How Parallel Computing Speeds Up Estimation” on page 2-55.

For information on configuring your system and using parallel computing, see “How to Use Parallel Computing” on page 2-59.

### How Parallel Computing Speeds Up Estimation

You can enable parallel computing with the Nonlinear least squares, Gradient descent and Pattern search estimation methods. The following

sections describes the potential speedup using parallel computing for estimation:

- “Parallel Computing with Nonlinear least squares and Gradient descent Methods” on page 2-56
- “Parallel Computing with the Pattern search Method” on page 2-57

### **Parallel Computing with Nonlinear least squares and Gradient descent Methods**

When you select Gradient descent as the estimation method, the model is simulated during the following computations:

- Objective value computation — One simulation per iteration
- Objective gradient computations — Two simulations for every tuned parameter per iteration
- Line search computations — Multiple simulations per iteration

The total time,  $T_{total}$ , taken per iteration to perform these simulations is given by the following equation:

$$T_{total} = T + (N_p \times 2 \times T) + (N_{ls} \times T) = T \times (1 + (2 \times N_p) + N_{ls})$$

where  $T$  is the time taken to simulate the model and is assumed to be equal for all simulations,  $N_p$  is the number of parameters to estimate, and  $N_{ls}$  is the number of line searches.  $N_{ls}$  is difficult to estimate and you generally assume it to be equal to one, two, or three.

When you use parallel computing, the software distributes the simulations required for objective gradient computations. The simulation time taken per iteration when the gradient computations are performed in parallel,  $T_{totalP}$ , is approximately given by the following equation:

$$T_{totalP} = T + (\text{ceil}\left(\frac{N_p}{N_w}\right) \times 2 \times T) + (N_{ls} \times T) = T \times (1 + 2 \times \text{ceil}\left(\frac{N_p}{N_w}\right) + N_{ls})$$

where  $N_w$  is the number of MATLAB workers.

---

**Note** The equation does not include the time overheads associated with configuring the system for parallel computing and loading Simulink software on the remote MATLAB workers.

---

The expected reduction of the total estimation time is given by the following equation:

$$\frac{T_{totalP}}{T_{total}} = \frac{1 + 2 \times \text{ceil}\left(\frac{N_p}{N_w}\right) + N_{ls}}{1 + (2 \times N_p) + N_{ls}}$$

For example, for a model with  $N_p=3$ ,  $N_w=4$ , and  $N_{ls}=3$ , the expected reduction of

the total estimation time equals  $\frac{1 + 2 \times \text{ceil}\left(\frac{3}{4}\right) + 3}{1 + (2 \times 3) + 3} = 0.6$ .

### Parallel Computing with the Pattern search Method

The Pattern search method uses search and poll sets to create and compute a set of candidate solutions at each estimation iteration.

The total time,  $T_{total}$ , taken per iteration to perform these simulations, is given by the following equation:

$$T_{total} = (T \times N_p \times N_{ss}) + (T \times N_p \times N_{ps}) = T \times N_p \times (N_{ss} + N_{ps})$$

where  $T$  is the time taken to simulate the model and is assumed to be equal for all simulations,  $N_p$  is the number of parameters to estimate,  $N_{ss}$  is a factor for the search set size, and  $N_{ps}$  is a factor for the poll set size.  $N_{ss}$  and  $N_{ps}$  are typically proportional to  $N_p$ .

When you use parallel computing, Simulink Design Optimization software distributes the simulations required for the search and poll set computations, which are evaluated in separate parfor loops. The simulation time taken per iteration when the search and poll sets are computed in parallel,  $T_{totalP}$ , is given by the following equation:

$$\begin{aligned}
 T_{totalP} &= (T \times \text{ceil}(N_p \times \frac{N_{ss}}{N_w})) + (T \times \text{ceil}(N_p \times \frac{N_{ps}}{N_w})) \\
 &= T \times (\text{ceil}(N_p \times \frac{N_{ss}}{N_w}) + \text{ceil}(N_p \times \frac{N_{ps}}{N_w}))
 \end{aligned}$$

where  $N_w$  is the number of MATLAB workers.

---

**Note** The equation does not include the time overheads associated with configuring the system for parallel computing and loading Simulink software on the remote MATLAB workers.

---

The expected speed up for the total estimation time is given by the following equation:

$$\frac{T_{totalP}}{T_{total}} = \frac{\text{ceil}(N_p \times \frac{N_{ss}}{N_w}) + \text{ceil}(N_p \times \frac{N_{ps}}{N_w})}{N_p \times (N_{ss} + N_{ps})}$$

For example, for a model with  $N_p=3$ ,  $N_w=4$ ,  $N_{ss}=15$ , and  $N_{ps}=2$ , the expected

$$\text{speedup equals } \frac{\text{ceil}(3 \times \frac{15}{4}) + \text{ceil}(3 \times \frac{2}{4})}{3 \times (15 + 2)} = 0.27 .$$

Using the Pattern search method with parallel computing may not speed up the estimation time. When you do not use parallel computing, the method stops searching for a candidate solution at each iteration as soon as it finds a solution better than the current solution. When you use parallel computing, the candidate solution search is more comprehensive. Although the number of iterations may be larger, the estimation without using parallel computing may be faster.

### Related Examples

- “How to Use Parallel Computing” on page 2-59

# How to Use Parallel Computing

## In this section...

“Configure Your System for Parallel Computing” on page 2-59

“Model Dependencies” on page 2-59

“Estimate Parameters Using Parallel Computing (GUI)” on page 2-61

“Estimate Parameters Using Parallel Computing (Code)” on page 2-64

“Troubleshooting” on page 2-65

## Configure Your System for Parallel Computing

You can speed up parameter estimation using parallel computing on multicore processors or multiprocessor networks. You can use parallel computing with the parameter estimation GUI and `sdo.optimize`. When you estimate model parameters using parallel computing, the software uses the available parallel pool. If no parallel pool is available and **Automatically create a parallel pool** is selected in your Parallel Computing Toolbox preferences, then the software starts a parallel pool using the settings in those preferences.

When you begin estimation, the software automatically detects model dependencies and temporarily adds them to the parallel pool workers. However, to ensure that workers are able to access the undetected file and path dependencies, create a cluster profile that specifies the same. The parallel pool used for estimation must be associated with this cluster profile. For information regarding creating a cluster profile, see “Create and Modify Cluster Profiles” in the Parallel Computing Toolbox documentation.

To manually open a parallel pool that uses a specific cluster profile, use:

```
parpool(MyProfile);
```

`MyProfile` is the name of a cluster profile.

## Model Dependencies

*Model dependencies* are any referenced models, data (model variables etc.), S-functions, and additional files necessary to run the model. Before starting

the optimization, you must verify that all the remote workers can access the model dependencies. Otherwise, you may get unexpected results.

### **Making File Dependencies Accessible to Remote Workers**

When you use parallel computing, the Simulink Design Optimization software helps you identify model path dependencies. To do so, the software uses the Simulink Manifest Tools. However, the dependency analysis may not find all the files required by your model. For example, folders containing code for your model or block callbacks may not be detected. To learn more, see “Scope of Dependency Analysis” in the Simulink documentation.

If your model has undetected file dependencies, then specify them in the Files and Folders section of the cluster profile.

If your model has path dependencies that are undetected or inaccessible by the remote workers, then add them to the list of model path dependencies. For more information, see:

- “Estimate Parameters Using Parallel Computing (GUI)” on page 2-61
- “Estimate Parameters Using Parallel Computing (Code)” on page 2-64

### **Making Data Dependencies Accessible to Remote Workers**

You can check whether a model has access to all its data dependencies, such as variables required for model initialization. On your local machine, complete the following steps:

- 1** Close the model, and clear the MATLAB workspace.
- 2** Load the model. Verify that only the specified dependencies are accessible to the model.
- 3** Simulate the model. If the model errors, a dependency is missing. For example, if a simulation error occurs because a variable is not defined, you can correct the problem in one of the following ways:
  - Add the variable to the model workspace.

- Create a MATLAB script that creates the variable, and add the file to the list of dependencies. Modify the `PreLoadFcn` callback of the model to add a call to the MATLAB script.

## Estimate Parameters Using Parallel Computing (GUI)

To estimate model parameters using parallel computing in the GUI:

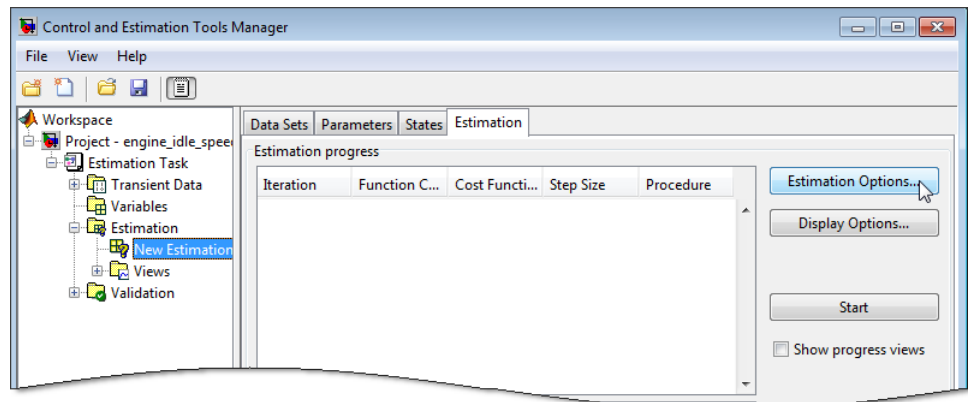
- 1 Ensure that the software can access parallel pool workers that use the appropriate cluster profile.

For more information, see “Configure Your System for Parallel Computing” on page 2-59.

- 2 Open the parameter estimation GUI for the model.
- 3 Configure the estimation data, estimation parameters and states, and, optionally, estimation settings.

For more information, see “Import Data (GUI)” on page 1-4, “Specify Parameters to Estimate” on page 2-7, and “Estimation Options” on page 2-26.

- 4 Open the **Parallel Options** tab.
  - a In the **Estimation** tab of the **New Estimation** node, click **Estimation Options**.



- b** When the Options dialog box opens, click the **Parallel Options** tab.
- 5** Select the **Use the parallel pool during optimization** check box.

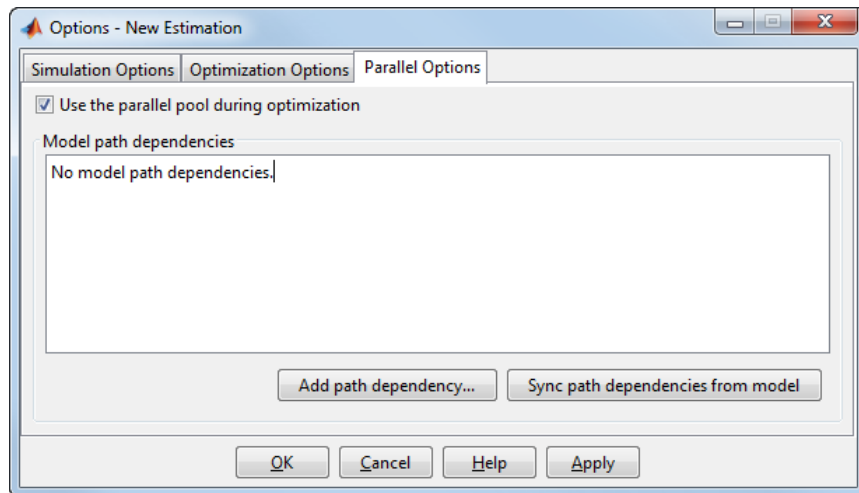
This option checks for model path dependencies in your Simulink model and displays the path dependencies in the **Model path dependencies** list box.

---

**Note** The automatic path dependencies check may not detect all the path dependencies in your model.

For more information, see “Model Dependencies” on page 2-59.

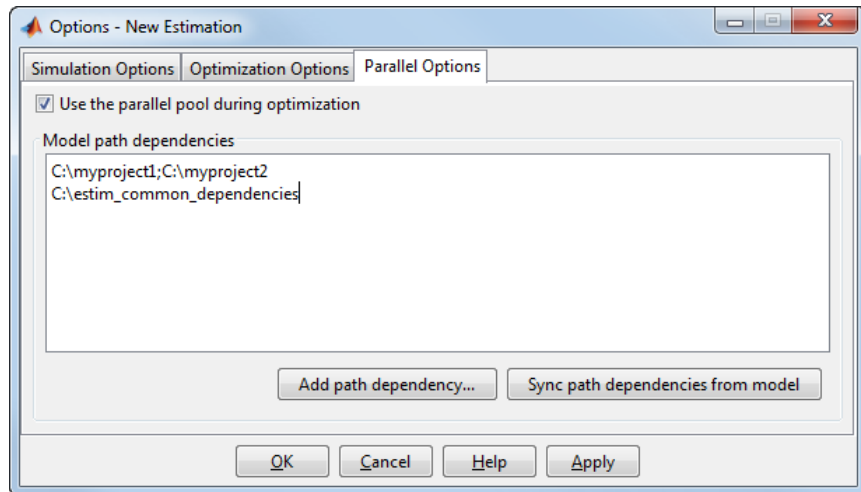
---



- 6** (Optional) Add the path dependencies that the automatic check does not detect.

Specify the paths in the **Model path dependencies** list box. You can specify the paths separated with a semicolons or on a new line.





Alternatively, you can click **Add path dependency** to open a dialog box, and select the folder to add.

- 7** (Optional) In the **Model path dependencies** list box, update the paths on local drives to make them accessible to remote workers. For example, change `C:\` to `\\hostname\C$\`.
- 8** (Optional) If you modify the Simulink model such that it introduces a new path dependency, then resync the path dependencies. Click **Sync path dependencies from model** in the **Parallel Options** tab to rerun the automatic dependency check for your model.

This action updates the **Model path dependencies** list box with any new path dependency found in the model.

- 9** Click **OK**.
- 10** In the **Estimation** tab, click **Start** to estimate the model parameters using parallel computing.

For information on troubleshooting problems related to estimation using parallel computing, see “Troubleshooting” on page 2-65.

### Estimate Parameters Using Parallel Computing (Code)

To use parallel computing for parameter estimation at the command line:

- 1 Ensure that the software can access parallel pool workers that use the appropriate cluster profile.

For more information, see “Configure Your System for Parallel Computing” on page 2-59.

- 2 Open the model.
- 3 Configure an estimation experiment.
- 4 Enable parallel computing using an optimization option set, `opt`.

```
opt = sdo.OptimizeOptions;  
opt.UseParallel = 'always';
```

- 5 Find the model path dependencies.

```
dirs = sdo.getModelDependencies(modelname)
```

---

**Note** `sdo.getModelDependencies` may not detect all the path dependencies in your model.

For more information, see “Model Dependencies” on page 2-59.

---

- 6 (Optional) Modify `dirs` to include the path dependencies that `sdo.getModelDependencies` does not detect.

```
dirs = vertcat(dirs, '\\hostname\C$\matlab\work')
```

- 7 (Optional) Modify `dirs` to make paths on local drives accessible to remote workers.

```
dirs = regexprep(dirs, 'C:/', '\\\\hostname\C$\')
```

- 8 Add the path dependencies for optimization.

```
opt.ParallelPathDependencies = dirs;
```

- 9 Run the optimization.

```
[pOpt,opt_info] = sdo.optimize(opt_fcn,param,opt);
```

For information on troubleshooting problems related to estimation using parallel computing, see “Troubleshooting” on page 2-65.

## Troubleshooting

- “Why are the estimation results with and without using parallel computing different?” on page 2-65
- “Why do I not see the estimation speedup I expected using parallel computing?” on page 2-66
- “Why does the estimation using parallel computing not make any progress?” on page 2-66
- “Why do I receive an error "Cannot save model tpe5468c55\_910c\_4275\_94ef\_305e2eeeeef4"?" on page 2-67
- “Why does the estimation using parallel computing not stop when I click **Stop**?” on page 2-67

### **Why are the estimation results with and without using parallel computing different?**

- Different numerical precision on the client and worker machines can produce marginally different simulation results. Thus, the optimization method can take a completely different solution path and produce a different result.
- The client and worker machines must have models in identical states. For example, you must verify that the model running on the client uses exactly the same variable values as the workers. You must also verify that the client and workers are accessing model dependencies in identical states.
- When you use parallel computing with the `Pattern` search method, the search is more comprehensive and can result in a different solution.

To learn more, see “Parallel Computing with the Pattern search Method” on page 2-57.

### Why do I not see the estimation speedup I expected using parallel computing?

- When you estimate a small number of model parameters or when the model does not take long to simulate, you might not see a speedup in the estimation time. In such cases, the overhead associated with creating and distributing the parallel tasks outweighs the benefits of running the estimation in parallel.
- Using the `Pattern` search method with parallel computing might not speed up the optimization time. Without parallel computing, the method stops the search at each iteration as soon as it finds a solution better than the current solution. The candidate solution search is more comprehensive when you use parallel computing. Although the number of iterations might be larger, the optimization without using parallel computing might be faster.

To learn more about the expected speedup, see “Parallel Computing with the `Pattern` search Method” on page 2-57.

### Why does the estimation using parallel computing not make any progress?

In some cases, the gradient computations on the remote worker machines may silently error out when you use parallel computing. In such cases, the **Estimation progress** table shows that the  $f(x)$  values do not change, and the optimization terminates after two iterations.

To troubleshoot the problem:

- 1 Run the optimization for a few iterations without parallel computing to see if the optimization progresses.
- 2 Check whether the remote workers have access to all model dependencies. Model dependencies include data variables and files required by the model to run.

To learn more, see “Model Dependencies” on page 2-59.

### **Why do I receive an error "Cannot save model tpe5468c55\_910c\_4275\_94ef\_305e2eeeeef4"?**

When you specify the **Gradient type** as **Refined**, the software may error out when it attempts to save a temporary model to a nonwriteable folder. To clear this error, change the **Gradient type** to **Basic**. To learn more, see “Selecting Additional Optimization Options” on page 2-30.

### **Why does the estimation using parallel computing not stop when I click Stop?**

When you use parallel computing, the software must wait until the current optimization iteration completes before it notifies the workers to stop the optimization. The optimization does not terminate immediately when you click **Stop**, and, instead, appears to continue running.

#### **See Also**

`sdo.optimize` | `sdo.OptimizeOptions` | `sdo.getModelDependencies` | `parpool`

#### **Concepts**

- “Speedup Using Parallel Computing” on page 2-55

## **Estimating Initial Conditions for Blocks with External Initial Conditions**

When an integrator block uses an initial-condition port, which you specify by an IC block, you cannot estimate the initial conditions (ICs) of the integrator using Simulink Design Optimization software. Estimation is not possible because external ICs have priority over the ICs of a specific block to maintain the integrity of the model.

To tune the ICs of an integrator block with external ICs, you must modify the model to make the external signal into a tunable parameter. For example, you can set the IC block that feeds into the integrator to be a tunable variable and estimate it.

## Estimate Model Parameters and Initial States (GUI)

### In this section...

“Loading the Example” on page 2-69

“Model Parameters” on page 2-70

“Setting Up the Estimation Project” on page 2-71

“Importing Transient Data and Selecting Parameters for Estimation” on page 2-72

“Selecting Parameters and Initial Conditions for Estimation” on page 2-74

“Creating the Estimation Task” on page 2-76

“Running the Estimation and Viewing Results” on page 2-78

“Related Examples” on page 2-79

This example shows how to estimate the initial states and parameters of a model.

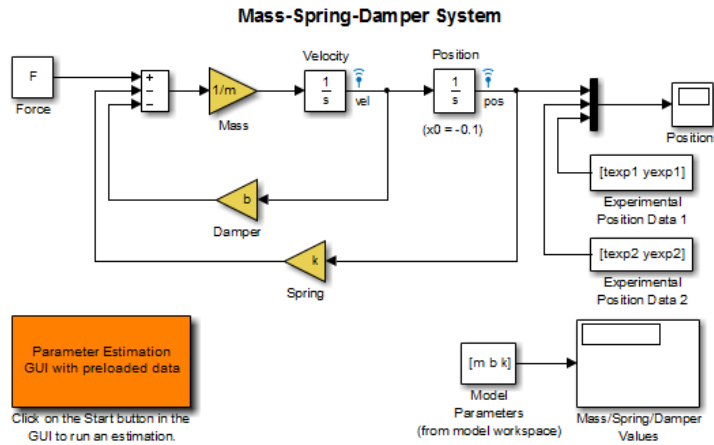
### Loading the Example

To open the Simulink model of a mass-spring-damper system, type:

```
msd_system
```

at the MATLAB prompt.

This action also loads the two sets of measured data with differing initial conditions.



### Model Parameters

The output of the Simulink model, `msd_system`, is the position of the mass in a mass-spring-damper system. The model is subject to a constant force  $F$ , and an initial condition,  $x_0$ , for the mass displacement.  $x_0$  is the initial condition of the integrator block, Position.

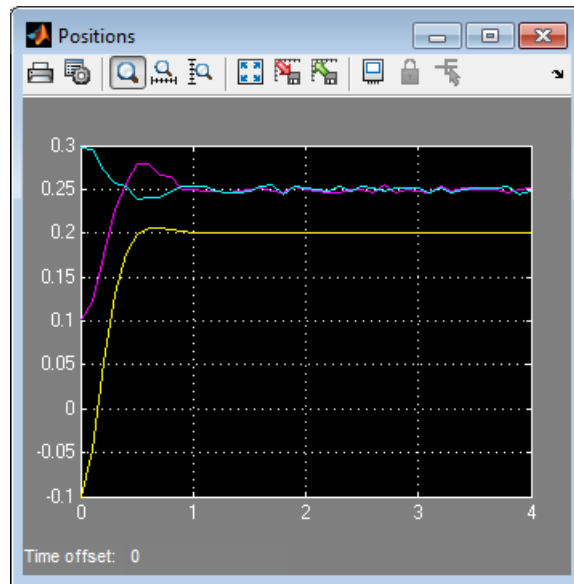
The model parameters of interest are the mass,  $m$ , the viscous damping,  $b$ , and the spring constant,  $k$ . For more information about physical modeling of mass-spring-damper systems, see any book on mathematical modeling or on automatic control systems.

For estimating the model parameters  $m$ ,  $b$ , and  $k$ , this model uses two experimental data sets. The data sets contain output data measured using two different initial positions,  $x_0=0.1$  and  $x_0=0.3$ , and additive noise.

In the Simulink editor window, select **Simulation > Run** to run a simulation. The simulation generates the following plots, as shown in the next figure:

- Simulated response of the model for  $x_0=-0.1$  and parameter values,  $m=8$ ,  $k=500$ , and  $b=100$
- Experimental data sets

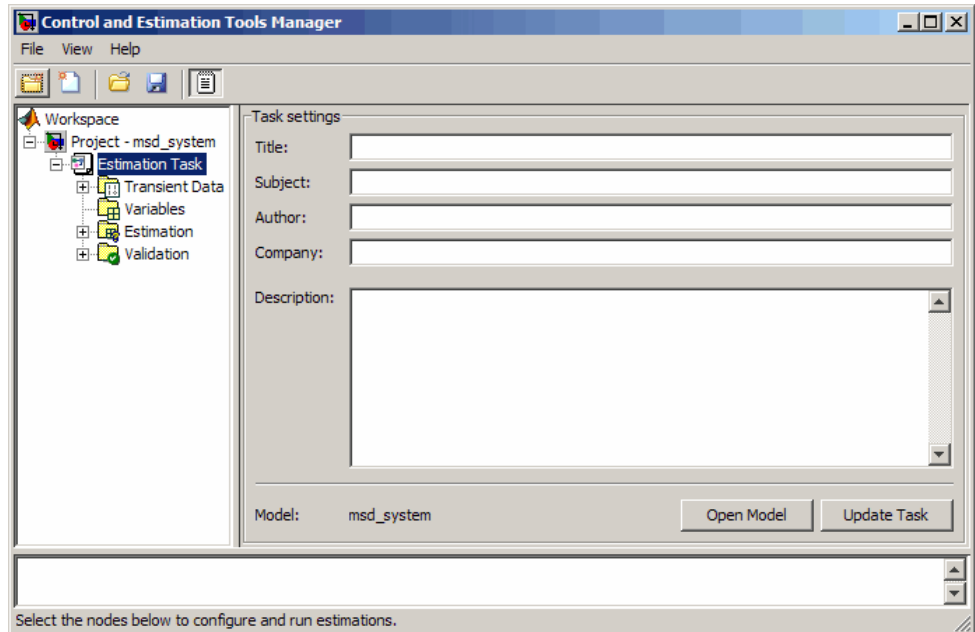




The magenta and cyan lines show experimental data with different initial conditions. The yellow line is the model response to a constant force.

## Setting Up the Estimation Project

To set up the estimation of initial conditions and then transient state space data, select **Analysis > Parameter Estimation** in the `msd_system` model window.



### Importing Transient Data and Selecting Parameters for Estimation

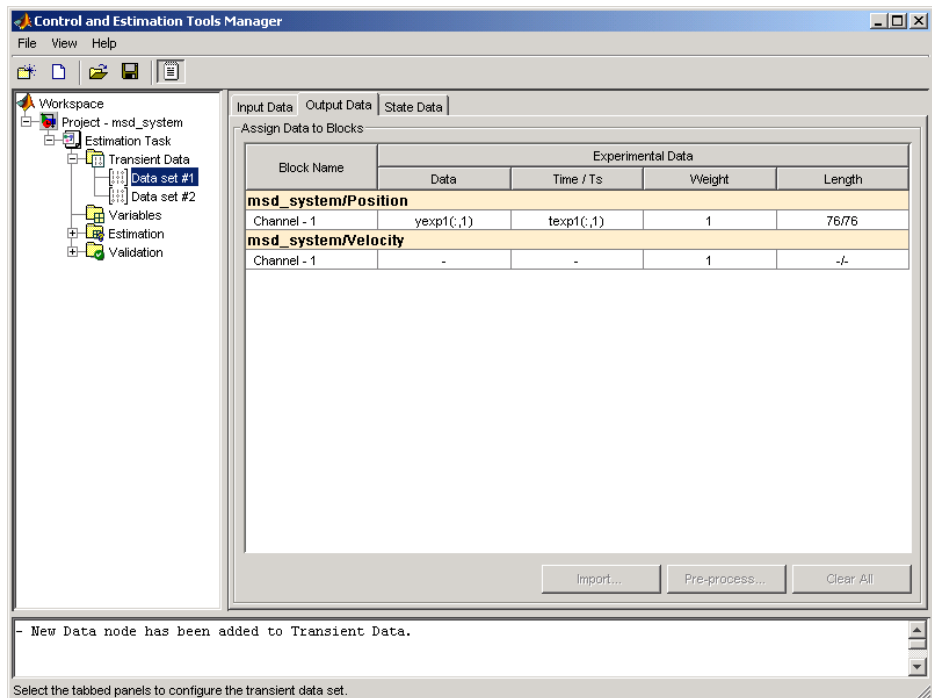
To import data for initial state estimation:

- 1 In the Control and Estimation Tools Manager, select **Transient Data** under the **Estimation Task** node.
- 2 Right-click **Transient Data**, and select **New** to create a **New Data** node.
- 3 Select **New Data** under the **Transient Data** node.
- 4 In the **Output Data** tab of the **New Data** node, select the **Data** column of `msd_system/Position`, and click **Import**. The Data Import dialog box opens.

Select `yexp1`, and click **Import** to assign the data `yexp1` to the model.

- 5 In the **Output Data** pane, select the **Time/Ts** column of `msd_system/Position`. In the Data Import dialog box, select `texp1`, and click **Import** to assign the time vector `texp1` to the model.
- 6 Right-click **New Data** in the **Workspace** tree, and rename it to **Data set #1**.
- 7 Repeat steps 2–5 to add a second data set, `yexp2` and `texp2`. Rename the data set to **Data set #2**.

The Control and Estimation Tools Manager GUI now resembles the next figure.



For more information on importing data, see “Import Data (GUI)” on page 1-4.

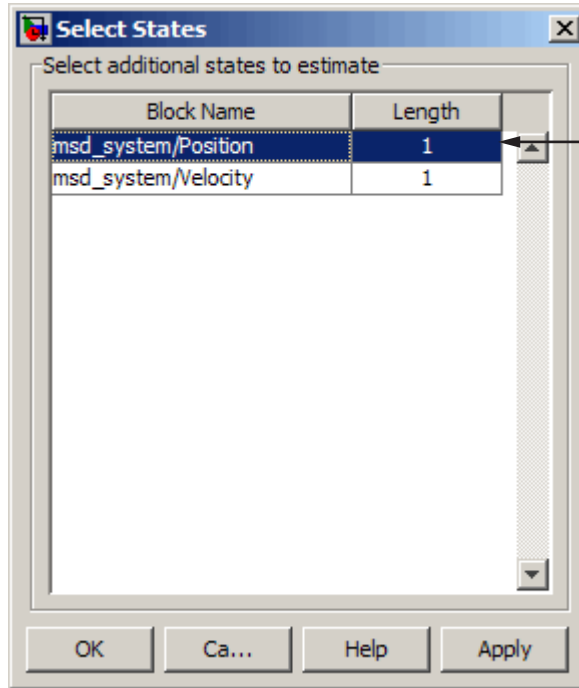
### Selecting Parameters and Initial Conditions for Estimation

To select the parameters and initial states you want to estimate for the Simulink model `msd_system`:

- 1 Select the **Variables** node in the **Workspace** tree of the Control and Estimation Tools Manager GUI.
- 2 In the **Estimated Parameters** pane, click **Add** to open the Select Parameters dialog box.
- 3 Select the parameters `b`, `k`, and `m`, and then click **OK**. The selected parameters now appear in the **Selected parameters** area of the **Estimated Parameters** pane.

**4** In the **Estimated States** pane, click **Add**.

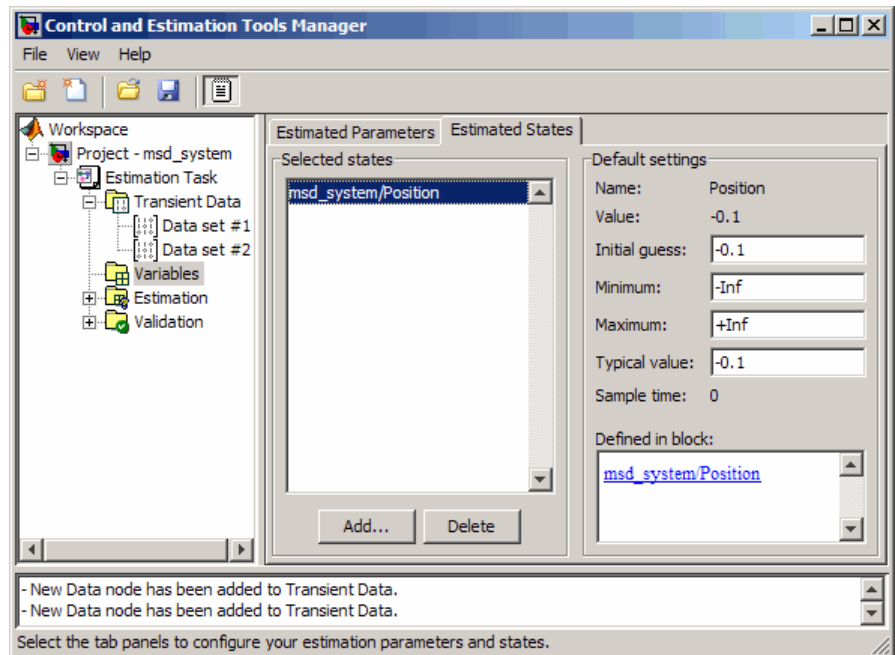
The Select States dialog box opens, which displays all the available states of the `msd_system` model. Select `msd_system/Position`, and click **OK**.



Select states with initial conditions that you want to estimate. Hold down Shift, and use your mouse to select groups of adjacent states. Hold down Ctrl, and use your mouse to select non-adjacent states.

**Note** For states that you do not estimate, the software uses the initial condition value specified in the Simulink model. In this example, the value of initial velocity, as specified in the model is 0.

The selected state appears in the **Selected states** area of the **Estimated States** pane, as shown in the next figure.



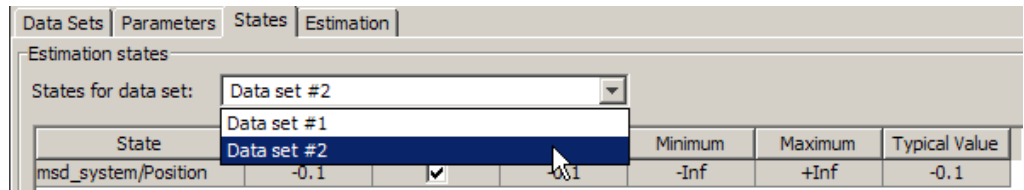
For more information on selecting parameters to estimate, see “Specify Parameters to Estimate” on page 2-7.

### Creating the Estimation Task

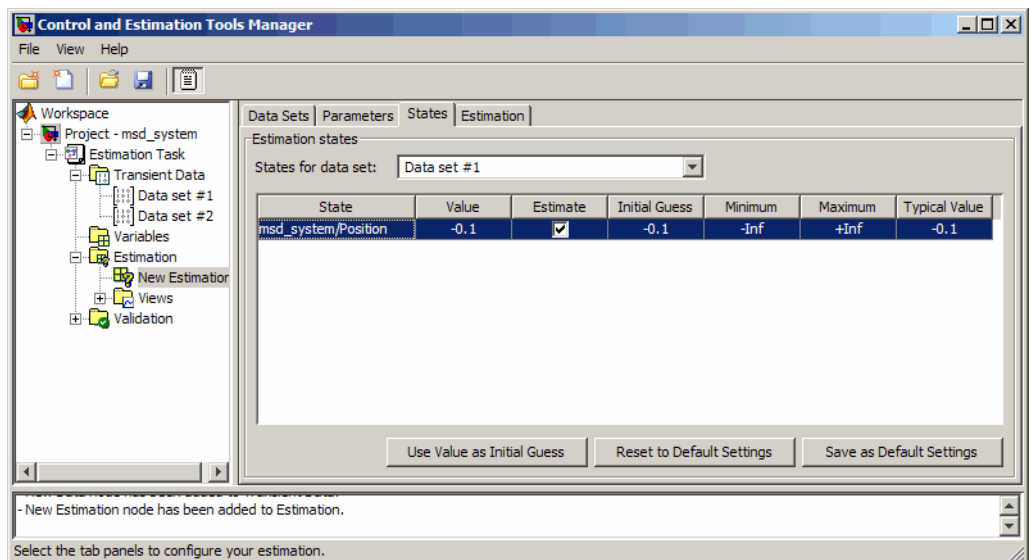
To create an estimation task in the Control and Estimation Tools Manager GUI, select the **Estimation** node in the **Workspace** tree, and click **New**. This action creates a **New Estimation** node.

In the **New Estimation** node, select the following check boxes:

- Data Set #1 and Data Set #2 in the **Data Sets** pane.
- **Estimate** for b, k, and m in the **Parameters** pane.
- **Estimate** for Position in the **States** pane. Make sure to select this check box for both Data Set #1 and Data Set #2 to estimate the initial position for the spring.



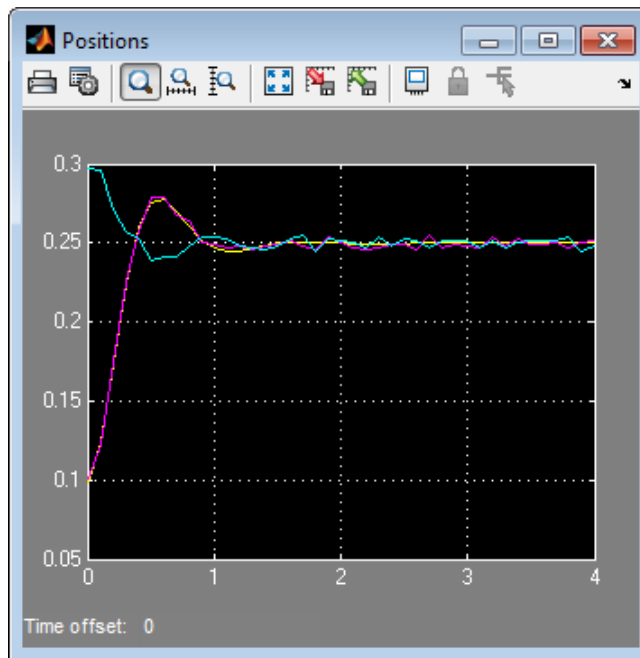
Although the initial positions for the two data sets differ, specify the initial state guesses for both data sets as  $-0.1$ . The Control and Estimation Tools Manager GUI now resembles the following figure.



## Running the Estimation and Viewing Results

Click **Start** in the **Estimation** pane to run the estimation.

As the estimation proceeds, the most current estimation of the position response (yellow curve) updates in the Scope. The curve toggles between the two experimental data sets because the software uses the two data sets successively to update the estimates of the parameter values. The software converges to the correct parameter values, within the scope of experimental noise and optimization options settings. The closeness of the estimated response (yellow) to the experimental data (magenta) indicates that simulated data is a good match to the measured data.



View the initial position estimates for Data Set #1 and Data Set #2 in the **Value** column of the **States** tab. The estimated values match closely with the known values, 0.1 and 0.3 of initial position.



State	Value	Estimate	Initial Guess	Minimum	Maximum	Typical Value
msd_system/Position	0.29945	<input checked="" type="checkbox"/>	-0.1	-Inf	+Inf	-0.1

View the estimated parameter values in the **Value** column of the **Parameters** tab.

Name	Value	Estimate	Initial Guess	Minimum	Maximum	Typical Value
b	57.967	<input checked="" type="checkbox"/>	b	-Inf	+Inf	b
k	400.27	<input checked="" type="checkbox"/>	k	-Inf	+Inf	k
m	9.7662	<input checked="" type="checkbox"/>	m	-Inf	+Inf	m

The estimation of initial states is important for obtaining the correct estimates of the model parameters. You do not set the initial states ( $x_0$  in this case) as parameters because the initial states do not represent fixed physical properties of the system. For different experimental data or operating conditions, these states need not be unique.

In this example, you use two data sets with distinct initial positions together for a single estimation of model parameters. While the estimates of the model parameters are unique, the initial state (position) is different, and you estimate them individually for each data set.

## Related Examples

- “Estimate Model Parameters and Initial States (GUI)”

## Estimation Projects

In this section...
“Structure of an Estimation Project” on page 2-80
“Managing Multiple Projects and Tasks” on page 2-81
“Adding, Deleting and Renaming an Estimation Project” on page 2-82
“Saving Control and Estimation Tools Manager Projects” on page 2-83
“Loading Control and Estimation Tools Manager Projects” on page 2-84

### Structure of an Estimation Project

The Control and Estimation Tools Manager, which is a graphical user interface (GUI) for performing parameter estimation, stores and organizes all data from a given Simulink model inside a *project*. To open the Control and Estimation Tools Manager GUI, select **Analysis > Parameter Estimation** in the Simulink model window.

When using the Control and Estimation Tools Manager for parameter estimation, you can

- Manage estimation projects.
- Select parameters and initial conditions to configure the estimation.
- Specify cost functions.
- Import experimental data (to be matched by the output of your Simulink model).
- Specify the initial conditions of your model.

Each estimation task can include

- One or more data sets
- Parameter information
- One or more sets of estimation settings, or configurations

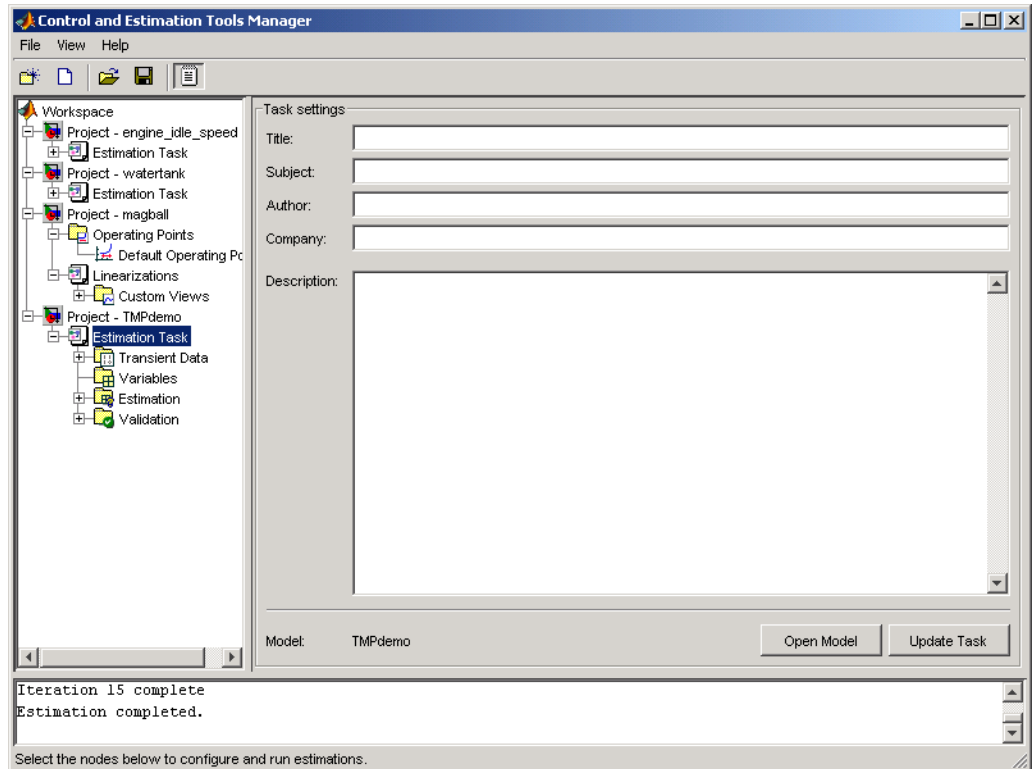
The default project name is the same as the Simulink model name. The project name is shown in the **Workspace** tree of the Control and Estimation Tools Manager.

You can also add tasks from Simulink Control Design™ and Model Predictive Control Toolbox™ software to the current project, if these products are installed on your system.

## **Managing Multiple Projects and Tasks**

The Control and Estimation Tools Manager works seamlessly with products in the Controls and Estimation family. In particular, if you have licenses for Simulink Control Design or Model Predictive Control Toolbox software, you can use these products to perform tasks on projects that you have created in Simulink Design Optimization software, and vice versa.

This figure shows a tools manager with multiple projects and multiple tasks.



You can save projects individually, or group multiple projects together in one saved file, as described in:

- “Saving Control and Estimation Tools Manager Projects” on page 2-83
- “Loading Control and Estimation Tools Manager Projects” on page 2-84

### **Adding, Deleting and Renaming an Estimation Project**

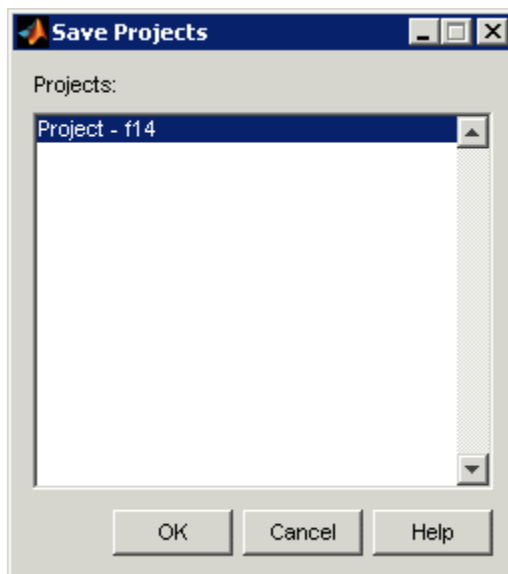
To add, delete, or rename the project or task:

- 1** Right-click the project or task node in the **Workspace** tree.
- 2** Select the appropriate command from the shortcut menu.

## Saving Control and Estimation Tools Manager Projects

A Control and Estimation Tools Manager project can consist of tasks from products such as Simulink Control Design, Simulink Design Optimization, and Model Predictive Control Toolbox software. Each task contains data, objects, and results for the analysis of a particular model.

To save your project as a MAT-file, select **File > Save** in the Control and Estimation Tools Manager window.

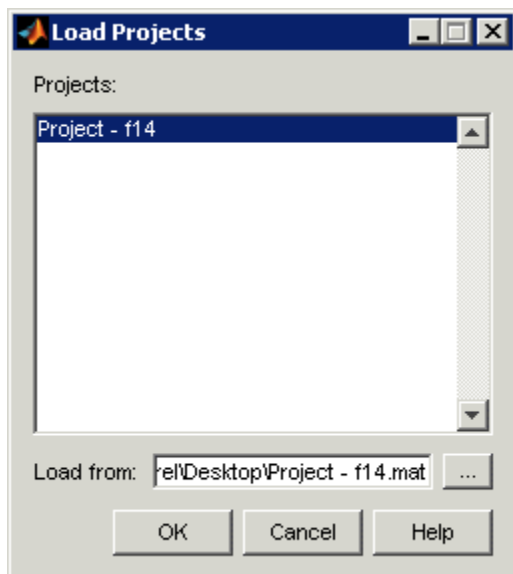


To save multiple projects within one file:

- 1** In the Save Projects dialog box, select the projects that you want to save.
- 2** Click **OK**.
- 3** Choose a folder and name for your project file by either browsing for a file or typing the full path and filename in the **Save as** field. Click **Save**.

### Loading Control and Estimation Tools Manager Projects

To open previously saved projects, select **File > Load** in the Control and Estimation Tools Manager window.



In the Load Projects dialog box, choose a project file by either browsing for the folder and file, or by typing the full path and filename in the **Load from** field. Project files are always MAT-files. The projects within this file appear in the **Projects** list.

Select the projects that you want to load, then click **OK**. When a file contains multiple projects, you can choose to load them all or just a few.

# How the Software Formulates Parameter Estimation as an Optimization Problem

## In this section...

“Overview of Parameter Estimation as an Optimization Problem” on page 2-85

“Cost Function” on page 2-85

“Bounds and Constraints” on page 2-88

“Optimization Methods and Problem Formulations” on page 2-89

## Overview of Parameter Estimation as an Optimization Problem

When you perform parameter estimation, the software formulates an optimization problem. The optimization problem solution is the estimated parameter values set. This optimization problem consists of:

- $x$  — *Design variables*. The model parameters and initial states to be estimated.
- $F(x)$  — *Objective function*. A function that calculates a measure of the difference between the simulated and measured responses. Also called *cost function* or *estimation error*.
- (Optional)  $\underline{x} \leq x \leq \bar{x}$  — *Bounds*. Limits on the estimated parameter values.
- (Optional)  $C(x)$  — *Constraint function*. A function that specifies restrictions on the design variables.

The optimization solver tunes the values of the design variables to satisfy the specified objectives and constraints. The exact formulation of the optimization depends on the optimization method that you use.

## Cost Function

- “Types” on page 2-86
- “Time Base” on page 2-87

The software tunes the model parameters to obtain a simulated response ( $y_{sim}$ ) that tracks the measured response or reference signal ( $y_{ref}$ ). To do so, the solver minimizes the *cost function* or *estimation error*, a measure of the difference between the simulated and measured responses. The cost function,  $F(x)$ , is the objective function of the optimization problem.

### Types

The raw estimation error,  $e(t)$ , is defined as:

$$e(t) = y_{ref}(t) - y_{sim}(t)$$

$e(t)$  is also referred to as the *error residuals* or, simply, *residuals*.

Simulink Design Optimization software provides you the following cost functions to process  $e(t)$ :

Cost Function	Formulation	Option Name in GUI or Command Line
Sum squared error (default)	$F(x) = \sum_{t=0}^{t_N} e(t) \times e(t)$ <p><math>N</math> is the number of samples.</p>	'SSE'
Sum absolute error	$F(x) = \sum_{t=0}^{t_N}  e(t) $ <p><math>N</math> is the number of samples.</p>	'SAE'



Cost Function	Formulation	Option Name in GUI or Command Line
Raw error	$F(x) = \begin{bmatrix} e(0) \\ \vdots \end{bmatrix}$	'Residuals' This option is available only at the command line.
Custom function	N/A	This option is available only at the command line.

### Time Base

The software evaluates the cost function for a specific time interval. This interval is dependent on the *measured signal time base* and the *simulated signal time base*.

- The measured signal time base consists of all the time points for which the measured signal is specified. In case of multiple measured signals, this time base is the union of the time points of all the measured signals.
- The simulated signal time base consists of all the time points for which the model is simulated.

If the model uses a variable-step solver, then the simulated signal time base can change from one optimization iteration to another. The simulated and measured signal time bases can be different. The software evaluates the cost function for only the time interval that is common to both. By default, the software uses only the time points specified by the measured signal in the common time interval.

- In the GUI, you can specify the simulation start and stop times in the **Simulation time** area of the **Simulation Options** dialog box.
- At the command line, the software specifies the simulation stop time as the last point of the measured signal time base. For example, the following code simulates the model until the end time of the longest running output signal of `exp`, an `sdo.Experiment` object:

```
sim_obj = createSimulator(exp);
```

```
sim_obj = sim(sim_obj);
```

`sim_obj` contains the simulated response for the model associated with `exp`.

## Bounds and Constraints

You can specify bounds for the design variables (estimated model parameters), based on your knowledge of the system. Bounds are expressed as:

$$\underline{x} \leq x \leq \bar{x}$$

$\underline{x}$  and  $\bar{x}$  are the lower and upper bounds for the design variables.

For example, in a battery discharging experiment, the estimated battery initial charge must be greater than zero and less than `Inf`. These bounds are expressed as:

$$0 < x < \infty$$

For an example of how to specify these types of bounds, see “Estimate Model Parameters and Initial States (Code)” on page 2-115.

You can also specify other constraints,  $C(x)$ , on the design variables at the command line.  $C(x)$  can be linear or nonlinear and can describe equalities or inequalities.  $C(x)$  can also specify multiparameter constraints. For example, for a simple friction model,  $C(x)$  can specify that the static friction coefficient must be greater than or equal to the dynamic friction coefficient. One way of expressing this constraint is:

$$\begin{aligned} C(x) &: x_1 - x_2 \\ C(x) &\leq 0 \end{aligned}$$

$x_1$  and  $x_2$  are the dynamic and static friction coefficients, respectively.

For an example of how to specify a constraint, see “Estimate Model Parameters with Parameter Constraints (Code)” on page 2-148.

## Optimization Methods and Problem Formulations

An optimization problem can be one of the following types:

- Minimization problem — Minimizes an objective function,  $F(x)$ . You specify the measured signal that you want the model output to track. You can optionally specify bounds for the estimated parameters.
- Mixed minimization and feasibility problem — Minimizes an objective function,  $F(x)$ , subject to specified bounds and constraints,  $C(x)$ . You specify the measured signal that you want the model to track and bounds and constraints for the estimated parameters.
- Feasibility problem — Finds a solution that satisfies the specified constraints,  $C(x)$ . You specify only bounds and constraints for the estimated parameters. This type of problem is not common in parameter estimation.

The optimization method that you specify determines the formulation of the estimation problem. The software provides the following optimization methods:

Optimization Method Name	Description	Optimization Problem Formulation
<ul style="list-style-type: none"> <li>• User interface: <b>Nonlinear Least Squares</b></li> <li>• Command line: 'lsqnonlin'</li> </ul>	<p>Minimizes the squares of the residuals, recommended method for parameter estimation.</p> <p>This method requires a vector of error residuals, computed using a fixed time base. Do not use this approach if you have a scalar cost function or if the number of error residuals can change from one iteration to another.</p>	<p><b>Minimization Problem</b></p> $\min_x \ F(x)\ _2^2 = \min_x (f_1(x)^2 + f_2(x)^2 + \dots)$ <p><i>s.t.</i> <math>\underline{x} \leq x \leq \bar{x}</math></p> <p><math>f_1(x), f_2(x), \dots, f_n(x)</math> represent residuals. <math>n</math> is the number of samples.</p> <p><b>Mixed Minimization and Feasibility Problem</b></p> <p>Not supported.</p>

Optimization Method Name	Description	Optimization Problem Formulation
	<p>This method uses the Optimization Toolbox function, <code>lsqnonlin</code>.</p>	<p><b>Feasibility Problem</b> Not supported.</p>
<ul style="list-style-type: none"> <li>• User interface: <b>Gradient Descent</b></li> <li>• Command line: '<code>fmincon</code>'</li> </ul>	<p>General nonlinear solver, uses the cost function gradient.</p> <p>Use this approach if you want to specify one or any combination of the following:</p> <ul style="list-style-type: none"> <li>• Custom cost functions</li> <li>• Parameter-based constraints</li> <li>• Signal-based constraints</li> </ul> <p>This method uses the Optimization Toolbox function, <code>fmincon</code>.</p> <p>For information on how the gradient is computed, see “Gradient Computations” on page 2-103.</p>	<p><b>Minimization Problem</b></p> $\min_x F(x)$ $s.t. \underline{x} \leq x \leq \bar{x}$ <p><b>Mixed Minimization and Feasibility Problem</b></p> $\min_x F(x)$ $s.t. C(x) \leq 0$ $\underline{x} \leq x \leq \bar{x}$ <hr/> <p><b>Note</b> When tracking a reference signal, the software ignores the maximally feasible solution option.</p> <hr/> <p><b>Feasibility Problem</b></p> <ul style="list-style-type: none"> <li>• If you select the maximally feasible solution option (i.e., the optimization continues after an initial feasible</li> </ul>

Optimization Method Name	Description	Optimization Problem Formulation
		<p>solution is found), the software uses the following problem formulation:</p> $\begin{aligned} \min_{[x,\gamma]} \quad & \gamma \\ \text{s.t.} \quad & C(x) \leq \gamma \\ & \underline{x} \leq x \leq \bar{x} \\ & \gamma \leq 0 \end{aligned}$ <p><math>\gamma</math> is a slack variable that permits a feasible solution with <math>C(x) \leq \gamma</math> rather than <math>C(x) \leq 0</math>.</p> <ul style="list-style-type: none"> <li>• If you do not select the maximally feasible solution option (i.e., the optimization terminates as soon as a feasible solution is found), the software uses the following problem formulation:</li> </ul> $\begin{aligned} \min_x \quad & 0 \\ \text{s.t.} \quad & C(x) \leq 0 \\ & \underline{x} \leq x \leq \bar{x} \end{aligned}$

Optimization Method Name	Description	Optimization Problem Formulation
<ul style="list-style-type: none"> <li>• User interface: <b>Simplex Search</b></li> <li>• Command line: 'fminsearch'</li> </ul>	<p>Based on the Nelder-Mead algorithm, this approach does not use the cost function gradient.</p> <p>Use this approach if your cost function or constraints are not continuous or differentiable.</p> <p>This method uses the Optimization Toolbox functions, <code>fminsearch</code> and <code>fminbnd</code>. <code>fminbnd</code> is used if one scalar parameter is being optimized. Otherwise, <code>fminsearch</code> is used. You cannot specify parameter bounds, <math>\underline{x} \leq x \leq \bar{x}</math>, with <code>fminsearch</code>.</p>	<p><b>Minimization Problem</b></p> $\min_x F(x)$ <p><b>Mixed Minimization and Feasibility Problem</b></p> <p>The software formulates the problem in two steps:</p> <ol style="list-style-type: none"> <li><b>1</b> Finds a feasible solution.</li> </ol> $\min_x \max(C(x))$ <ol style="list-style-type: none"> <li><b>2</b> Minimizes the objective. The software uses the results from step 1 as initial guesses. It maintains feasibility by introducing a discontinuous barrier in the optimization objective.</li> </ol>

Optimization Method Name	Description	Optimization Problem Formulation
		$\min_x \Gamma(x)$ <p>where</p> $\Gamma(x) = \begin{cases} \inf & \text{if } \max(C(x)) > 0 \\ F(x) & \text{otherwise} \end{cases}$ <p><b>Feasibility Problem</b></p> $\min_x \max(C(x))$
<ul style="list-style-type: none"> <li>• User interface: <b>Pattern Search</b></li> <li>• Command line: 'patternsearch'</li> </ul>	<p>Direct search method, based on the generalized pattern search algorithm, this method does not use the cost function gradient.</p> <p>Use this approach if your cost function or constraints are not continuous or differentiable.</p> <p>This method uses the Global Optimization Toolbox function, patternsearch.</p>	<p><b>Minimization Problem</b></p> $\min_x F(x)$ <p>s.t. <math>\underline{x} \leq x \leq \bar{x}</math></p> <p><b>Mixed Minimization and Feasibility Problem</b></p> <p>The software formulates the problem in two steps:</p> <ol style="list-style-type: none"> <li>1 Finds a feasible solution.</li> </ol> $\min_x \max(C(x))$ <p>s.t. <math>\underline{x} \leq x \leq \bar{x}</math></p> <ol style="list-style-type: none"> <li>2 Minimizes the objective. The software uses the</li> </ol>

Optimization Method Name	Description	Optimization Problem Formulation
		<p>results from step 1 as initial guesses. It maintains feasibility by introducing a discontinuous barrier in the optimization objective.</p> $\min_x \Gamma(x)$ $s.t. \quad \underline{x} \leq x \leq \bar{x}$ <p>where</p> $\Gamma(x) = \begin{cases} \inf & \text{if } \max(C(x)) > 0 \\ F(x) & \text{otherwise} \end{cases}$ <p><b>Feasibility Problem</b></p> $\min_x \max(C(x))$ $s.t. \quad \underline{x} \leq x \leq \bar{x}$

**See Also**

sdo.SimulationTest | sdo.Experiment | sdo.requirements.SignalTracking | sdo.requirements.SignalTracking | lsqnonlin | fmincon | fminsearch | fminbnd | patternsearch

**Related Examples**

- “Estimate Model Parameter Values (Code)” on page 2-104
- “Estimate Model Parameters with Parameter Constraints (Code)” on page 2-148
- “Estimate Parameters from Measured Data (GUI)”

**Concepts**

- “Writing a Cost Function” on page 2-95



## Writing a Cost Function

### In this section...

“Cost Function Overview” on page 2-95

“Convenience Objects” on page 2-96

“Inputs” on page 2-98

“Evaluate Requirements” on page 2-99

“Outputs” on page 2-100

### Cost Function Overview

When you use `sdo.optimize` to optimize model parameters (*design variables*), you must provide a MATLAB function as an input to `sdo.optimize`. This function, also called a *cost function*, must evaluate the cost and constraint values for the design variable values for an iteration. (The cost and constraint functions are collectively referred to as *requirements*.) `sdo.optimize` calls this function at every optimization iteration and use the function output to decide the optimization direction.

The cost function can also be used for global sensitivity analysis. You generate samples of the model parameters and evaluate the cost function for each sample using `sdo.evaluate`.

The cost function must have:

- Input — `params`, a vector of the design variables (`param.Continuous` objects) to be optimized.
- Output:
  - (Required) `vals`, a structure with one or more fields that specify the values of the cost and constraint violations.
  - (Optional) `derivs`, a structure with one or more fields that specify the values of the gradients of the cost and constraint violations.

You perform the following tasks within the function:

- Extract the current design variable values from `params`.
- If the simulated response is required for evaluating the requirements, then simulate the model using the current design variable values.
- Evaluate the requirements.
- Specify the requirement values as fields of `vals`.

To use a cost function with `sdo.optimize`, enter:

```
[param_opt,opt_info] = sdo.optimize(@myCostFunc,param)
```

Here, `myCostFunc` is the name of the MATLAB function and `param` is a vector of the design variables.

Similarly, to use a cost function with `sdo.evaluate`, enter:

```
[y,info] = sdo.evaluate(@myCostFunc,param)
```

## Convenience Objects

The software provides you with the following convenience objects that can you can use in the cost function:

Class Name	Description
<code>sdo.SimulationTest</code>	<p>Use an <code>sdo.SimulationTest</code> object, also referred to as a <i>simulator</i>, to simulate a model. The simulator allows you to simulate the model using alternative inputs, model parameter and initial-state values, without modifying the model.</p> <p>You configure the simulator to log the signals needed to evaluate requirements and use the <code>sim</code> method to simulate the model. Then, you extract the model response</p>

Class Name	Description
	from the object and evaluate the requirements.
<p><b>Requirements objects:</b></p> <p>Time-domain requirements:</p> <ul style="list-style-type: none"> <li>• <code>sdo.requirements.SignalBound</code></li> <li>• <code>sdo.requirements.StepResponseEnvelope</code></li> <li>• <code>sdo.requirements.SignalTracking</code></li> </ul> <p>Frequency-domain requirements:</p> <ul style="list-style-type: none"> <li>• <code>sdo.requirements.GainPhaseMargin</code></li> <li>• <code>sdo.requirements.BodeMagnitude</code></li> <li>• <code>sdo.requirements.ClosedLoopPeakGain</code></li> <li>• <code>sdo.requirements.PZDampingRatio</code></li> <li>• <code>sdo.requirements.PZNaturalFrequency</code></li> <li>• <code>sdo.requirements.PZSettlingTime</code></li> <li>• <code>sdo.requirements.SignalTracking</code></li> <li>• <code>sdo.requirements.StepResponseEnvelope</code></li> <li>• <code>sdo.requirements.OpenLoopGainPhase</code></li> </ul>	<p>Use these <i>requirements objects</i> to specify time- and frequency-domain costs or constraints on the design variables.</p> <p>You configure the properties of the object and then use the object's <code>evaluateRequirement</code> method to evaluate how closely the current design variables satisfy your design requirement.</p>
<code>sdo.Experiment</code>	<p>Use an <code>sdo.Experiment</code> object, also referred to as simply an <i>experiment</i>, to specify the input/output data, model parameter and initial-state values for parameter estimation.</p> <p>You update the design variable values associated with the experiment using the <code>setEstimatedValues</code> method. Then, you create a simulator, using</p>

Class Name	Description
	the createSimulator method, to simulate the model using the updated model configuration.

## Inputs

- “Model Parameters and States” on page 2-98
- “Multiple Inputs” on page 2-98

## Model Parameters and States

The function must take as input a vector of model parameter objects (`param.Continuous` objects) and, optionally, initial-state objects (`param.State` objects). These objects represent the *design variables* of the optimization problem. You obtain these objects by using the `sdo.getParameterFromModel` and `sdo.getStateFromModel` commands.

To access a design variable value, use:

```
param_val = p(1).Value;
```

Here, `p` is a vector of `param.Continuous` objects and `p(1)` is either a model parameter or an initial-state object.

## Multiple Inputs

`sdo.optimize` requires that the cost function accept only one input argument, `params`. However, you might want to use additional inputs. For instance, you could make the model name an input argument and configure the function to be used for multiple models. To call `sdo.optimize` and use a function that accepts more than one input argument, you use an anonymous function. For example, suppose `myCostFunc_mult_inputs` is a cost function that takes `param`, `arg1`, and `arg2` as inputs. Then, assuming that all input arguments are variables in the workspace, you enter:

```
myCostFunc = @(param) myCostFunc_mult_inputs(param,arg1,arg2);  
[param_opt,opt_info] = sdo.optimize(@myCostFunc,param);
```

Additional inputs can also help reduce code redundancy and computation cost, given that the function is called repeatedly by `sdo.optimize` during optimization. For instance, if you use a convenience object in your function, you can create it once, before calling `sdo.optimize`. Then, you can modify the convenience object's properties as required within the function for each iteration.

## Evaluate Requirements

The core of the function is where you evaluate how well the current design variables satisfy the design requirements. You can use MATLAB functions to do so. You can also use the requirements objects that the Simulink Design Optimization software provides. These objects enable you to specify requirements such as step-response characteristics, gain/phase margin bounds, Bode magnitude bounds, etc.

- **Parameter-only requirements** — Extract the design variable values and compute the requirement values.

For example, you can minimize the cylinder cross-sectional area, a design variable, in a hydraulic cylinder. See “Design Optimization to Meet a Custom Objective (Code)” on page 3-112.

- **Model response-based requirements** — Simulate the model using the current design variable values, extract the model response, and compute the requirement values.

There are multiple ways to simulate the model, including:

- Using an `sdo.SimulationTest` object. You update the model parameter values using the simulator's `Parameters` property. Then, you use the `sim` method to simulate the model and extract the logged signals from the simulator that are of interest. For an example, see “Design Optimization to Meet a Custom Objective (Code)” on page 3-112.

In parameter estimation, you can use the `createSimulator` method of the `sdo.Experiment` object to create the simulator. Before creating the simulator, you update the experiment with the current design variable values using the `setEstimatedValues` method. For an example, see “Estimate Model Parameters Per Experiment (Code)” on page 2-136

- Using `sdo.setValueInModel` to update the model and then calling `sim` to simulate the model.

- Linear model-based requirements — Update the model with the current design variable values, linearize the model, and compute the requirement values.

Use `sdo.setValueInModel` to update the model and functions such as `linmod` or `linearize` to linearize the model. `linearize` requires a Simulink Control Design license.

### Outputs

- “Cost and Constraint Values” on page 2-100
- “Multiple Objectives” on page 2-101

### Cost and Constraint Values

Your function must return a structure containing the cost and constraint values for the current design variables. This structure must have one or more of the following fields, as required by your optimization problem:

- `F` — Cost value.
- `C1eq`, `Ceq` — Nonlinear constraint values. The solver satisfies  $C1eq \leq 0$  and  $Ceq = 0$ .
- `1eq`, `eq` — Linear constraint values. The solver satisfies  $1eq \leq 0$  and  $eq = 0$ .

If you have multiple constraints of one type, concatenate the values into a vector, and specify this vector as the corresponding field value. For instance, if you have a hydraulic cylinder, you can specify nonlinear inequality constraints on the piston position (`C1eq1`) and cylinder pressure (`C1eq2`). In this case, specify the `C1eq` field of the output structure, `vals`, as:

```
vals.C1eq = [C1eq1; C1eq2];
```

For an example, see “Design Optimization to Meet a Custom Objective (Code)” on page 3-112.

By default, the software computes the cost and constraint gradients using numeric perturbation. However, you can specify the gradients and return them as an additional output. This output must be a structure with one or more of the following fields, as required by your optimization problem:

- `F` — Cost derivatives.
- `C1eq` — Nonlinear inequality constraints derivatives.
- `Ceq` — Nonlinear equality constraints derivatives.

You must also set the `GradFcn` property of the optimization option set to `'on'`.

## Multiple Objectives

Simulink Design Optimization does not support multi-objective optimization. However, you can return the cost value (`F`) as a vector, representing the multiple objective values. Using this approach does not halt the optimization. Instead, the software sums the elements of the vector and minimizes this sum. The exception to this behavior is if you are using the nonlinear least squares (`lsqnonlin`) optimization method. The nonlinear least squares method, used for parameter estimation, requires that you return the error residuals as a vector. In this case, the software minimizes the sum square of this vector.

If you are tracking multiple signals and using `lsqnonlin`, then you must concatenate the error residuals for the different signals into one vector. Specify this vector as the `F` field value.

For an example of single objective optimization using the gradient descent method, see “Design Optimization to Meet a Custom Objective (Code)” on page 3-112.

For an example of multiple objective optimization using the nonlinear least squares method, see “Estimate Model Parameters Per Experiment (Code)” on page 2-136.

## See Also

`sdo.optimize` | `sdo.OptimizeOptions` | `sdo.setValueInModel` | `param.Continuous` | `sdo.SimulationTest` | `sdo.Experiment`

## Related Examples

- “Design Optimization to Meet a Custom Objective (Code)” on page 3-112
- “Estimate Model Parameter Values (Code)” on page 2-104

## Concepts

- “How the Optimization Algorithm Formulates Minimization Problems” on page 3-3

- “How the Software Formulates Parameter Estimation as an Optimization Problem” on page 2-85



## Gradient Computations

For the Gradient descent (fmincon) optimization solver, the gradients are computed using numerical perturbation:

$$dx = \sqrt[3]{eps} \times \max\left(|x|, \frac{1}{10} x_{typical}\right)$$

$$dL = \max(x - dx, x_{min})$$

$$dR = \min(x + dx, x_{max})$$

$$F_L = opt\_fcn(dL)$$

$$F_R = opt\_fcn(dR)$$

$$\frac{dF}{dx} = \frac{(F_L - F_R)}{(dL - dR)}$$

- $x$  is a scalar design variable.
- $x_{min}$  is the lower bound of  $x$ .
- $x_{max}$  is the upper bound of  $x$ .
- $x_{typical}$  is the scaled value of  $x$ .
- $opt\_fcn$  is the objective function.

$dx$  is relatively large to accommodate simulation solver tolerances.

If you want to compute the gradients in any other way, you can do so in the cost function you write for performing design optimization programmatically. See `sdo.optimize` and `GradFcn` of `sdo.OptimizeOptions` for more information.

### See Also

fmincon

### Concepts

- “How the Software Formulates Parameter Estimation as an Optimization Problem” on page 2-85
- “How the Optimization Algorithm Formulates Minimization Problems” on page 3-3

## Estimate Model Parameter Values (Code)

This example shows how to use experimental data to estimate model parameter values.

### **Aircraft Model**

The Simulink model, `sdoAircraftEstimation`, models the longitudinal flight control system of an aircraft.

```
open_system('sdoAircraftEstimation')
close(findall(0,'Type','figure','Tag','SIMULINK_SIMSCOPE_FIGURE'))
```

### **Estimation Problem**

You use measured data to estimate the aircraft model parameters and states.

Measured output data:

- Pilot G force, output of the `Pilot G-force` calculation block
- Angle of attack, fourth output of the `Aircraft Dynamics Model` block

Parameters:

- Actuator time constant,  $T_a$ , used by the `Actuator Model` block
- Vertical velocity,  $Z_d$ , used by the `Aircraft Dynamics Model` block
- Pitch rate gains,  $M_d$ , used by the `Aircraft Dynamics Model` block

State:

- Initial state of the first-order actuator model, `sdoAircraftEstimation/Actuator Model`

### **Define the Estimation Experiment**

Get the measured data.

```
[time,iodata] = sdoAircraftEstimation_Experiment;
```

The `sdoAircraftEstimation_Experiment` function returns the measured output data, `iodata`, and the corresponding time vector. The first column of `iodata` is the pilot G force and the second column is the angle of attack.

To see the code for this function, type `edit sdoAircraftEstimation_Experiment`.

Create an experiment object to store the measured input/output data.

```
Exp = sdo.Experiment('sdoAircraftEstimation');
```

Create an object to store the measured pilot G-Force output.

```
PilotG = Simulink.SimulationData.Signal;  
PilotG.Name = 'PilotG';  
PilotG.BlockPath = 'sdoAircraftEstimation/Pilot G-force calculation';  
PilotG.PortType = 'outport';  
PilotG.PortIndex = 1;  
PilotG.Values = timeseries(iodata(:,2),time);
```

Create an object to store the measured angle of attack (alpha) output.

```
AoA = Simulink.SimulationData.Signal;  
AoA.Name = 'AngleOfAttack';  
AoA.BlockPath = 'sdoAircraftEstimation/Aircraft Dynamics Model';  
AoA.PortType = 'outport';  
AoA.PortIndex = 4;  
AoA.Values = timeseries(iodata(:,1),time);
```

Add the measured pilot G-Force and angle of attack data to the experiment as the expected output data.

```
Exp.OutputData = [...  
    PilotG; ...  
    AoA];
```

Add the initial state for the `Actuator Model` block to the experiment. Set its `Free` field to `true` so that it is estimated.

```
Exp.InitialStates = sdo.getStateFromModel('sdoAircraftEstimation','Actuator');
Exp.InitialStates.Minimum = 0;
Exp.InitialStates.Free = true;
```

### Compare the Measured Output and the Initial Simulated Output

Create a simulation scenario using the experiment and obtain the simulated output.

```
Simulator = createSimulator(Exp);
Simulator = sim(Simulator);
```

Search for the pilot G-Force and angle of attack signals in the logged simulation data.

```
SimLog = find(Simulator.LoggedData,get_param('sdoAircraftEstimation','PilotG'));
PilotGSignal = find(SimLog,'PilotG');
AoASignal = find(SimLog,'AngleOfAttack');
```

Plot the measured and simulated data.

As expected, the model response does not match the experimental output data.

```
plot(time, iodata, ...
      AoASignal.Values.Time,AoASignal.Values.Data,'--', ...
      PilotGSignal.Values.Time,PilotGSignal.Values.Data,'-.');
title('Simulated and Measured Responses Before Estimation')
legend('Measured angle of attack', 'Measured pilot g force', ...
      'Simulated angle of attack', 'Simulated pilot g force');
```

### Specify the Parameters to Estimate

Select the model parameters that describe the flight control actuation system. Specify bounds for the estimated parameter values based on our understanding of the actuation system.

```
p = sdo.getParameterFromModel('sdoAircraftEstimation',{'Ta','Md','Zd'});
p(1).Minimum = 0.01; %Ta
p(1).Maximum = 1;
```

```
p(2).Minimum = -10;   %Md
p(2).Maximum = 0;
p(3).Minimum = -100; %Zd
p(3).Maximum = 0;
```

Get the actuator initial state value that is to be estimated from the experiment.

```
s = getValuesToEstimate(Exp);
```

Group the model parameters and initial states to be estimated together.

```
v = [p;s]
```

```
v(1,1) =
```

```
    Name: 'Ta'
    Value: 0.5000
  Minimum: 0.0100
  Maximum: 1
    Free: 1
    Scale: 0.5000
    Info: [1x1 struct]
```

```
v(2,1) =
```

```
    Name: 'Md'
    Value: -1
  Minimum: -10
  Maximum: 0
    Free: 1
    Scale: 1
    Info: [1x1 struct]
```

```
v(3,1) =
```

```
    Name: 'Zd'
```

```
Value: -80
Minimum: -100
Maximum: 0
Free: 1
Scale: 128
Info: [1x1 struct]
```

```
v(4,1) =
```

```
Name: 'sdoAircraftEstimation/Actuator
Model'
Value: 0
Minimum: 0
Maximum: Inf
Free: 1
Scale: 1
dxValue: 0
dxFree: 1
Info: [1x1 struct]
```

```
4x1 param.Continuous
```

### Define the Estimation Objective Function

Create an estimation objective function to evaluate how closely the simulation output, generated using the estimated parameter values, matches the measured data.

Use an anonymous function with one input argument that calls the `sdoAircraftEstimation_Objective` function. We pass the anonymous function to `sdo.optimize`, which evaluates the function at each optimization iteration.

```
estFcn = @(v) sdoAircraftEstimation_Objective(v,Exp);
```

The `sdoAircraftEstimation_Objective` function:

- Has one input argument that specifies the actuator parameter values and the actuator initial state.
- Has one input argument that specifies the experiment object containing the measured data.
- Returns a vector of errors between simulated and experimental outputs.

The `sdoAircraftEstimation_Objective` function requires two inputs, but `sdo.optimize` requires a function with one input argument. To work around this, `estFcn` is an anonymous function with one input argument, `v`, but it calls `sdoAircraftEstimation_Objective` using two input arguments, `v` and `Exp`.

For more information regarding anonymous functions, see "Anonymous Functions".

The `sdo.optimize` command minimizes the return argument of the anonymous function `estFcn`, that is, the residual errors returned by `sdoAircraftEstimation_Objective`. For more details on how to write an objective/constraint function to use with the `sdo.optimize` command, type `help sdoExampleCostFunction` at the MATLAB command prompt.

To examine the estimation objective function in more detail, type `edit sdoAircraftEstimation_Objective` at the MATLAB command prompt.

```
type sdoAircraftEstimation_Objective
```

```
function vals = sdoAircraftEstimation_Objective(v,Exp)
%SDOAIKRAFTESTIMATION_OBJECTIVE
%
%   The sdoAircraftEstimation_Objective function is used to compare model
%   outputs against experimental data.
%
%   vals = sdoAircraftEstimation_Objective(v,Exp)
%
%   The |v| input argument is a vector of estimated model parameter values
%   and initial states.
%
%   The |Exp| input argument contains the estimation experiment data.
```

```
%
% The |vals| return argument contains information about how well the
% model simulation results match the experimental data and is used by
% the |sdo.optimize| function to estimate the model parameters.
%
% See also sdo.optimize, sdoExampleCostFunction,
% sdoAircraftEstimation_cmddemo
%

% Copyright 2012 The MathWorks, Inc.

%%
% Define a signal tracking requirement to compute how well the model output
% matches the experiment data. Configure the tracking requirement so that
% it returns the tracking error residuals (rather than the
% sum-squared-error) and does not normalize the errors.
%
r = sdo.requirements.SignalTracking;
r.Type      = '==';
r.Method    = 'Residuals';
r.Normalize = 'off';

%%
% Update the experiments with the estimated parameter values.
%
Exp = setEstimatedValues(Exp,v);

%%
% Simulate the model and compare model outputs with measured experiment
% data.
%
Simulator = createSimulator(Exp);
Simulator = sim(Simulator);

SimLog      = find(Simulator.LoggedData,get_param('sdoAircraftEstimation',
PilotGSignal = find(SimLog,'PilotG');
AoASignal   = find(SimLog,'AngleOfAttack');

PilotGError = evalRequirement(r,PilotGSignal.Values,Exp.OutputData(1).Values);
AoAError    = evalRequirement(r,AoASignal.Values,Exp.OutputData(2).Values);
```



```

%%
% Return the residual errors to the optimization solver.
%
vals.F = [PilotGError(:); AoAError(:)];
end

```

### Estimate the Parameters

Use the `sdo.optimize` function to estimate the actuator parameter values and initial state.

Specify the optimization options. The estimation function `sdoAircraftEstimation_Objective` returns the error residuals between simulated and experimental data and does not include any constraints, making this problem ideal for the 'lsqnonlin' solver.

```

opt = sdo.OptimizeOptions;
opt.Method = 'lsqnonlin';

```

Estimate the parameters.

```

vOpt = sdo.optimize(estFcn,v,opt)

```

Optimization started 18-Jan-2014 17:14:28

Iter	F-count	f(x)	Step-size	First-order optimality
0	9	27972.2	1	
1	18	10124.8	0.4744	5.69e+04
2	27	3128.4	0.3854	1.24e+04
3	36	872.772	0.4288	2.81e+03
4	45	238.635	0.5157	618
5	54	71.6214	0.4934	147
6	63	16.8765	0.4271	43.6
7	72	1.82856	0.2932	11.4
8	81	0.0443162	0.1352	1.49
9	90	0.0010707	0.02918	0.301
10	99	0.0010707	0.008147	0.301

```
11    108  0.000803483    0.002037    0.135  
Local minimum possible.
```

lsqnonlin stopped because the final change in the sum of squares relative to its initial value is less than the selected value of the function tolerance

```
v0pt(1,1) =
```

```
    Name: 'Ta'  
    Value: 0.0500  
  Minimum: 0.0100  
  Maximum: 1  
    Free: 1  
    Scale: 0.5000  
    Info: [1x1 struct]
```

```
v0pt(2,1) =
```

```
    Name: 'Md'  
    Value: -6.8857  
  Minimum: -10  
  Maximum: 0  
    Free: 1  
    Scale: 1  
    Info: [1x1 struct]
```

```
v0pt(3,1) =
```

```
    Name: 'Zd'  
    Value: -63.9966  
  Minimum: -100  
  Maximum: 0  
    Free: 1  
    Scale: 128  
    Info: [1x1 struct]
```

```
v0pt(4,1) =
```

```

        Name: 'sdoAircraftEstimation/Actuator
Model'
        Value: 2.2681e-04
        Minimum: 0
        Maximum: Inf
        Free: 1
        Scale: 1
        dxValue: 0
        dxFree: 1
        Info: [1x1 struct]

```

```
4x1 param.Continuous
```

### Compare the Measured Output and the Final Simulated Output

Update the experiments with the estimated parameter values.

```
Exp = setEstimatedValues(Exp,vOpt);
```

Simulate the model using the updated experiment and compare the simulated output with the experimental data.

The model response using the estimated parameter values closely matches the experiment output data.

```

Simulator = createSimulator(Exp);
Simulator = sim(Simulator);
SimLog    = find(Simulator.LoggedData,get_param('sdoAircraftEstimation',
PilotGSignal = find(SimLog,'PilotG');
AoASignal = find(SimLog,'AngleOfAttack');

plot(time, iodata, ...
      AoASignal.Values.Time,AoASignal.Values.Data,'-.', ...
      PilotGSignal.Values.Time,PilotGSignal.Values.Data,'--')
title('Simulated and Measured Responses After Estimation')
legend('Measured angle of attack', 'Measured pilot g force', ...
       'Simulated angle of attack', 'Simulated pilot g force');

```

### **Update the Model Parameter Values**

Update the model with the estimated actuator parameter values. Do not update the model actuator initial state (fourth element of `vOpt`) as it is dependent on the experiment.

```
sdo.setValueInModel('sdoAircraftEstimation',vOpt(1:3));
```

Close the model

```
bdclose('sdoAircraftEstimation')
```

## Estimate Model Parameters and Initial States (Code)

This example shows how to estimate the initial state and parameters of a model.

This example requires Simscape®.

### RC Circuit Model

The Simulink model, `sdoRCCircuit`, models a simple resistor-capacitor (RC) circuit.

```
open_system('sdoRCCircuit');
```

### Estimation Problem

You use the measured data to estimate the RC model parameter and state values.

Measured output data:

- Capacitor voltage, output of the PS-Simulink Converter block

Parameter:

- Capacitance, `C1`, used by the `C1` block

State:

- Initial voltage of the capacitor, `C1`

### Define the Estimation Experiment

Get the measured data.

```
load sdoRCCircuit_ExperimentData
```

The variables `time` and `data` are loaded into the workspace, where `data` is the measured capacitor voltage for times `time`.

Create an experiment object to store the experimental voltage data.

```
Exp = sdo.Experiment('sdoRCCircuit');
```

Create an object to store the measured capacitor voltage output.

```
Voltage = Simulink.SimulationData.Signal;  
Voltage.Name      = 'Voltage';  
Voltage.BlockPath = 'sdoRCCircuit/PS-Simulink Converter';  
Voltage.PortType  = 'outport';  
Voltage.PortIndex = 1;  
Voltage.Values    = timeseries(data,time);
```

Add the measured capacitor data to the experiment as the expected output data.

```
Exp.OutputData = Voltage;
```

### **Compare the Measured Output and the Initial Simulated Output**

Create a simulation scenario using the experiment and obtain the simulated output.

```
Simulator = createSimulator(Exp);  
Simulator = sim(Simulator);
```

Search for the voltage signal in the logged simulation data.

```
SimLog      = find(Simulator.LoggedData,get_param('sdoRCCircuit','SignalLo  
Voltage     = find(SimLog,'Voltage');
```

Plot the measured and simulated data.

The model response does not match the experimental output data.

```
plot(time,data,'ro',Voltage.Values.Time,Voltage.Values.Data,'b')  
title('Simulated and Measured Responses Before Estimation')  
legend('Measured Voltage','Simulated Voltage')
```

### Specify the Parameters to Estimate

Select the capacitance parameter from the model. Specify an initial guess for the capacitance value (460 uF) and a minimum bound (0 F).

```
p = sdo.getParameterFromModel('sdoRCCircuit','C1');  
p.Value = 460e-6;  
p.Minimum = 0;
```

### Define the Estimation Objective Function

Create an estimation objective function to evaluate how closely the simulation output, generated using the estimated parameter value, matches the measured data.

Use an anonymous function with one input argument that calls the `sdoRCCircuit_Objective` function. We pass the anonymous function to `sdo.optimize`, which evaluates the function at each optimization iteration.

```
estFcn = @(v) sdoRCCircuit_Objective(v,Exp);
```

The `sdoRCCircuit_Objective` function:

- Has one input argument that specifies the estimated circuit capacitance value.
- Has one input argument that specifies the experiment object containing the measured data.
- Returns a vector of errors between simulated and experimental outputs.

The `sdoRCCircuit_Objective` function requires two inputs, but `sdo.optimize` requires a function with one input argument. To work around this, `estFcn` is an anonymous function with one input argument, `v`, but it calls `sdoRCCircuit_Objective` using two input arguments, `v` and `Exp`.

For more information regarding anonymous functions, see "Anonymous Functions".

The optimization solver minimizes the residual errors. For more details on how to write an objective/constraint function to use with the `sdo.optimize` command, type `help sdoExampleCostFunction` at the MATLAB command prompt.

To examine the estimation object function in more detail, type `edit sdoRCCircuit_Objective` at the MATLAB command prompt.

```
type sdoRCCircuit_Objective
```

```
function vals = sdoRCCircuit_Objective(v,Exp)
%SDORCCIRCUIT_OBJECTIVE
%
%   The sdoRCCircuit_Objective function is used to compare model
%   outputs against experimental data.
%
%   vals = sdoRCCircuit_Objective(v,Exp)
%
%   The |v| input argument is a vector of estimated model parameter values
%   and initial states.
%
%   The |Exp| input argument contains the estimation experiment data.
%
%   The |vals| return argument contains information about how well the
%   model simulation results match the experimental data and is used by
%   the |sdo.optimize| function to estimate the model parameters.
%
%   See also sdo.optimize, sdoExampleCostFunction, sdoRCCircuit_cmddemo
%
% Copyright 2012 The MathWorks, Inc.

%%
% Define a signal tracking requirement to compute how well the model output
% matches the experiment data. Configure the tracking requirement so that
% it returns the tracking error residuals (rather than the
```



```

% sum-squared-error) and does not normalize the errors.
%
r = sdo.requirements.SignalTracking;
r.Type      = '==';
r.Method    = 'Residuals';
r.Normalize = 'off';

%%
% Update the experiments with the estimated parameter values.
%
Exp = setEstimatedValues(Exp,v);

%%
% Simulate the model and compare model outputs with measured experiment
% data.
%
Simulator = createSimulator(Exp);
Simulator = sim(Simulator);

SimLog = find(Simulator.LoggedData,get_param('sdoRCCircuit','SignalLogging'));
Voltage = find(SimLog,'Voltage');

VoltageError = evalRequirement(r,Voltage.Values,Exp.OutputData(1).Values);

%%
% Return the residual errors to the optimization solver.
%
vals.F = VoltageError(:);
end

```

### **Estimate the Parameters**

Use the `sdo.optimize` function to estimate the capacitance value.

Specify the optimization options. The estimation function `sdoRCCircuit_Objective` returns the error residuals between simulated and experimental data and does not include any constraints, making this problem ideal for the 'lsqnonlin' solver.

```
opt = sdo.OptimizeOptions;
```

```
opt.Method = 'lsqnonlin';
```

Estimate the parameters.

```
pOpt = sdo.optimize(estFcn,p,opt)
```

```
Optimization started 18-Jan-2014 17:15:59
```

Iter	F-count	f(x)	Step-size	First-order optimality
0	3	54.999	1	
1	6	21.0094	0.2124	17.3
2	9	11.5162	0.1273	5.9
3	12	9.59875	0.06504	1.93
4	15	9.32857	0.02715	0.645
5	18	9.28738	0.01003	0.143
6	21	9.28455	0.002316	0.0219

```
Local minimum possible.
```

```
lsqnonlin stopped because the final change in the sum of squares relative to its initial value is less than the selected value of the function tolerance
```

```
pOpt =
```

```
    Name: 'C1'  
    Value: 1.1128e-04  
  Minimum: 0  
  Maximum: Inf  
    Free: 1  
    Scale: 0.0020  
    Info: [1x1 struct]
```

```
1x1 param.Continuous
```

### **Compare the Measured Output and the Simulated Output**

Update the experiment with the estimated capacitance value.

```
Exp = setEstimatedValues(Exp,pOpt);
```

Create a simulation scenario using the experiment and obtain the simulated output.

```
Simulator = createSimulator(Exp);
Simulator = sim(Simulator);
```

Search for the voltage signal in the logged simulation data.

```
SimLog = find(Simulator.LoggedData,get_param('sdoRCCircuit','SignalLogging'));
Voltage = find(SimLog,'Voltage');
```

Plot the measured and simulated data.

The simulated and measured signals match well, except for near time zero. This mismatch is because the capacitor initial voltage defined in the model does not match the initial voltage from the experiment.

```
plot(time,data,'ro',Voltage.Values.Time,Voltage.Values.Data,'b')
title('Simulated and Measured Responses After Estimation')
legend('Measured Voltage','Simulated Voltage')
```

### **Estimate the Initial State**

Add the capacitor initial voltage for the C1 block to the experiment. Set its initial guess value to 1 V.

```
Exp.InitialStates = sdo.getStateFromModel('sdoRCCircuit','C1');
Exp.InitialStates.Value = 1;
```

Recreate the estimation function to use the experiment with initial state estimation

```
estFcn = @(v) sdoRCCircuit_Objective(v,Exp);
```

Get the initial state and capacitance value that is to be estimated from the experiment.

```
v = getValuesToEstimate(Exp);
```

Estimate the parameters.

```
vOpt = sdo.optimize(estFcn,v,opt)
```

```
Optimization started 18-Jan-2014 17:16:14
```

Iter	F-count	f(x)	Step-size	First-order optimality
0	5	4.82677	1	
1	10	2.19679	1.57	23.6
2	15	1.34958	0.1596	0.0883
3	20	1.34358	0.05594	0.135
4	25	1.34355	0.001457	0.00085

```
Local minimum found.
```

```
Optimization completed because the size of the gradient is less than  
the selected value of the function tolerance.
```

```
vOpt(1,1) =
```

```
    Name: 'sdoRCCircuit/C1:sdoRCCircuit.C1.vc'  
    Value: 2.3592  
    Minimum: -Inf  
    Maximum: Inf  
    Free: 1  
    Scale: 1  
    dxValue: 0  
    dxFree: 1  
    Info: [1x1 struct]
```

```
vOpt(2,1) =
```

```
    Name: 'C1'  
    Value: 2.2663e-04  
    Minimum: 0  
    Maximum: Inf
```

```

Free: 1
Scale: 0.0020
Info: [1x1 struct]

```

```
2x1 param.Continuous
```

### Compare the Measured Output and the Final Simulated Output

Update the experiment with the estimated capacitance and capacitor initial voltage values.

```
Exp = setEstimatedValues(Exp,vOpt);
```

Simulate the model with the estimated initial-state and parameter values and compare the simulated output with the experiment data.

```

Simulator = createSimulator(Exp);
Simulator = sim(Simulator);
SimLog     = find(Simulator.LoggedData,get_param('sdoRCCircuit','SignalLoggi
Voltage    = find(SimLog,'Voltage');

```

```

plot(time,data,'ro',Voltage.Values.Time,Voltage.Values.Data,'b')
title('Simulated and Measured Responses After Initial State and Model Param
legend('Measured Voltage','Simulated Voltage')

```

### Update the Model Parameter Values

Update the model with the estimated capacitance value. Do not update the model capacitor initial voltage (first element of vOpt) as it is dependent on the experiment.

```
sdo.setValueInModel('sdoRCCircuit',vOpt(2));
```

Close the model

```
bdclose('sdoRCCircuit')
```

## Estimate Model Parameters using Multiple Experiments (Code)

This example shows how to estimate model parameters from multiple sets of experimental data. You estimate the parameters of a mass-spring-damper system.

### Open the Model and Get Experimental Data

This example uses the `sdoMassSpringDamper` model. The model includes two integrators to model the velocity and position of a mass in a mass-spring-damper system.

```
open_system('sdoMassSpringDamper');
```

Load the experiment data.

```
load sdoMassSpringDamper_ExperimentData
```

The variables `texp1`, `yexp1`, `texp2`, and `yexp2` are loaded into the workspace. `yexp1` and `yexp2` describe the mass position for times `texp1` and `texp2` respectively.

### Define the Estimation Experiments

Create a 2-element array of experiment objects to store the measured data for the two experiments.

Create an experiment object for the first experiment.

```
Exp = sdo.Experiment('sdoMassSpringDamper');
```

Create an object to store the measured mass position output.

```
MeasuredPos          = Simulink.SimulationData.Signal;  
MeasuredPos.Values   = timeseries(yexp1,texp1);  
MeasuredPos.BlockPath = 'sdoMassSpringDamper/Position';  
MeasuredPos.PortType = 'outport';
```

```
MeasuredPos.PortIndex = 1;
MeasuredPos.Name      = 'Position';
```

Add the measured mass position data to the experiment as the expected output data.

```
Exp.OutputData = MeasuredPos;
```

Create an object to specify the initial state for the Velocity block. The initial velocity of the mass is 0 m/s.

```
sVel      = sdo.getStateFromModel('sdoMassSpringDamper','Velocity');
sVel.Value = 0;
sVel.Free  = false;
```

`sVel.Free` is set to `false` because the initial velocity is known and does not need to be estimated.

Create an object to specify the initial state for the Position block. Specify a guess for the initial mass position. Set the `Free` field of the initial position object to `true` so that it is estimated.

```
sPos      = sdo.getStateFromModel('sdoMassSpringDamper','Position');
sPos.Free  = true;
sPos.Value = -0.1;
```

Add the initial states to the experiment.

```
Exp.InitialStates = [sVel;sPos];
```

Create a 2-element array of experiments. As the two experiments are identical except for the expected output data, copy the first experiment twice.

```
Exp = [Exp; Exp];
```

Modify the expected output data of the second experiment object in `Exp`.

```
Exp(2).OutputData.Values = timeseries(yexp2,texp2);
```

### **Compare the Measured Output and the Initial Simulated Output**

Create a simulation scenario using the first experiment and obtain the simulated output.

```
Simulator = createSimulator(Exp(1));  
Simulator = sim(Simulator);
```

Search for the position signal in the logged simulation data.

```
SimLog = find(Simulator.LoggedData,get_param('sdoMassSpringDamper','Signal')  
Position = find(SimLog,'Position');
```

Obtain the simulated position signal for the second experiment.

```
Simulator = createSimulator(Exp(2));  
Simulator = sim(Simulator);  
SimLog = find(Simulator.LoggedData,get_param('sdoMassSpringDamper','Signal')  
Position(2) = find(SimLog,'Position');
```

Plot the measured and simulated data.

The model response does not match the experimental output data.

```
subplot(211)  
plot(...  
    Position(1).Values.Time,Position(1).Values.Data, ...  
    Exp(1).OutputData.Values.Time, Exp(1).OutputData.Values.Data,'--')  
title('Experiment 1: Simulated and Measured Responses Before Estimation')  
ylabel('Position')  
legend('Measured Position','Simulated Position','Location','SouthEast')  
subplot(212)  
plot(...  
    Position(2).Values.Time,Position(2).Values.Data, ...  
    Exp(2).OutputData.Values.Time, Exp(2).OutputData.Values.Data,'--')  
title('Experiment 2: Simulated and Measured Responses Before Estimation')  
xlabel('Time (seconds)')  
ylabel('Position')  
legend('Measured Position','Simulated Position','Location','SouthEast')
```

### **Specify Parameters to Estimate**



Select the mass  $m$ , spring constant  $k$ , and damping coefficient  $b$  parameters from the model. Specify that the estimated values for these parameters must be positive.

```
p = sdo.getParameterFromModel('sdoMassSpringDamper', {'b', 'k', 'm'});  
p(1).Minimum = 0;  
p(2).Minimum = 0;  
p(3).Minimum = 0;
```

Get the position initial state values to be estimated from the experiment.

```
s = getValuesToEstimate(Exp);
```

`s` contains two initial state objects, both for the Position block. Each object corresponds to an experiment in `Exp`.

Group the model parameters and initial states to be estimated together.

```
v = [p;s]
```

```
v(1,1) =
```

```
    Name: 'b'  
    Value: 100  
  Minimum: 0  
  Maximum: Inf  
    Free: 1  
    Scale: 128  
    Info: [1x1 struct]
```

```
v(2,1) =
```

```
    Name: 'k'  
    Value: 500  
  Minimum: 0  
  Maximum: Inf  
    Free: 1  
    Scale: 512
```

Info: [1x1 struct]

v(3,1) =

Name: 'm'  
Value: 8  
Minimum: 0  
Maximum: Inf  
Free: 1  
Scale: 8  
Info: [1x1 struct]

v(4,1) =

Name: 'sdoMassSpringDamper/Position'  
Value: -0.1000  
Minimum: -Inf  
Maximum: Inf  
Free: 1  
Scale: 0.1250  
dxValue: 0  
dxFree: 1  
Info: [1x1 struct]

v(5,1) =

Name: 'sdoMassSpringDamper/Position'  
Value: -0.1000  
Minimum: -Inf  
Maximum: Inf  
Free: 1  
Scale: 0.1250  
dxValue: 0  
dxFree: 1  
Info: [1x1 struct]

```
5x1 param.Continuous
```

### Define the Estimation Objective

Create an estimation objective function to evaluate how closely the simulation output, generated using the estimated parameter values, matches the measured data.

Use an anonymous function with one input argument that calls the `sdoMassSpringDamper_Objective` function. We pass the anonymous function to `sdo.optimize`, which evaluates the function at each optimization iteration.

```
estFcn = @(v) sdoMassSpringDamper_Objective(v,Exp);
```

The `sdoMassSpringDamper_Objective` function:

- Has one input argument that specifies the mass, spring constant and damper values as well as the initial mass position.
- Has one input argument that specifies the experiment object containing the measured data.
- Returns a vector of errors between simulated and experimental outputs.

The `sdoMassSpringDamper_Objective` function requires two inputs, but `sdo.optimize` requires a function with one input argument. To work around this, `estFcn` is an anonymous function with one input argument, `v`, but it calls `sdoMassSpringDamper_Objective` using two input arguments, `v` and `Exp`.

For more information regarding anonymous functions, see "Anonymous Functions".

The `sdo.optimize` command minimizes the return argument of the anonymous function `estFcn`, that is, the residual errors returned by `sdoMassSpringDamper_Objective`. For more details on how to write an objective/constraint function to use with the `sdo.optimize` command, type `help sdoExampleCostFunction` at the MATLAB command prompt.

To examine the estimation objective function in more detail, type `edit sdoMassSpringDamper_Objective` at the MATLAB command prompt.

```
type sdoMassSpringDamper_Objective
```

```
function vals = sdoMassSpringDamper_Objective(v,Exp)
%SDOMASSSPRINGDAMPER_OBJECTIVE
%
%   The sdoMassSpringDamper_Objective function is used to compare model
%   outputs against experimental data.
%
%   vals = sdoMassSpringDamper_Objective(v,Exp)
%
%   The |v| input argument is a vector of estimated model parameter values
%   and initial states.
%
%   The |Exp| input argument contains the estimation experiment data.
%
%   The |vals| return argument contains information about how well the
%   model simulation results match the experimental data and is used by
%   the |sdo.optimize| function to estimate the model parameters.
%
%   see also sdo.optimize, sdoExampleCostFunction
%
% Copyright 2012 The MathWorks, Inc.

%%
% Define a signal tracking requirement to compute how well the model output
% matches the experiment data. Configure the tracking requirement so that
% it returns the tracking error residuals (rather than the
% sum-squared-error) and does not normalize the errors.
%
r = sdo.requirements.SignalTracking;
r.Type      = '==';
r.Method    = 'Residuals';
r.Normalize = 'off';

%%
```

```

% Update the experiments with the estimated parameter values.
%
Exp = setEstimatedValues(Exp,v);

%%
% Simulate the model and compare model outputs with measured experiment
% data.
%
Error = [];
for ct=1:numel(Exp)

    Simulator = createSimulator(Exp(ct));
    Simulator = sim(Simulator);

    SimLog = find(Simulator.LoggedData,get_param('sdoMassSpringDamper','Si
    Position = find(SimLog,'Position');

    PositionError = evalRequirement(r,Position.Values,Exp(ct).OutputData.Va

    Error = [Error; PositionError(:)];
end

%%
% Return the residual errors to the optimization solver.
%
vals.F = Error(:);
end

```

### Estimate the Parameters

Use the `sdo.optimize` function to estimate the actuator parameter values and initial state.

Specify the optimization options. The estimation function `sdoMassSpringDamper_Objective` returns the error residuals between simulated and experimental data and does not include any constraints, making this problem ideal for the 'lsqnonlin' solver.

```

opt = sdo.OptimizeOptions;
opt.Method = 'lsqnonlin';

```

Estimate the parameters. Notice that the initial mass position is estimated twice, once for each experiment.

```
vOpt = sdo.optimize(estFcn,v,opt)
```

```
Optimization started 18-Jan-2014 17:16:46
```

Iter	F-count	f(x)	Step-size	First-order optimality
0	11	0.777696	1	
1	22	0.00413099	3.696	0.00648
2	33	0.00118327	0.3194	0.00243
3	44	0.0011106	0.06718	5.09e-05

Local minimum found.

Optimization completed because the size of the gradient is less than the selected value of the function tolerance.

```
vOpt(1,1) =
```

```
    Name: 'b'  
    Value: 58.1959  
    Minimum: 0  
    Maximum: Inf  
    Free: 1  
    Scale: 128  
    Info: [1x1 struct]
```

```
vOpt(2,1) =
```

```
    Name: 'k'  
    Value: 399.9452  
    Minimum: 0  
    Maximum: Inf  
    Free: 1  
    Scale: 512  
    Info: [1x1 struct]
```

```
v0pt(3,1) =
```

```
    Name: 'm'  
    Value: 9.7225  
    Minimum: 0  
    Maximum: Inf  
    Free: 1  
    Scale: 8  
    Info: [1x1 struct]
```

```
v0pt(4,1) =
```

```
    Name: 'sdoMassSpringDamper/Position'  
    Value: 0.2995  
    Minimum: -Inf  
    Maximum: Inf  
    Free: 1  
    Scale: 0.1250  
    dxValue: 0  
    dxFree: 1  
    Info: [1x1 struct]
```

```
v0pt(5,1) =
```

```
    Name: 'sdoMassSpringDamper/Position'  
    Value: 0.0994  
    Minimum: -Inf  
    Maximum: Inf  
    Free: 1  
    Scale: 0.1250  
    dxValue: 0  
    dxFree: 1  
    Info: [1x1 struct]
```

```
5x1 param.Continuous
```

**Compare the Measured Output and the Final Simulated Output**

Update the experiments with the estimated parameter values.

```
Exp = setEstimatedValues(Exp,vOpt);
```

Obtain the simulated output for the first experiment.

```
Simulator = createSimulator(Exp(1));  
Simulator = sim(Simulator);  
SimLog = find(Simulator.LoggedData,get_param('sdoMassSpringDamper','Si  
Position(1) = find(SimLog,'Position');
```

Obtain the simulated output for the second experiment.

```
Simulator = createSimulator(Exp(2));  
Simulator = sim(Simulator);  
SimLog = find(Simulator.LoggedData,get_param('sdoMassSpringDamper','Si  
Position(2) = find(SimLog,'Position');
```

Plot the measured and simulated data.

The model response using the estimated parameter values nicely matches the output data for the experiments.

```
subplot(211)  
plot(...  
    Position(1).Values.Time,Position(1).Values.Data, ...  
    Exp(1).OutputData.Values.Time, Exp(1).OutputData.Values.Data,'--')  
title('Experiment 1: Simulated and Measured Responses After Estimation')  
ylabel('Position')  
legend('Measured Position','Simulated Position','Location','NorthEast')  
subplot(212)  
plot(...  
    Position(2).Values.Time,Position(2).Values.Data, ...  
    Exp(2).OutputData.Values.Time, Exp(2).OutputData.Values.Data,'--')  
title('Experiment 2: Simulated and Measured Responses After Estimation')  
xlabel('Time (seconds)')  
ylabel('Voltage')
```



```
legend('Measured Position','Simulated Position','Location','SouthEast')
```

### **Update the Model Parameter Values**

Update the model  $m$ ,  $k$ , and  $b$  parameter values. Do not update the model initial position value as this is dependent on the experiment.

```
sdo.setValueInModel('sdoMassSpringDamper',vOpt(1:3));
```

Close the model

```
bdclose('sdoMassSpringDamper')
```

## Estimate Model Parameters Per Experiment (Code)

This example shows how to use multiple experiments to estimate a mix of model parameter values; some that are estimated using all the experiments and others that are estimated using individual experiments. The example also shows how to configure the model with experiment dependent parameter values.

You estimate the parameters of a rechargeable battery based on data collected in experiments that discharge and charge the battery.

### Open the Model and Get Experimental Data

This example estimates parameters of a simple, rechargeable battery model, `sdoBattery`. The model input is the battery current and the model output, the battery terminal voltage, is computed from the battery state-of-charge.

```
open_system('sdoBattery');
```

The model is based on the equation

Where:

- is the battery terminal voltage in Volts.
- is the battery constant voltage in Volts.
- is the battery polarization resistance in Ohms.
- is the maximum battery capacity in Ampere-Hour.
- is the battery charge state, with 1 being fully charged and 0 zero charge. The battery state-of-charge is computed from the integral of the battery current with a +ve current indicating discharge and a -ve current indicating charging. The battery initial state-of-charge is specified by in Ampere-Hour.

- is the voltage drop when charging, expressed as a fraction of the battery constant voltage. When the battery is discharging this value is zero.

V, K, Qmax, Q0, and Loss are variables defined in the model workspace.

Load the experiment data. A 1.2V (6500mAh) battery was subjected to a discharge experiment and a charging experiment.

```
load sdoBattery_ExperimentData
```

The variables Charge\_Data and DCharge\_Data are loaded into the workspace. The first column of Charge\_Data contains time data. The second and third columns of Charge\_Data describe the current and voltage during a battery charging experiment. DCharge\_Data is similarly structured and contains data for a battery discharging experiment.

### Plot the Experiment Data

```
subplot(221),
plot(DCharge_Data(:,1)/3600,DCharge_Data(:,2))
title('Experiment: Discharge')
xlabel('Time (hours)')
ylabel('Current (A)')
subplot(223)
plot(DCharge_Data(:,1)/3600,DCharge_Data(:,3))
xlabel('Time (hours)')
ylabel('Voltage (V)')
subplot(222),
plot(Charge_Data(:,1)/3600,Charge_Data(:,2))
title('Experiment: Charge')
xlabel('Time (hours)')
ylabel('Current (A)')
subplot(224)
plot(Charge_Data(:,1)/3600,Charge_Data(:,3))
xlabel('Time (hours)')
ylabel('Voltage (V)')
```

### Define the Estimation Experiments

Create a 2-element array of experiment objects to specify the measured data for the two experiments.

Create an experiment object for the battery discharge experiment. The measured current data is specified as a timeseries in the experiment object.

```
DCharge_Exp = sdo.Experiment('sdoBattery');
```

Specify the input data (current) as a timeseries object.

```
DCharge_Exp.InputData = timeseries(DCharge_Data(:,2),DCharge_Data(:,1));
```

Create an object to specify the measured voltage output data.

```
VoltageSig = Simulink.SimulationData.Signal;  
VoltageSig.Name      = 'Voltage';  
VoltageSig.BlockPath = 'sdoBattery/SOC -> Voltage';  
VoltageSig.PortType  = 'outport';  
VoltageSig.PortIndex = 1;  
VoltageSig.Values    = timeseries(DCharge_Data(:,3),DCharge_Data(:,1));
```

Add the voltage signal to the discharge experiment as the expected output data.

```
DCharge_Exp.OutputData = VoltageSig;
```

Specify the battery initial charge state for the experiment. The battery charge state is modeled by the Q (Ah) block and its initial value is specified by the variable Q0. Create a parameter for the Q0 variable and add the parameter to the experiment. Q0 is experiment dependent and assumes different values in the discharging and charging experiments.

```
Q0 = sdo.getParameterFromModel('sdoBattery','Q0');  
Q0.Value = 6.5;  
Q0.Free = false;
```

Q0.Free is set to false because the initial battery charge is known and does not need to be estimated.

Add the Q0 parameter to the experiment.

```
DCharge_Exp.Parameters = Q0;
```

Create an experiment object to store the charging experiment data. Add the measured current input and measured voltage output data to the object.

```
Charge_Exp = sdo.Experiment('sdoBattery');
Charge_Exp.InputData = timeseries(Charge_Data(:,2),Charge_Data(:,1));
VoltageSig.Values    = timeseries(Charge_Data(:,3),Charge_Data(:,1));
Charge_Exp.OutputData = VoltageSig;
```

Add the battery initial charge and charging loss fraction parameters to the experiment. For this experiment, the initial charge (Q0) is known (0 Ah), but the value of the charging loss fraction (Loss) is not known.

```
Q0.Value = 0;
```

```
Loss = sdo.getParameterFromModel('sdoBattery','Loss');
Loss.Free = true;
Loss.Minimum = 0;
Loss.Maximum = 0.5;
```

```
Charge_Exp.Parameters = [Q0;Loss];
```

Loss.Free is set to true so that the value of Loss is estimated.

Collect both experiments into one vector.

```
Exp = [DCharge_Exp; Charge_Exp];
```

### **Compare the Measured Output and the Initial Simulated Output**

Create a simulation scenario using the first (discharging) experiment and obtain the simulated output.

```
Simulator = createSimulator(Exp(1));
Simulator = sim(Simulator);
```

Search for the voltage signal in the logged simulation data.

```
SimLog = find(Simulator.LoggedData,get_param('sdoBattery','SignalLogging'));
Voltage(1) = find(SimLog,'Voltage');
```

Obtain the simulated voltage signal for the second (charging) experiment.

```
Simulator = createSimulator(Exp(2));  
Simulator = sim(Simulator);  
SimLog    = find(Simulator.LoggedData,get_param('sdoBattery','SignalLogging'));  
Voltage(2) = find(SimLog,'Voltage');
```

Plot the measured and simulated data.

The model response does not match the experimental output data.

```
subplot(211)  
plot(...  
    Voltage(1).Values.Time/3600,Voltage(1).Values.Data, ...  
    Exp(1).OutputData.Values.Time/3600, Exp(1).OutputData.Values.Data, '-.')  
title('Discharging Experiment: Simulated and Measured Responses Before Estimation')  
ylabel('Voltage (V)')  
legend('Simulated Voltage','Measured Voltage','Location','SouthWest')  
subplot(212)  
plot(...  
    Voltage(2).Values.Time/3600,Voltage(2).Values.Data, ...  
    Exp(2).OutputData.Values.Time/3600, Exp(2).OutputData.Values.Data, '-.')  
title('Charging Experiment: Simulated and Measured Responses Before Estimation')  
xlabel('Time (hours)')  
ylabel('Voltage (V)')  
legend('Simulated Voltage','Measured Voltage','Location','SouthEast')
```

### **Specify Parameters to Estimate**

Estimate the values of the battery voltage  $V$ , the battery polarization resistance  $K$ , and the charging loss fraction  $Loss$ . The  $V$  and  $K$  parameters are estimated using all the experiment data while the  $Loss$  parameter is estimated using only the charging data.

Select the battery voltage  $V$  and the battery polarization resistance  $K$  parameters from the model. Specify minimum and maximum bounds for these parameters.

```
p = sdo.getParameterFromModel('sdoBattery',{'V','K'});

p(1).Minimum = 0;
p(1).Maximum = 2;

p(2).Minimum = 1e-6;
p(2).Maximum = 1e-1;

Get the experiment-specific Loss parameter from the experiment.

s = getValuesToEstimate(Exp);

Group all the parameters to be estimated.

v = [p;s]

v(1,1) =

    Name: 'V'
    Value: 1.2000
    Minimum: 0
    Maximum: 2
    Free: 1
    Scale: 2
    Info: [1x1 struct]

v(2,1) =

    Name: 'K'
    Value: 1.0000e-03
    Minimum: 1.0000e-06
    Maximum: 0.1000
    Free: 1
    Scale: 0.0020
    Info: [1x1 struct]

v(3,1) =
```

```
Name: 'Loss'  
Value: 0.0100  
Minimum: 0  
Maximum: 0.5000  
Free: 1  
Scale: 0.0156  
Info: [1x1 struct]
```

```
3x1 param.Continuous
```

### Define the Estimation Objective

Create an estimation objective function to evaluate how closely the simulation output, generated using the estimated parameter values, matches the measured data.

Use an anonymous function with one input argument that calls the `sdoBattery_Objective` function. We pass the anonymous function to `sdo.optimize`, which evaluates the function at each optimization iteration.

```
estFcn = @(v) sdoBattery_Objective(v,Exp);
```

The `sdoBattery_Objective` function:

- Has one input argument that specifies the estimated battery parameter values.
- Has one input argument that specifies the experiment object containing the measured data.
- Returns a vector of errors between simulated and experimental outputs.

The `sdoBattery_Objective` function requires two inputs, but `sdo.optimize` requires a function with one input argument. To work around this, `estFcn` is an anonymous function with one input argument, `v`, but it calls `sdoBattery_Objective` using two input arguments, `v` and `Exp`.



For more information regarding anonymous functions, see "Anonymous Functions".

The `sdo.optimize` command minimizes the return argument of the anonymous function `estFcn`, that is, the residual errors returned by `sdoBattery_Objective`. For more details on how to write an objective/constraint function to use with the `sdo.optimize` command, type `help sdoExampleCostFunction` at the MATLAB command prompt.

To examine the estimation objective function in more detail, type `edit sdoBattery_Objective` at the MATLAB command prompt.

```
type sdoBattery_Objective
```

```
function vals = sdoBattery_Objective(v,Exp)
%SDOBATTERY_OBJECTIVE
%
%   The sdoBattery_Objective function is used to compare model
%   outputs against experimental data.
%
%   vals = sdoBattery_Objective(v,Exp)
%
%   The |v| input argument is a vector of estimated model parameter values
%   and initial states.
%
%   The |Exp| input argument contains the estimation experiment data.
%
%   The |vals| return argument contains information about how well the
%   model simulation results match the experimental data and is used by
%   the |sdo.optimize| function to estimate the model parameters.
%
%   See also sdo.optimize, sdoExampleCostFunction, sdoBattery_cmddemo
%
% Copyright 2012 The MathWorks, Inc.
%%
% Define a signal tracking requirement to compute how well the model output
% matches the experiment data. Configure the tracking requirement so that
```

```
% it returns the tracking error residuals (rather than the
% sum-squared-error) and does not normalize the errors.
%
r = sdo.requirements.SignalTracking;
r.Type      = '==';
r.Method    = 'Residuals';
r.Normalize = 'off';

%%
% Update the experiments with the estimated parameter values.
%
Exp = setEstimatedValues(Exp,v);

%%
% Simulate the model and compare model outputs with measured experiment
% data.
%
Error = [];
for ct=1:numel(Exp)

    Simulator = createSimulator(Exp(ct));
    Simulator = sim(Simulator);

    SimLog = find(Simulator.LoggedData,get_param('sdoBattery','SignalLoggi
    Voltage = find(SimLog,'Voltage');

    VoltageError = evalRequirement(r,Voltage.Values,Exp(ct).OutputData(1).V

    Error = [Error; VoltageError(:)];
end

%%
% Return the residual errors to the optimization solver.
%
vals.F = Error(:);
end
```

### **Estimate the Parameters**

Use the `sdo.optimize` function to estimate the battery parameter values.

Specify the optimization options. The estimation function `sdoBattery_Objective` returns the error residuals between simulated and experimental data and does not include any constraints, making this problem ideal for the 'lsqnonlin' solver.

```
opt = sdo.OptimizeOptions;
opt.Method = 'lsqnonlin';
```

Estimate the parameters.

```
vOpt = sdo.optimize(estFcn,v,opt)
```

Optimization started 18-Jan-2014 17:17:40

Iter	F-count	f(x)	Step-size	First-order optimality
0	7	3272.22	1	
1	14	619.356	0.1634	3.15e+05
2	21	411.131	0.2175	28.7
3	28	405.529	0.3838	2.16e+03
4	35	403.727	0.2767	15.2
5	42	403.379	0.1645	1.14e+03

Local minimum possible.

lsqnonlin stopped because the final change in the sum of squares relative to its initial value is less than the selected value of the function tolerance

```
vOpt(1,1) =
```

```
    Name: 'V'
    Value: 1.3083
  Minimum: 0
  Maximum: 2
    Free: 1
    Scale: 2
    Info: [1x1 struct]
```

```
vOpt(2,1) =
```

```
Name: 'K'  
Value: 0.0010  
Minimum: 1.0000e-06  
Maximum: 0.1000  
Free: 1  
Scale: 0.0020  
Info: [1x1 struct]
```

```
vOpt(3,1) =
```

```
Name: 'Loss'  
Value: 5.1801e-05  
Minimum: 0  
Maximum: 0.5000  
Free: 1  
Scale: 0.0156  
Info: [1x1 struct]
```

```
3x1 param.Continuous
```

### **Compare the Measured Output and the Final Simulated Output**

Update the experiments with the estimated parameter values.

```
Exp = setEstimatedValues(Exp,vOpt);
```

Obtain the simulated output for the first (discharging) experiment.

```
Simulator = createSimulator(Exp(1));  
Simulator = sim(Simulator);  
SimLog = find(Simulator.LoggedData,get_param('sdoBattery','SignalLogging'));  
Voltage(1) = find(SimLog,'Voltage');
```

Obtain the simulated output for the second (charging) experiment.

```
Simulator = createSimulator(Exp(2));
```

```

Simulator = sim(Simulator);
SimLog    = find(Simulator.LoggedData,get_param('sdoBattery','SignalLogging'));
Voltage(2) = find(SimLog,'Voltage');

```

Plot the measured and simulated data.

The simulation results match the experimental data well except in the regions when the battery is fully charged. This is not unexpected as the simple battery model does not model the exponential voltage drop when the battery is fully charged.

```

subplot(211)
plot(...
    Voltage(1).Values.Time/3600,Voltage(1).Values.Data, ...
    Exp(1).OutputData.Values.Time/3600, Exp(1).OutputData.Values.Data, '-.')
title('Discharging Experiment: Simulated and Measured Responses After Estimation')
ylabel('Voltage (V)')
legend('Simulated Voltage','Measured Voltage','Location','SouthWest')
subplot(212)
plot(...
    Voltage(2).Values.Time/3600,Voltage(2).Values.Data, ...
    Exp(2).OutputData.Values.Time/3600, Exp(2).OutputData.Values.Data, '-.')
title('Charging Experiment: Simulated and Measured Responses After Estimation')
xlabel('Time (hours)')
ylabel('Voltage (V)')
legend('Simulated Voltage','Measured Voltage','Location','SouthEast')

```

### Update the Model Parameter Values

Update the model V, K, and Loss parameter values.

```
sdo.setValueInModel('sdoBattery',vOpt);
```

Close the model

```
bdclose('sdoBattery')
```

## Estimate Model Parameters with Parameter Constraints (Code)

This example shows how to estimate model parameters while imposing constraints on the parameter values.

You estimate dynamic and static friction coefficients of a simple friction system.

### Open the Model and Get Experimental Data

This example estimates parameters for a simple friction system, `sdoFriction`. The model input is the force applied to a mass and the model outputs are the mass position and velocity.

```
open_system('sdoFriction');
```

The model is based on a mass sliding on a surface. The mass is subject to a static friction that must be overcome before the mass moves and a dynamic friction once the mass moves. The static friction, `u_static`, is a fraction of the mass normal force; similarly the dynamic friction, `u_dynamic`, is a fraction of the mass normal force.

Load the experiment data. The mass was subjected to an applied force and its position recorded.

```
load sdoFriction_ExperimentData
```

The variables `AppliedForce`, `Position`, and `Velocity` are loaded into the workspace. The first column of each of these variables represents time and the second column represents the measured data. Because velocity is the first derivative of position, we only use the position measurements for this example.

### Plot the Experiment Data

```
subplot(211),  
plot(AppliedForce(:,1),AppliedForce(:,2))  
title('Measured Applied Force Input for Simple Friction System');
```

```

ylabel('Applied Force (N)')
subplot(212)
plot(Position(:,1),Position(:,2))
title('Measured Mass Position for Simple Friction System');
xlabel('Time (seconds)')
ylabel('Position (m)')

```

### Define the Estimation Experiment

Create an experiment object to specify the experiment data.

```
Exp = sdo.Experiment('sdoFriction');
```

Specify the input data (applied force) as a timeseries object.

```
Exp.InputData = timeseries(AppliedForce(:,2),AppliedForce(:,1));
```

Create an object to specify the measured mass position output.

```

PositionSig = Simulink.SimulationData.Signal;
PositionSig.Name      = 'Position';
PositionSig.BlockPath = 'sdoFriction/x';
PositionSig.PortType  = 'outport';
PositionSig.PortIndex = 1;
PositionSig.Values    = timeseries(Position(:,2),Position(:,1));

```

Add the measured mass position data to the experiment as the expected output data.

```
Exp.OutputData = PositionSig;
```

### Compare the Measured Output and the Initial Simulated Output

Create a simulation scenario using the experiment and obtain the simulated output.

```

Simulator = createSimulator(Exp);
Simulator = sim(Simulator);

```

Search for the position signal in the logged simulation data.

```
SimLog      = find(Simulator.LoggedData,get_param('sdoFriction','SignalLoggi  
Position    = find(SimLog,'Position');
```

Plot the measured and simulated data.

As expected, the model response does not match the experimental output data.

```
figure  
plot(...  
    Position.Values.Time,Position.Values.Data, ...  
    Exp.OutputData.Values.Time, Exp.OutputData.Values.Data,'-.')  
title('Simulated and Measured Responses Before Estimation')  
ylabel('Position (m)')  
xlabel('Time (seconds)')  
legend('Simulated Position','Measured Position','Location','NorthWest')
```

### **Specify Parameters to Estimate**

Estimate the `u_static` and `u_dynamic` friction coefficients using the experiment data. These coefficients are used as gains in the `Static Friction` and `Dynamic Friction` blocks, respectively. Physics indicates that friction coefficients should be constrained so that `u_static >= u_dynamic`; this parameter constraint is implemented in the estimation objective function.

Select the `u_static` and `u_dynamic` model parameters. Specify bounds for the estimated parameter values. Both coefficients are limited to the range [0 1].

```
p = sdo.getParameterFromModel('sdoFriction',{'u_static','u_dynamic'});  
  
p(1).Minimum = 0;  
p(1).Maximum = 1;  
  
p(2).Minimum = 0;  
p(2).Maximum = 1;
```

### **Define the Estimation Objective**



Create an estimation objective function to evaluate how closely the simulation output, generated using the estimated parameter values, matches the measured data.

Use an anonymous function with one input argument that calls the `sdoFriction_Objective` function. We pass the anonymous function to `sdo.optimize`, which evaluates the function at each optimization iteration.

```
estFcn = @(v) sdoFriction_Objective(v,Exp);
```

The `sdoFriction_Objective` function:

- Has one input argument that specifies the estimated friction coefficients.
- Has one input argument that specifies the experiment object containing the measured data.
- Returns the sum-squared-error errors between simulated and experimental outputs, and returns the parameter constraint.

The `sdoFriction_Objective` function requires two inputs, but `sdo.optimize` requires a function with one input argument. To work around this, `estFcn` is an anonymous function with one input argument, `v`, but it calls `sdoFriction_Objective` using two input arguments, `v` and `Exp`.

For more information regarding anonymous functions, see "Anonymous Functions".

The `sdo.optimize` command minimizes the return argument of the anonymous function `estFcn`, that is, the residual errors returned by `sdoFriction_Objective`. For more details on how to write an objective/constraint function to use with the `sdo.optimize` command, type `help sdoExampleCostFunction` at the MATLAB command prompt.

To examine the estimation objective function in more detail, type `edit sdoFriction_Objective` at the MATLAB command prompt.

```
type sdoFriction_Objective
```

```
function vals = sdoFriction_Objective(p,Exp)
%SDOFRICTION_OBJECTIVE
%
%   The sdoFriction_Objective function is used to compare model
%   outputs against experimental data and measure how well constraints are
%   satisfied.
%
%   vals = sdoFriction_Objective(p,Exp)
%
%   The |p| input argument is a vector of estimated model parameter values
%
%   The |Exp| input argument contains the estimation experiment data.
%
%   The |vals| return argument contains information about how well the
%   model simulation results match the experimental data and how well
%   constraints are satisfied. The |vals| argument is used by the
%   |sdo.optimize| function to estimate the model parameters.
%
%   See also sdo.optimize, sdoExampleCostFunction, sdoFriction_cmddemo
%
% Copyright 2012 The MathWorks, Inc.

%%
% Define a signal tracking requirement to compute how well the model output
% matches the experiment data. Configure the tracking requirement so that
% it returns the sum-squared-error.
%
r = sdo.requirements.SignalTracking;
r.Type = '==';
r.Method = 'SSE';

%%
% Update the experiments with the estimated parameter values.
%
Exp = setEstimatedValues(Exp,p);

%%
% Simulate the model and compare model outputs with measured experiment
% data.
```

```

%
Simulator = createSimulator(Exp);
Simulator = sim(Simulator);

SimLog = find(Simulator.LoggedData,get_param('sdoFriction','SignalLoggingName'));
Position = find(SimLog,'Position');

PositionError = evalRequirement(r,Position.Values,Exp.OutputData(1).Values);

%%
% Measure how well the parameters satisfy the friction coefficient constraint
% |u_static| >= |u_dynamic|. Note that constraints are returned to the
% optimizer in a c <=0 format. The friction coefficient constraint is
% rewritten accordingly.
PConstr = p(2).Value - p(1).Value; % u_dynamic - u_static <= 0

%%
% Return the sum-squared-error and constraint violation to the optimization
% solver.
%
vals.F = PositionError(:);
vals.Cleq = PConstr;
end

```

The friction coefficient constraint,  $u_{\text{static}} \geq u_{\text{dynamic}}$ , is implemented in the `sdoFriction_Objective` function as  $u_{\text{dynamic}} - u_{\text{static}} \leq 0$ . This is because the optimizer requires constraint values in a  $c \leq 0$  format. For more information, type `help sdo.optimize` at the MATLAB command prompt.

### Estimate the Parameters

Use the `sdo.optimize` function to estimate the friction model parameter values.

Specify the optimization options. The estimation function `sdoFriction_Objective` returns the sum-squared-error between simulated and experimental data and includes a parameter constraint. The default 'fmincon' solver is ideal for this type of problem.

Estimate the parameters.

```
pOpt = sdo.optimize(estFcn,p)
```

```
Optimization started 18-Jan-2014 17:19:28
```

Iter	F-count	f(x)	max constraint	Step-size	First-order optimality
0	5	27.7267	0		
1	11	22.5643	0	2.21	72.9
2	15	17.4771	0	0.51	16
3	22	0.762174	0	1.33	10.7
4	29	0.40765	0	0.263	3.15
5	34	0.0254254	0	0.0897	1.22
6	39	0.00522001	0	0.0296	0.276
7	44	0.00398126	0	0.0209	0.185
8	49	0.00120167	0	0.111	0.17
9	60	0.00118106	0	0.0212	0.173
10	72	0.00110164	0	0.0262	0.165
11	91	0.00110097	0	0.0031	0.174
12	108	0.00110097	0	0.00165	0.174

```
Local minimum possible. Constraints satisfied.
```

```
fmincon stopped because the size of the current step is less than  
the selected value of the step size tolerance and constraints are  
satisfied to within the selected value of the constraint tolerance.
```

```
pOpt(1,1) =
```

```
    Name: 'u_static'  
    Value: 0.7973  
    Minimum: 0  
    Maximum: 1  
    Free: 1  
    Scale: 0.5000  
    Info: [1x1 struct]
```

```
pOpt(2,1) =
```

```
    Name: 'u_dynamic'
```

```

Value: 0.4021
Minimum: 0
Maximum: 1
Free: 1
Scale: 0.2500
Info: [1x1 struct]

```

```
2x1 param.Continuous
```

### Compare the Measured Output and the Final Simulated Output

Update the experiments with the estimated parameter values.

```
Exp = setEstimatedValues(Exp,pOpt);
```

Obtain the simulated output for the experiment.

```

Simulator = createSimulator(Exp);
Simulator = sim(Simulator);
SimLog     = find(Simulator.LoggedData,get_param('sdoFriction','SignalLogging'));
Position   = find(SimLog,'Position');

```

Plot the measured and simulated data.

It can be seen that the model response using the estimated parameter values nicely matches the experiment output data.

```

plot(...
    Position.Values.Time,Position.Values.Data, ...
    Exp.OutputData.Values.Time, Exp.OutputData.Values.Data,'-.')
title('Simulated and Measured Responses After Model Parameter Estimation')
ylabel('Position (m)')
xlabel('Time (seconds)')
legend('Simulated Position','Measured Position','Location','NorthWest')

```

### Update the Model Parameter Values

Update the model `u_static` and `u_dynamic` parameter values.

```
sdo.setValueInModel('sdoFriction',pOpt);
```

Close the model

```
bdclose('sdoFriction')
```

## Estimate Model Parameter Values (GUI)

This example shows how to estimate the parameters of an engine throttle.

### **Simulink® Model of the Engine Throttle System**

The Simulink® model for the system is shown below.

### **Throttle Model Description**

The throttle controls the air mass flow into the intake manifold of an engine. The throttle body contains a butterfly valve that opens when the driver presses down on the accelerator pedal. This lets more air enter the cylinders and causes the engine to produce more torque.

A DC motor controls the opening angle of the butterfly valve. There is also a spring attached to the valve to return it to its closed position when the DC motor is de-energized. The amount of rotation of the valve is limited to approximately 90 degrees. Therefore, if a large command input is applied to the motor, the valve hits the hard stops preventing it from rotating further.

The motor is modeled as a torque gain and a time-delay input with parameters  $K_t$  and  $\text{input\_delay}$ . The butterfly valve is modeled as a mass-spring-damper system with parameters  $J$ ,  $c$  and  $k$ . This system is augmented with hard stops to limit the valve opening to 90 degrees. We know the model components, however, the parameter values of the system are not known accurately. A look at the response of this system (shown below) shows that it does not match the experimental data; hence the parameters need to be estimated for a better fit.

### **Estimation Data**

Double-click the Parameter Estimation GUI with preloaded data block in the model to open a pre-configured estimation GUI session.

A new data set can be created by clicking on the "Transient Data" node and pressing the "New" button in the right-hand-side panel. These data sets can then be used for estimation and/or validation.

We have already defined three data sets. The first one will be used for parameter estimation and the remaining two for validating the response of the Simulink model with the estimated parameters.

These data sets can be imported from various sources including MATLAB® variables, MAT files, Excel® files, or comma-separated-value files. Once we import the data, we can plot them to confirm that we have the right data sets in our estimation project.

### **Define Variables**

The next step is to define the variables for the estimation. This establishes which parameters of the simulation can be adjusted, and any rules governing their values.

The Estimation variables are selected by clicking on the "Variables" node and pressing the "Add" button. This opens a "Parameter Selection Dialog" from which we can select the model parameters that we desire to estimate.

We have already added the four unknown parameters in our model using the selection dialog. These parameters are the butterfly valve inertia,  $J$ ; the damping coefficient,  $c$ ; the return spring constant,  $k$ ; and the time lag in motor response, `input_delay`.

On the panel to the right of the list of parameters, you can set the initial guesses for the parameter values, and the minimum and maximum bounds on these values.

Since we know from our physical insight that all of these parameters have positive values, we set their lower limits to zero. We also put an upper bound



of 0.1 sec on the time delay parameter. We can also select an initial value for the parameters. These may come from some quick calculations of some formulas that determine the parameters.

### **The Estimation Task**

In order to run an estimation, we first need to create an "Estimation" node. This is done by clicking on the "Estimation" node and pressing the "New" button in the right-hand-side panel.

In our project, we have already created an estimation node called "New Estimation". We can click on this node to set up its various options.

The first panel is where we select the data sets to be used in this estimation. It is possible to use one or more data sets at once in a given estimation. For this model, we will use the data set called "Estimation Data".

The next panel called "Parameters" is where we select which parameters to adjust in this estimation. Even though we selected four parameters, in general, it is not necessary to estimate all of them at once. However, since our model is simple enough we will estimate all four parameters.

Now we are almost ready to start our estimation. However, in order to monitor the progress of the estimation process, we would like to create a number of dynamics plots, called "Views".

### **Viewing the Results**

Two plot types are created to view the estimation results. The plot below shows the experimental data overlaid with the simulated data. The simulated data come from the model with the estimated parameters. The results of the estimation appear satisfactory as the estimated (blue) curve closely matches the measured results.

We can also view how the parameters changed in the model. The plot below shows the trajectory of the parameters at each iteration of the estimation process. It is shown that the parameters settle to their final values as the estimation process converges to a solution.

### **Validation**

It is important to validate the results against other data sets. A successful estimation will not only match the experimental data that was used for estimation, but also the other data sets that were collected in experiments. A validation was already created for this project. Clicking on this validation node will create a measured vs. simulation plot that can be used to compare the simulation response against experimental data.

Using the other two data sets for the validation, we can confirm that our estimation was successful. This shows that the estimation process is robust enough to handle a variety of inputs.

It is therefore shown that the parameters in the model were estimated well to match the experimental data and the estimation was robust enough to be able to validate the model with additional experimental data.

### **Conclusion**

We conclude the validation of the estimated model is an important step in determining how robust the estimation was. We could ask why validate when the estimation data set returned very good results. Without validation of our model, there is no way of telling if the parameters estimated were over fitted

for a particular data set. Using additional data sets for validation shows how the model responds to a variety of different inputs and if our original estimation was appropriate.



# Response Optimization

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- “Optimization Speed and Parallel Computing” on page 3-191
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- “Reverting to Initial Parameter Values” on page 3-196
- “Manage Design Optimization Tool Session” on page 3-197
- “Optimizing Time-Domain Response of Simulink® Models Using Parallel Computing” on page 3-199

## How the Optimization Algorithm Formulates Minimization Problems

When you optimize parameters of a Simulink model to meet design requirements, Simulink Design Optimization software automatically converts the requirements into a constrained optimization problem and then solves the problem using optimization techniques. The constrained optimization problem iteratively simulates the Simulink model, compares the results of the simulations with the constraint objectives, and uses optimization methods to adjust tuned parameters to better meet the objectives.

This topic describes how the software formulates the constrained optimization problem used by the optimization algorithms. For each optimization algorithm, the software formulates one of the following types of minimization problems:

- Feasibility
- Tracking
- Mixed feasibility and tracking

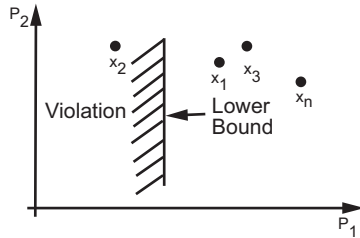
For more information on how each optimization algorithm formulates these problems, see:

- “Gradient Descent Method Problem Formulations” on page 3-7
- “Simplex Search Method Problem Formulations” on page 3-9
- “Pattern Search Method Problem Formulations” on page 3-10
- “Gradient Computations” on page 3-11

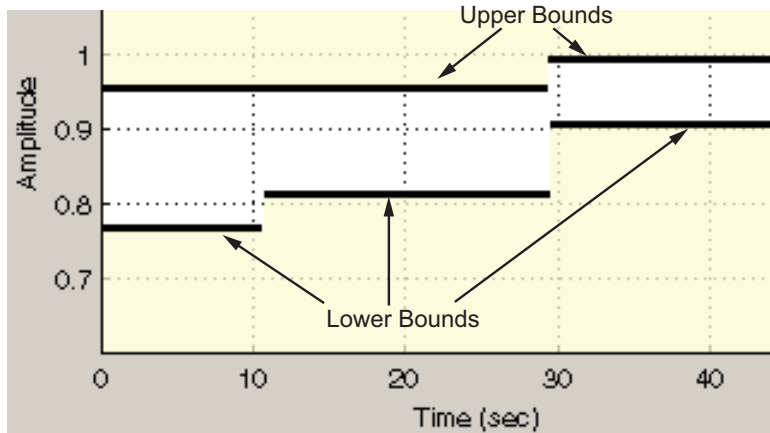
### Feasibility Problem and Constraint Formulation

*Feasibility* means that the optimization algorithm finds parameter values that satisfy all constraints to within specified tolerances but does not minimize any objective or cost function in doing so.

In the following figure,  $x_1$ ,  $x_3$ , and  $x_n$  represent a combination of parameter values  $P_1$  and  $P_2$  and are feasible solutions because they do not violate the lower bound constraint.



In a Simulink model, you constrain a signal by specifying lower and upper bounds in a Check block (Check Step Response Characteristics, ...) or a requirement object (sdo.requirements.StepResponseEnvelope, ...), as shown in the following figure.



These constraints are *piecewise linear bounds*. A piecewise linear bound  $y_{bnd}$  with  $n$  edges can be represented as:

$$y_{bnd}(t) = \begin{cases} y_1(t) & t_1 \leq t \leq t_2 \\ y_2(t) & t_2 \leq t \leq t_3 \\ \vdots & \vdots \\ y_n(t) & t_n \leq t \leq t_{n+1} \end{cases},$$

The software computes the signed distance between the simulated response and the edge. The signed distance for lower bounds is:



$$c = \begin{bmatrix} \max_{t_1 \leq t \leq t_2} y_{bnd} - y_{sim} \\ \max_{t_2 \leq t \leq t_3} y_{bnd} - y_{sim} \\ \max_{t_n \leq t \leq t_{n+1}} y_{bnd} - y_{sim} \end{bmatrix},$$

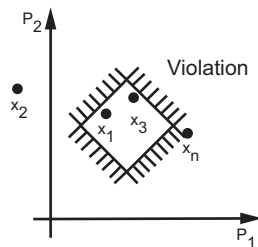
where  $y_{sim}$  is the simulated response and is a function of the parameters being optimized.

The signed distance for upper bounds is:

$$c = \begin{bmatrix} \max_{t_1 \leq t \leq t_2} y_{sim} - y_{bnd} \\ \max_{t_2 \leq t \leq t_3} y_{sim} - y_{bnd} \\ \max_{t_n \leq t \leq t_{n+1}} y_{sim} - y_{bnd} \end{bmatrix}.$$

At the command line, `opt_fcn` supplies  $c$  directly from the `Cleq` field of `vals`.

If *all* the constraints are met ( $c \leq 0$ ) for some combination of parameter values, then that solution is said to be feasible. In the following figure,  $x_1$  and  $x_3$  are feasible solutions.



When your model has multiple requirements or vector signals feeding a requirement, the constraint vector is extended with the constraint violations for each signal and bound:

$$C = [c_1; c_2; \dots; c_n].$$

## Tracking Problem

In addition to lower and upper bounds, you can specify a reference signal in a Check Against Reference block or `sdo.requirements.SignalTracking` object, which the Simulink model output can track. The tracking objective is a sum-squared-error tracking objective.

You specify the reference signal as a sequence of time-amplitude pairs:

$$y_{ref}(t_{ref}), t_{ref} \in \{T_{ref0}, T_{ref1}, \dots, T_{refN}\}.$$

The software computes the simulated response as a sequence of time-amplitude pairs:

$$y_{sim}(t_{sim}), t_{sim} \in \{T_{sim0}, T_{sim1}, \dots, T_{simN}\},$$

where some values of  $t_{sim}$  may match the values of  $t_{ref}$ .

A new time base,  $t_{new}$ , is formed from the union of the elements of  $t_{ref}$  and  $t_{sim}$ . Elements that are not within the minimum-maximum range of both  $t_{ref}$  and  $t_{sim}$  are omitted:

$$t_{new} = \{t : t_{sim} \cup t_{ref}\}$$

Using linear interpolation, the software computes the values of  $y_{ref}$  and  $y_{sim}$  at the time points in  $t_{new}$  and then computes the scaled error:

$$e(t_{new}) = \frac{(y_{sim}(t_{new}) - y_{ref}(t_{new}))}{\max_{t_{new}} |y_{ref}|}.$$

Finally, the software computes the weighted, integral square error:

$$f = \int w(t) e(t)^2 dt.$$

---

**Note** The weight  $w(t)$  is 1 by default. You can specify a different value of weight only at the command line.

---

When your model has requirements or vector signals feeding a requirement, the tracking objective equals the sum of the individual tracking integral errors for each signal:

$$F = \sum f_i.$$

## Gradient Descent Method Problem Formulations

The Gradient Descent method uses the Optimization Toolbox function `fmincon` to optimize model parameters to meet design requirements.

Problem Type	Problem Formulation
Feasibility Problem	<p>The software formulates the constraint <math>C(x)</math> as described in “Feasibility Problem and Constraint Formulation” on page 3-3.</p> <ul style="list-style-type: none"> <li>If you select the maximally feasible solution option (i.e., the optimization continues after an initial feasible solution is found), the software uses the following problem formulation:           <math display="block">\begin{aligned} \min_{[x,\gamma]} \quad &amp; \gamma \\ \text{s.t.} \quad &amp; C(x) \leq \gamma \\ &amp; \underline{x} \leq x \leq \bar{x} \\ &amp; \gamma \leq 0 \end{aligned}</math> <p><math>\gamma</math> is a slack variable that permits a feasible solution with <math>C(x) \leq \gamma</math> rather than <math>C(x) \leq 0</math>.</p> </li> <li>If you do not select the maximally feasible solution option (i.e., the optimization terminates as soon as a feasible solution is found), the software uses the following problem formulation:</li> </ul>

Problem Type	Problem Formulation
	$\min_x 0$ $s.t. C(x) \leq 0$ $\underline{x} \leq x \leq \bar{x}$
<b>Tracking Problem</b>	<p>The software formulates the tracking objective <math>F(x)</math> as described in “Tracking Problem” on page 3-6 and minimizes the tracking objective:</p> $\min_x F(x)$ $s.t. \underline{x} \leq x \leq \bar{x}$

Problem Type	Problem Formulation
<b>Mixed Feasibility and Tracking Problem</b>	<p>The software minimizes following problem formulation:</p> $\begin{aligned} \min_x \quad & F(x) \\ \text{s.t.} \quad & C(x) \leq 0 \\ & \underline{x} \leq x \leq \bar{x} \end{aligned}$ <hr/> <p><b>Note</b> When tracking a reference signal, the software ignores the maximally feasible solution option.</p> <hr/>

### Simplex Search Method Problem Formulations

The Simplex Search method uses the Optimization Toolbox function `fminsearch` and `fminbnd` to optimize model parameters to meet design requirements. `fminbnd` is used if one scalar parameter is being optimized, otherwise `fminsearch` is used. You cannot use parameter bounds  $\underline{x} \leq x \leq \bar{x}$  with `fminsearch`.

Problem Type	Problem Formulation
<b>Feasibility Problem</b>	<p>The software formulates the constraint <math>C(x)</math> as described in “Feasibility Problem and Constraint Formulation” on page 3-3 and then minimizes the maximum constraint violation:</p> $\min_x \max(C(x))$
<b>Tracking Problem</b>	<p>The software formulates the tracking objective <math>F(x)</math> as described in “Tracking Problem” on page 3-6 and then minimizes the tracking objective:</p>

Problem Type	Problem Formulation
	$\min_x F(x)$
<b>Mixed Feasibility and Tracking Problem</b>	<p>The software formulates the problem in two steps:</p> <ol style="list-style-type: none"> <li>1 Finds a feasible solution.</li> </ol> $\min_x \max(C(x))$ <ol style="list-style-type: none"> <li>2 Minimizes the tracking objective. The software uses the results from step 1 as initial guesses and maintains feasibility by introducing a discontinuous barrier in the optimization objective.</li> </ol> $\min_x \Gamma(x)$ <p>where</p> $\Gamma(x) = \begin{cases} \inf & \text{if } \max(C(x)) > 0 \\ F(x) & \text{otherwise} \end{cases}$

### Pattern Search Method Problem Formulations

The Pattern Search method uses the Global Optimization Toolbox function `patternsearch` to optimize model parameters to meet design requirements.

Problem Type	Problem Formulation
<b>Feasibility Problem</b>	<p>The software formulates the constraint <math>C(x)</math> as described in “Feasibility Problem and Constraint Formulation” on page 3-3 and then minimizes the maximum constraint violation:</p> $\min_x \max(C(x))$ <p>s.t. <math>\underline{x} \leq x \leq \bar{x}</math></p>
<b>Tracking Problem</b>	<p>The software formulates the tracking objective <math>F(x)</math> as described in “Tracking Problem” on page 3-6 and then minimizes the tracking objective:</p>

Problem Type	Problem Formulation
	$\min_x F(x)$ $s.t. \quad \underline{x} \leq x \leq \bar{x}$
<b>Mixed Feasibility and Tracking Problem</b>	<p>The software formulates the problem in two steps:</p> <p><b>1</b> Finds a feasible solution.</p> $\min_x \max(C(x))$ $s.t. \quad \underline{x} \leq x \leq \bar{x}$ <p><b>2</b> Minimizes the tracking objective. The software uses the results from step 1 as initial guesses and maintains feasibility by introducing a discontinuous barrier in the optimization objective.</p> $\min_x \Gamma(x)$ $s.t. \quad \underline{x} \leq x \leq \bar{x}$ <p>where</p> $\Gamma(x) = \begin{cases} \inf & \text{if } \max(C(x)) > 0 \\ F(x) & \text{otherwise} \end{cases}$

## Gradient Computations

For the Gradient descent (fmincon) optimization solver, the gradients are computed using numerical perturbation:

$$dx = \sqrt[3]{eps} \times \max\left(|x|, \frac{1}{10} x_{typical}\right)$$

$$dL = \max(x - dx, x_{min})$$

$$dR = \min(x + dx, x_{max})$$

$$F_L = opt\_fcn(dL)$$

$$F_R = opt\_fcn(dR)$$

$$\frac{dF}{dx} = \frac{(F_L - F_R)}{(dL - dR)}$$

- $x$  is a scalar design variable.
- $x_{min}$  is the lower bound of  $x$ .
- $x_{max}$  is the upper bound of  $x$ .
- $x_{typical}$  is the scaled value of  $x$ .
- $opt\_fcn$  is the objective function.

$dx$  is relatively large to accommodate simulation solver tolerances.

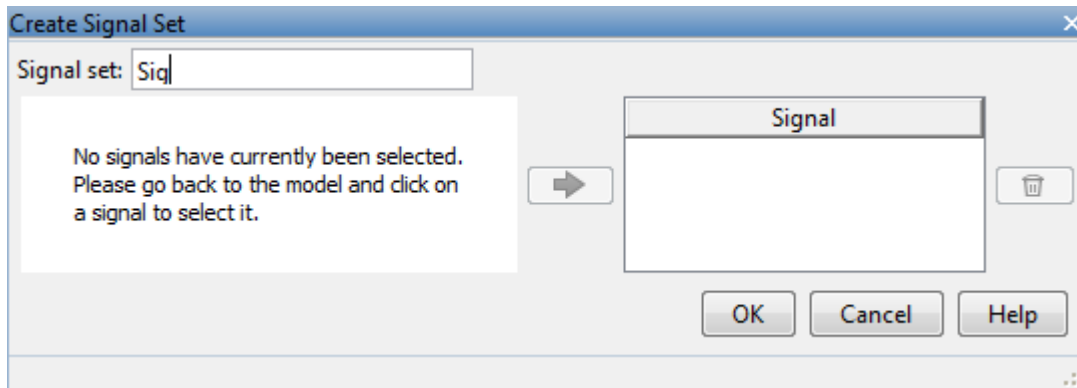
If you want to compute the gradients in any other way, you can do so in the cost function you write for performing design optimization programmatically. See `sdo.optimize` and `GradFcn` of `sdo.OptimizeOptions` for more information.




## Specify Signals to Log

Design requirements require logged model signals. During optimization, the model is simulated using the current value of the design variables and the logged signal is used to evaluate the design requirements.

- 1 In the **Design Optimization tool**, select **Signal** in the **New** drop-down list. A window opens where you select a signal to log.
- 2 In the Simulink model window, click the signal to which you want to add a requirement.



The window updates and displays the name of the block and the port number where the selected signal is located.

- 3 Select the signal and click  to add it to the signal set.
- 4 In the **Signal set** box, enter a name for the selected signal set.

Click **OK**. A new variable, with the specified name, appears in the **Design Optimization Workspace** of the Design Optimization tool window.

### See Also

- “Design Optimization to Track Reference Signal (GUI)”
- `sdo.SimulationTest`

## Specifying Step Response Characteristics

### Specify Step Response Characteristics

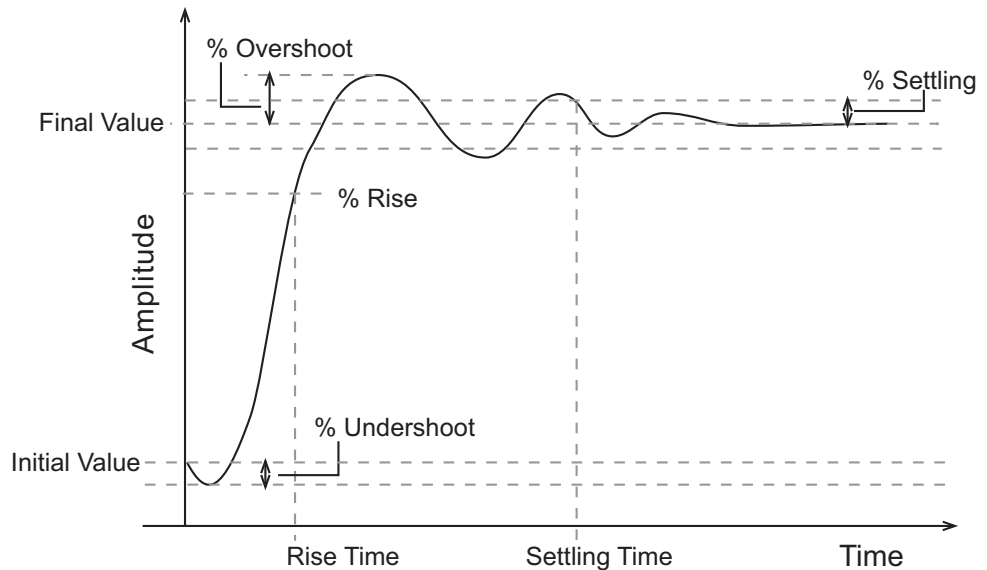
To specify step response characteristics:

- 1** You can apply this requirement to either a signal or a linearization of your model.

In the Design Optimization Tool, click **New**. To apply this requirement to a signal, select the **Step Response Envelope** entry in the **New Time Domain Requirement** section of the **New** list. To apply this requirement to a linearization of your model, select the **Step Response Envelope** entry in the **New Frequency Domain Requirement** section of the **New** list. The latter option requires Simulink Control Design software.

A window opens where you specify the step response requirements on a signal, or system.

- 2** Specify a requirement name in the **Name** box.
- 3** Specify the step response characteristics:



- **Initial value:** Input level before the step occurs
- **Step time:** Time at which the step takes place
- **Final value:** Input level after the step occurs
- **Rise time:** The time taken for the response signal to reach a specified percentage of the step's range. The step's range is the difference between the final and initial values.
- **% Rise:** The percentage used in the rise time.
- **Settling time:** The time taken until the response signal settles within a specified region around the final value. This settling region is defined as the final step value plus or minus the specified percentage of the final value.
- **% Settling:** The percentage used in the settling time.
- **Overshoot:** The amount by which the response signal can exceed the final value. This amount is specified as a percentage of the step's range. The step's range is the difference between the final and initial values.
- **Undershoot:** The amount by which the response signal can undershoot the initial value. This amount is specified as a percentage

of the step's range. The step's range is the difference between the final and initial values.

**4** Specify the signals or systems to be bound.


You can apply this requirement to a model signal or to a linearization of your Simulink model (requires Simulink Control Design software).

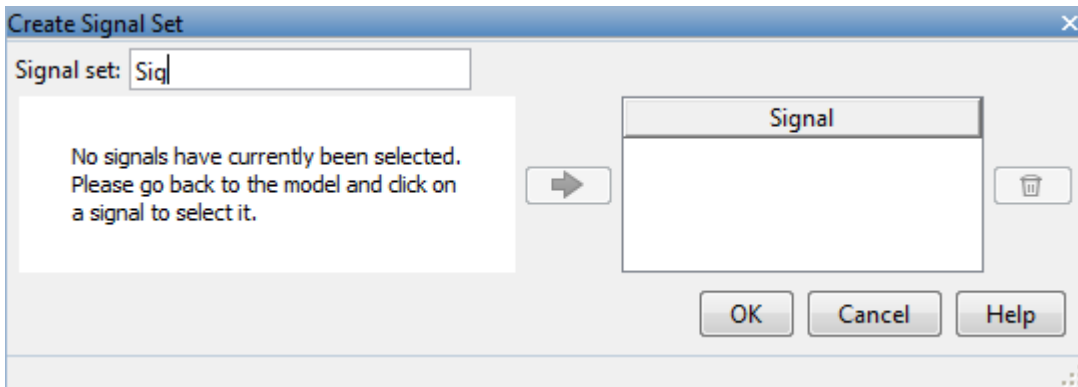
- Apply this requirement to a model signal:

In the **Select Signals to Bound** area, select a logged signal to which you will apply the requirement.


If you have already selected a signal to log, as described in “Specify Signals to Log” on page 3-13, it appears in the list. Select the corresponding check-box.

If you haven't selected a signal to log:

- Click . A window opens where you specify the logged signal.
- In the Simulink model window, click the signal to which you want to add a requirement.



The window updates and displays the name of the block and the port number where the selected signal is located.

- Select the signal and click  to add it to the signal set.
- In the **Signal set** box, enter a name for the selected signal set.


Click **OK**. A new variable, with the specified name, appears in the **Design Optimization Workspace** of the Design Optimization tool window.

- Apply this requirement to a linear system.

Linear systems are defined by snapshot times at which the model is linearized and sets of linearization I/O points defining the system inputs and outputs.

- a Specify the simulation time at which the model is linearized using the **Snapshot Times** box. For multiple simulation snapshot times, specify a vector.
- b Select the linearization input/output set from the **Linearization I/O** area.

If you have already created a linearization input/output set, it will appear in the list. Select the corresponding check box.

If you have not created a linearization input/output set, click  to open the Create linearization I/O set dialog box.

For more information on using this dialog box, see “Create Linearization I/O Sets” on page 3-82.

For more information on linearization, see “What Is Linearization?”.

## 5 Click **OK**.

A variable with the specified requirement name appears in the **Design Optimization Workspace**. A graphical display of the requirement also appears in the Design Optimization tool window.

Alternatively, you can use the Check Step Response Characteristics block to specify step response bounds for a signal.

## See Also


“Design Optimization to Meet Step Response Requirements (GUI)”


## Concepts

- “Specify Time-Domain Design Requirements” on page 3-25
- “Specify Frequency-Domain Design Requirements” on page 3-43

## Specifying Custom Requirements

To specify custom requirements, such as minimizing system energy:

- 1** In the Design Optimization tool, select **Custom Requirement** in the **New** list. A window opens where you specify the custom requirement.
- 2** Specify a requirement name in the **Name** box.
- 3** Specify the requirement type using the **Type** list.
- 4** Specify the name of the function that contains the custom requirement in the **Function** box. The field must be specified as a function handle using `@`. The function must be on the MATLAB path. Click  to review or edit the function.

If the function does not exist, clicking  opens a template MATLAB file. Use this file to implement the custom requirement. The default function name is `myCustomRequirement`.

- 5** (Optional) If you want to prevent the solver from considering specific parameter combinations, select the **Error if constraint is violated** check box. Use this option for parameter-only constraints.

During an optimization iteration, the solver evaluates requirements with this option selected first.

- If the constraint is violated, the solver skips evaluating any remaining requirements and proceeds to the next iterate.
- If the constraint is *not* violated, the solver evaluates the remaining requirements for the current iterate. If any of the remaining requirements bound signals or systems, then the solver simulates the model .

For more information, see “Skip Model Simulation Based on Parameter Constraint Violation (GUI)” on page 3-152.

---

**Note** If you select this check box, then do not specify signals or systems to bound. If you *do* specify signals or systems, then this check box is ignored.

---

**6** (Optional) Specify the signal or system, or both, to be bound.

You can apply this requirement to model signals, or a linearization of your Simulink model (requires Simulink Control Design software), or both.


Click **Select Signals and Systems to Bound (Optional)** to view the signal and linearization I/O selection area.

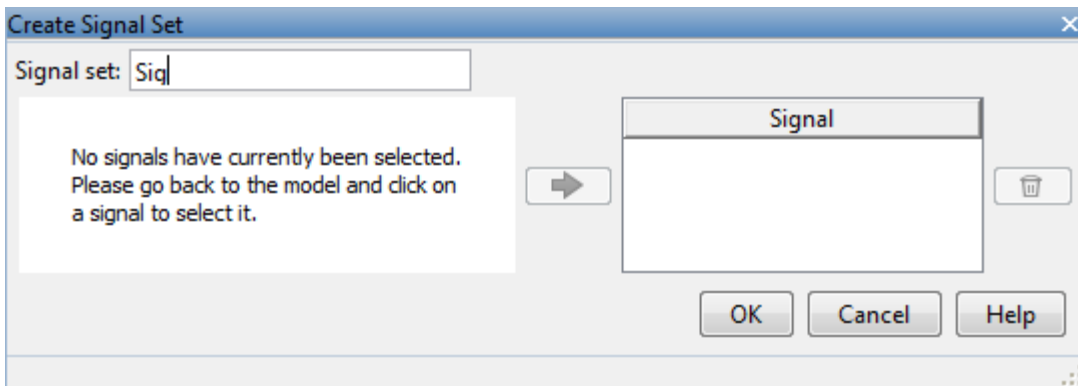
- Apply this requirement to a model signal:

In the **Signal** area, select a logged signal to which you will apply the requirement.


If you have already selected a signal to log, as described in “Specify Signals to Log” on page 3-13, it appears in the list. Select the corresponding check box.

If you have not selected a signal to log:

- Click . A window opens where you specify the logged signal.
- In the Simulink model window, click the signal to which you want to add a requirement.



The window updates and displays the name of the block and the port number where the selected signal is located.

- c Select the signal and click  to add it to the signal set.
- d In the **Signal set** box, enter a name for the selected signal set.


Click **OK**. A new variable, with the specified name, appears in the **Design Optimization Workspace** of the Design Optimization tool window.

- Apply this requirement to a linear system.

Linear systems are defined by snapshot times at which the model is linearized and sets of linearization I/O points defining the system inputs and outputs.

- a Specify the simulation time at which the model is linearized using the **Snapshot Times** box. For multiple simulation snapshot times, specify a vector.
- b Select the linearization input/output set from the **Linearization I/O** area.

If you have already created a linearization input/output set, it will appear in the list. Select the corresponding check box.

If you have not created a linearization input/output set, click  to open the Create linearization I/O set dialog box. For more information on using this dialog box, see “Create Linearization I/O Sets” on page 3-82.

For more information on linearization, see “What Is Linearization?”.

- 7 Click **OK**.

A new variable, with the specified name, appears in the **Design Optimization Workspace** of the Design Optimization tool. A graphical display of the requirement also appears in the Design Optimization tool window.



**Related  
Examples**

- “Design Optimization to Meet a Custom Objective (GUI)” on page 3-105
- “Design Optimization to Meet Custom Signal Requirements (GUI)” on page 3-122
- “Specify Time-Domain Design Requirements” on page 3-25
- “Specify Frequency-Domain Design Requirements” on page 3-43

## Move Constraints

### In this section...

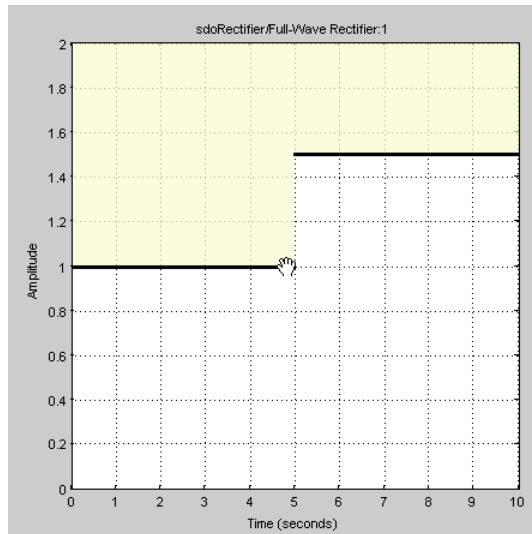
“Move Constraints Graphically” on page 3-22

“Position Constraints Exactly” on page 3-23

Constraint-bound edges define time-domain constraints you would like to place on a particular signal in your model. You can position these edges, which appear as a yellow shaded region bordered by a black line, graphically or exactly.

### Move Constraints Graphically

Use the mouse to click and drag edges in the amplitude versus time plot, as shown in the following figure.



- To move a constraint edge boundary or to change the slope of a constraint edge, position the pointer over a constraint edge endpoint, and press and hold down the left mouse button. The pointer should change to a hand symbol. While still holding the button down, drag the pointer to the target

location, and release the mouse button. Note that the edges on either side of the boundary might not maintain their slopes.

- To move an entire constraint edge up, down, left, or right, position the mouse pointer over the edge and press and hold down the left mouse button. The pointer should change to a four-way arrow. While still holding the button down, drag the pointer to the target location, and release the mouse button. Note that the edges on either side of the boundary might not maintain their slopes.

To move a constraint edge to a perfectly horizontal or vertical position, hold down the **Shift** key while clicking and dragging the constraint edge. This causes the constraint edge to *snap* to a horizontal or vertical position.

When moving constraint bound edges, it is sometimes helpful to display gridlines on the axes for careful alignment of the constraint bound edges. To turn the gridlines on or off, right-click within the axes and select **Grid**.

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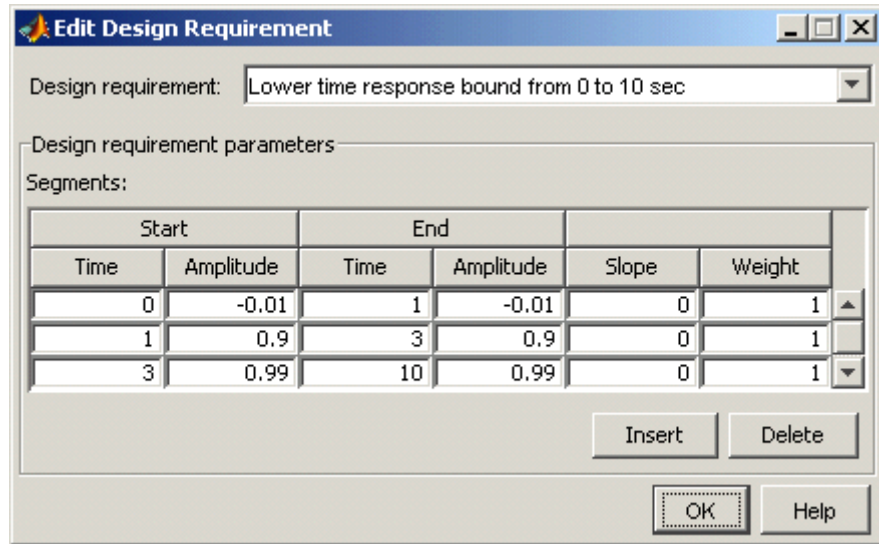
**Note** You can move a lower bound constraint edge above an upper bound constraint edge, or vice versa, but this produces an error when you attempt to run the optimization.

---

## Position Constraints Exactly

To position a constraint edge exactly:

- 1 Position the pointer over the edge you want to move and right-click. Select **Edit** to open the Edit Design Requirement dialog box.



- 2 Specify the position of each constraint edge in the **Time** and **Amplitude** columns.

### Concepts

- “Specify Time-Domain Design Requirements” on page 3-25
- “Specify Frequency-Domain Design Requirements” on page 3-43

## Specify Time-Domain Design Requirements

### In this section...

“Specify Piecewise-Linear Lower and Upper Bounds” on page 5-4

“Specify Signal Property Requirements” on page 3-27

“Specify Step Response Characteristics” on page 5-32


“Track Reference Signals” on page 5-9

“Specify Custom Requirements” on page 5-35

“Edit Design Requirements” on page 5-14

### Specify Piecewise-Linear Lower and Upper Bounds

To specify upper and lower bounds on a signal:


- 1 In the Design Optimization tool, select **Signal Bound** in the **New** drop-down list. A window opens where you specify upper or lower bounds on a signal.
- 2 Specify a requirement name in the **Name** box.
- 3 Select the requirement type using the **Type** list.
- 4 Specify the edge start and end times and corresponding amplitude in the **Time (s)** and **Amplitude** columns.
- 5 Click  to specify additional bound edges.

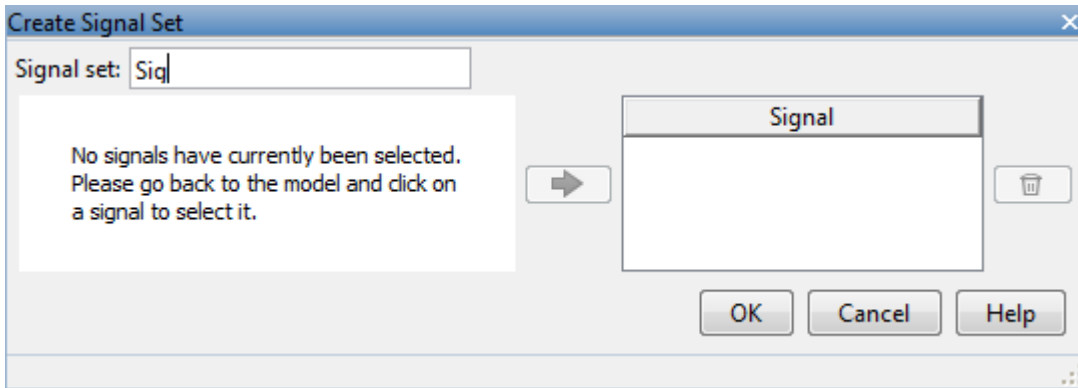
Select a row and click  to delete a bound edge.

- 6 In the **Select Signals to Bound** area, select a logged signal to apply the requirement to.


If you have already selected signals, as described in “Specify Signals to Log” on page 3-13, they appear in the list. Select the corresponding check-box.

If you haven’t selected a signal to log:

- a Click . A window opens where you specify the logged signal.
- b In the Simulink model window, click the signal to which you want to add a requirement.



The window updates and displays the name of the block and the port number where the selected signal is located.

- c Select the signal and click  to add it to the signal set.
- d In the **Signal set** box, enter a name for the selected signal set.

Click **OK**. A new variable, with the specified name, appears in the **Design Optimization Workspace** of the Design Optimization tool window.

#### 7 Click **OK**.

A variable with the specified requirement name appears in the **Design Optimization Workspace**. A graphical display of the requirement also appears in the Design Optimization tool window.

#### 8 (Optional) In the graphical display, you can:

- “Move Constraints Graphically” on page 3-22
- “Position Constraints Exactly” on page 3-23

Alternatively, you can add a Check Custom Bounds block to your model to specify piecewise-linear bounds.

## Specify Signal Property Requirements

To specify signal property requirements:

- 1 In the Design Optimization tool, select **Signal Property** in the **New** drop-down list. The Create Requirement window opens where you specify signal property requirements.
- 2 In the **Name** box, specify a requirement name.
- 3 In the **Specify Property** area, specify a signal property requirement using the **Property** and **Type** lists and the **Bound** box.

### Property List

For a signal  $S(t_0), \dots, S(t_N)$  you can specify one of the following properties using the **Property** list:

- Signal minimum —  $\min(S)$
- Signal maximum —  $\max(S)$
- Signal final value —  $S(t_N)$
- Signal mean —  $\text{mean}(S)$
- Signal median —  $\text{median}(S)$
- Signal variance —  $\text{variance}(S)$
- Signal interquartile range — Difference between the 75th and 25th percentiles of the signal values.

- Signal sum —  $\sum_{i=t_0}^{t_N} S(i)$

- Signal sum square —  $\sum_{i=t_0}^{t_N} S(i)^2$

- Signal sum absolute —  $\sum_{i=t_0}^{t_N} |S(i)|$

### Custom Signal Property

You can add a custom signal property to the **Property** list by editing the function `sdo.requirements.signalPropertyFcns`.


- At the MATLAB command prompt, enter `edit sdo.requirements.signalPropertyFcns`.
- Add your signal property function to the `FcnData` cell array.

Your signal property function must be on the path.

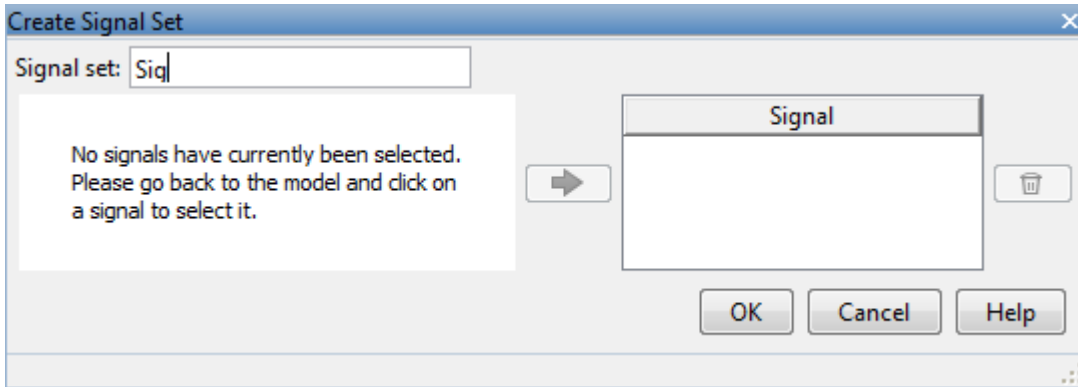
- In the **Select Signals to Bound** area, select the logged signal to which you want to apply the requirement.

If you have already selected a signal, as described in “Specify Signals to Log” on page 3-13, the signal appears in the list. Select the corresponding check box for that signal.


If you have not selected a signal to log:

- Click . The Create Signal Set window opens where you specify the logged signal.
- In the Simulink model window, click the signal to which you want to add a requirement.





The window updates and displays the name of the block and the port number where the selected signal is located.

- c Select the signal and click  to add it to the signal set.
- d In the **Signal set** box, enter a name for the selected signal set.

Click **OK**. A new variable, with the specified name, appears in the **Design Optimization Workspace** of the Design Optimization tool window.

##### 5 Click **OK**.

A variable with the specified requirement name appears in the **Design Optimization Workspace**. An iteration plot depicting the signal property for each iteration also appears in the Design Optimization tool window.

## Specify Step Response Characteristics

To specify step response characteristics:

- 1 You can apply this requirement to either a signal or a linearization of your model.

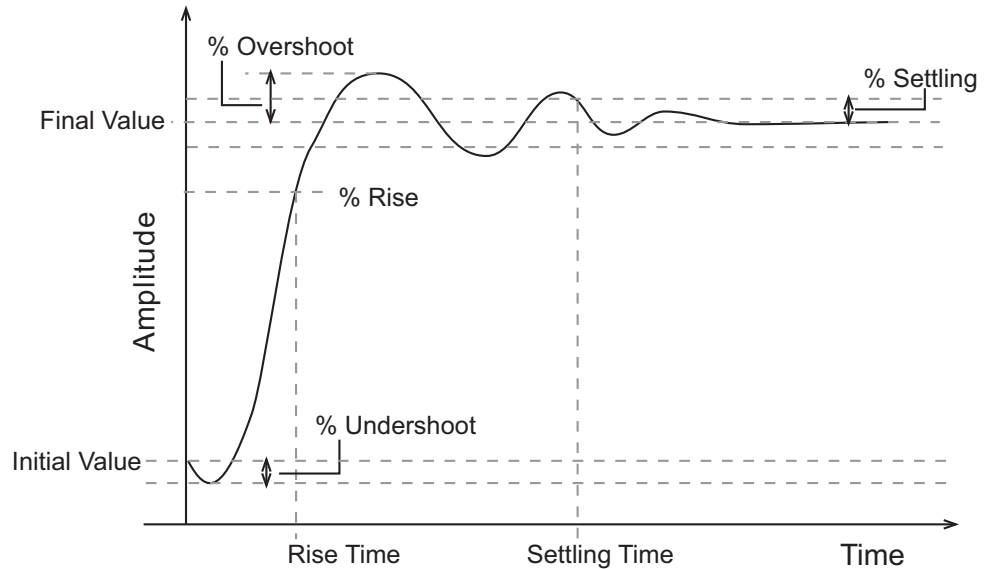
In the Design Optimization Tool, click **New**. To apply this requirement to a signal, select the **Step Response Envelope** entry in the **New Time Domain Requirement** section of the **New** list. To apply this requirement to a linearization of your model, select the **Step Response Envelope**

entry in the **New Frequency Domain Requirement** section of the **New** list. The latter option requires Simulink Control Design software.

A window opens where you specify the step response requirements on a signal, or system.

**2** Specify a requirement name in the **Name** box.

**3** Specify the step response characteristics:



- **Initial value:** Input level before the step occurs
- **Step time:** Time at which the step takes place
- **Final value:** Input level after the step occurs
- **Rise time:** The time taken for the response signal to reach a specified percentage of the step's range. The step's range is the difference between the final and initial values.
- **% Rise:** The percentage used in the rise time.

- **Settling time:** The time taken until the response signal settles within a specified region around the final value. This settling region is defined as the final step value plus or minus the specified percentage of the final value.
- **% Settling:** The percentage used in the settling time.
- **% Overshoot:** The amount by which the response signal can exceed the final value. This amount is specified as a percentage of the step's range. The step's range is the difference between the final and initial values.
- **% Undershoot:** The amount by which the response signal can undershoot the initial value. This amount is specified as a percentage of the step's range. The step's range is the difference between the final and initial values.

#### 4 Specify the signals or systems to be bound.


You can apply this requirement to a model signal or to a linearization of your Simulink model (requires Simulink Control Design software).

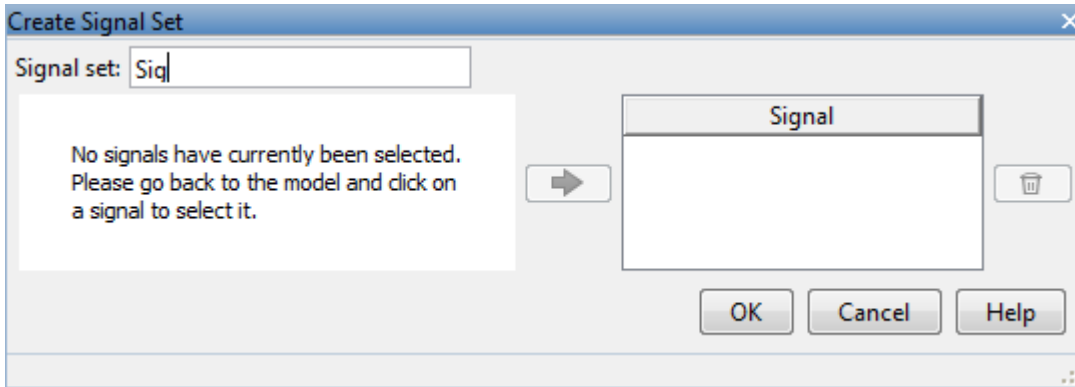
- Apply this requirement to a model signal:

In the **Select Signals to Bound** area, select a logged signal to which you will apply the requirement.


If you have already selected a signal to log, as described in “Specify Signals to Log” on page 3-13, it appears in the list. Select the corresponding check-box.

If you haven't selected a signal to log:

- a Click . A window opens where you specify the logged signal.
- b In the Simulink model window, click the signal to which you want to add a requirement.



The window updates and displays the name of the block and the port number where the selected signal is located.

- c Select the signal and click  to add it to the signal set.
- d In the **Signal set** box, enter a name for the selected signal set.


Click **OK**. A new variable, with the specified name, appears in the **Design Optimization Workspace** of the Design Optimization tool window.

- Apply this requirement to a linear system.

Linear systems are defined by snapshot times at which the model is linearized and sets of linearization I/O points defining the system inputs and outputs.

- a Specify the simulation time at which the model is linearized using the **Snapshot Times** box. For multiple simulation snapshot times, specify a vector.
- b Select the linearization input/output set from the **Linearization I/O** area.

If you have already created a linearization input/output set, it will appear in the list. Select the corresponding check box.

If you have not created a linearization input/output set, click  to open the Create linearization I/O set dialog box.

For more information on using this dialog box, see “Create Linearization I/O Sets” on page 3-82.

For more information on linearization, see “What Is Linearization?”.

#### 5 Click **OK**.

A variable with the specified requirement name appears in the **Design Optimization Workspace**. A graphical display of the requirement also appears in the Design Optimization tool window.

Alternatively, you can use the Check Step Response Characteristics block to specify step response bounds for a signal.

#### **See Also**

“Design Optimization to Meet Step Response Requirements (GUI)”

## **Track Reference Signals**

Use reference tracking to force a model signal to match a desired signal.

To track a reference signal:

- 1** In the Design Optimization tool, select **Signal Tracking** in the **New** drop-down list. A window opens where you specify the reference signal to track.
- 2** Specify a requirement name in the **Name** box.
- 3** Define the reference signal by entering vectors, or variables from the workspace, in the **Time vector** and **Amplitude** fields.


Click **Update reference signal data** to use the new amplitude and time vector as the reference signal.

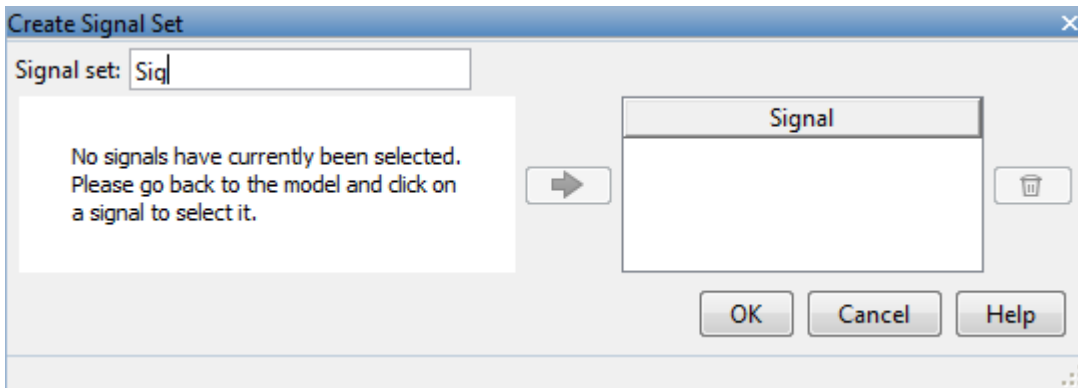
- 4** Specify how the optimization solver minimizes the error between the reference and model signals using the **Tracking Method** list:
  - SSE — Reduces the sum of squared errors
  - SAE — Reduces the sum of absolute errors

- 5 In the **Specify Signal to Track Reference Signal** area, select a logged signal to apply the requirement to.


If you already selected a signal to log, as described in “Specify Signals to Log” on page 3-13, they appear in the list. Select the corresponding check-box.

If you haven’t selected a signal to log:

- a Click . A window opens where you specify the logged signal.
- b In the Simulink model window, click the signal to which you want to add a requirement.



The window updates and displays the name of the block and the port number where the selected signal is located.

- c Select the signal and click  to add it to the signal set.
- d In the **Signal set** box, enter a name for the selected signal set.

Click **OK**. A new variable, with the specified name, appears in the **Design Optimization Workspace** of the Design Optimization tool window.

- e Select the check-box corresponding to the signal and click **OK**.

A variable with the specified requirement name appears in the **Design Optimization Workspace**. A graphical display of the signal bound also appears in the Design Optimization tool window.

---

**Note** When tracking a reference signal, the software ignores the maximally feasible solution option. For more information on this option, see “Selecting Optimization Termination Options” on page 3-79.

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Alternatively, you can use the Check Against Reference block to specify a reference signal to track.


### See Also

“Design Optimization to Track Reference Signal (GUI)”

## Specify Custom Requirements

To specify custom requirements, such as minimizing system energy:

- 1 In the Design Optimization tool, select **Custom Requirement** in the **New** list. A window opens where you specify the custom requirement.
- 2 Specify a requirement name in the **Name** box.
- 3 Specify the requirement type using the **Type** list.
- 4 Specify the name of the function that contains the custom requirement in the **Function** box. The field must be specified as a function handle using `@`. The function must be on the MATLAB path. Click  to review or edit the function.

If the function does not exist, clicking  opens a template MATLAB file. Use this file to implement the custom requirement. The default function name is `myCustomRequirement`.

- 5 (Optional) If you want to prevent the solver from considering specific parameter combinations, select the **Error if constraint is violated** check box. Use this option for parameter-only constraints.

During an optimization iteration, the solver evaluates requirements with this option selected first.

- If the constraint is violated, the solver skips evaluating any remaining requirements and proceeds to the next iterate.
- If the constraint is *not* violated, the solver evaluates the remaining requirements for the current iterate. If any of the remaining requirements bound signals or systems, then the solver simulates the model .

For more information, see “Skip Model Simulation Based on Parameter Constraint Violation (GUI)” on page 3-152.

---

**Note** If you select this check box, then do not specify signals or systems to bound. If you *do* specify signals or systems, then this check box is ignored.

---

#### 6 (Optional) Specify the signal or system, or both, to be bound.

You can apply this requirement to model signals, or a linearization of your Simulink model (requires Simulink Control Design software), or both.


Click **Select Signals and Systems to Bound (Optional)** to view the signal and linearization I/O selection area.

- Apply this requirement to a model signal:

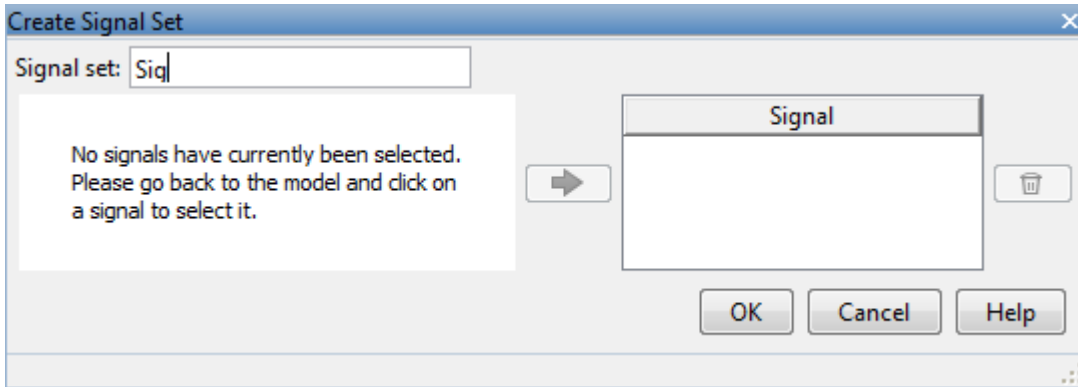
In the **Signal** area, select a logged signal to which you will apply the requirement.

If you have already selected a signal to log, as described in “Specify Signals to Log” on page 3-13, it appears in the list. Select the corresponding check box.


If you have not selected a signal to log:

- a Click . A window opens where you specify the logged signal.
- b In the Simulink model window, click the signal to which you want to add a requirement.





The window updates and displays the name of the block and the port number where the selected signal is located.

- c Select the signal and click  to add it to the signal set.
- d In the **Signal set** box, enter a name for the selected signal set.


Click **OK**. A new variable, with the specified name, appears in the **Design Optimization Workspace** of the Design Optimization tool window.

- Apply this requirement to a linear system.

Linear systems are defined by snapshot times at which the model is linearized and sets of linearization I/O points defining the system inputs and outputs.

- a Specify the simulation time at which the model is linearized using the **Snapshot Times** box. For multiple simulation snapshot times, specify a vector.
- b Select the linearization input/output set from the **Linearization I/O** area.

If you have already created a linearization input/output set, it will appear in the list. Select the corresponding check box.

If you have not created a linearization input/output set, click  to open the Create linearization I/O set dialog box. For more

information on using this dialog box, see “Create Linearization I/O Sets” on page 3-82.

For more information on linearization, see “What Is Linearization?”.

#### 7 Click **OK**.

A new variable, with the specified name, appears in the **Design Optimization Workspace** of the Design Optimization tool. A graphical display of the requirement also appears in the Design Optimization tool window.

#### **See Also**

- “Design Optimization to Meet a Custom Objective (GUI)” on page 3-105
- “Design Optimization to Meet Custom Signal Requirements (GUI)” on page 3-122

### **Edit Design Requirements**

The Edit Design Requirement dialog box allows you to exactly position constraint segments and to edit other properties of these constraints. The dialog box has two main components:

- An upper panel to specify the constraint you are editing
- A lower panel to edit the constraint parameters

The upper panel of the Edit Design Requirement dialog box resembles the image in the following figure.



In the context of the SISO Tool in Control System Toolbox™ software, **Design requirement** refers to both the particular editor within the SISO Tool that contains the requirement and the particular requirement within that editor. To edit other constraints within the SISO Tool, select another design requirement from the drop-down menu.

### Edit Design Requirement Dialog Box Parameters

The particular parameters shown within the lower panel of the Edit Design Requirement dialog box depend on the type of constraint/requirement. In some cases, the lower panel contains a grid with one row for each segment and one column for each constraint parameter. The following table summarizes the various constraint parameters.

#### Edit Design Requirement Dialog Box Parameters

Parameter	Found in	Description
<b>Time</b>	Upper and lower time response bounds on step and impulse response plots	Defines the time range of a segment within a constraint/requirement.
<b>Amplitude</b>	Upper and lower time response bounds on step and impulse response plots	Defines the beginning and ending amplitude of a constraint segment.
<b>Slope (1/s)</b>	Upper and lower time response bounds	Defines the slope, in 1/s, of a constraint segment. It is an alternative method of specifying the magnitude values. Entering a new <b>Slope</b> value changes any previously defined magnitude values.
<b>Final value</b>	Step response bounds	Defines the input level after the step occurs.
<b>Rise time</b>	Step response bounds	Defines a constraint segment for a particular rise time.
<b>% Rise</b>	Step response bounds	The percentage of the step's range used to describe the rise time.
<b>Settling time</b>	Step response bounds	Defines a constraint segment for a particular settling time.
<b>% Settling</b>	Step response bounds	The percentage of the final value that defines the settling region used to describe the settling time.

**Edit Design Requirement Dialog Box Parameters (Continued)**

<b>Parameter</b>	<b>Found in</b>	<b>Description</b>
<b>% Overshoot</b>	Step response bounds	
<b>% Undershoot</b>	Step response bounds	Defines the constraint segments for a particular percent undershoot.

## Edit Design Requirements

The Edit Design Requirement dialog box allows you to exactly position constraint segments and to edit other properties of these constraints. The dialog box has two main components:

- An upper panel to specify the constraint you are editing
- A lower panel to edit the constraint parameters

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### Edit Design Requirement Dialog Box Parameters

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#### Edit Design Requirement Dialog Box Parameters

Parameter	Found in	Description
Time	Upper and lower time response bounds on step and impulse response plots	Defines the time range of a segment within a constraint/requirement.
Amplitude	Upper and lower time response bounds on step and impulse response plots	Defines the beginning and ending amplitude of a constraint segment.

**Edit Design Requirement Dialog Box Parameters (Continued)**

<b>Parameter</b>	<b>Found in</b>	<b>Description</b>
<b>Slope (1/s)</b>	Upper and lower time response bounds	Defines the slope, in 1/s, of a constraint segment. It is an alternative method of specifying the magnitude values. Entering a new <b>Slope</b> value changes any previously defined magnitude values.
<b>Final value</b>	Step response bounds	Defines the input level after the step occurs.
<b>Rise time</b>	Step response bounds	Defines a constraint segment for a particular rise time.
<b>% Rise</b>	Step response bounds	The percentage of the step's range used to describe the rise time.
<b>Settling time</b>	Step response bounds	Defines a constraint segment for a particular settling time.
<b>% Settling</b>	Step response bounds	The percentage of the final value that defines the settling region used to describe the settling time.
<b>% Overshoot</b>	Step response bounds	
<b>% Undershoot</b>	Step response bounds	Defines the constraint segments for a particular percent undershoot.

## Specify Frequency-Domain Design Requirements

### In this section...

“Specify Lower Bounds on Gain and Phase Margin” on page 5-17

“Specify Piecewise-Linear Lower and Upper Bounds on Frequency Response” on page 5-19

“Specify Bound on Closed-Loop Peak Gain” on page 5-21

“Specify Lower Bound on Damping Ratio” on page 5-23

“Specify Upper and Lower Bounds on Natural Frequency” on page 5-25

“Specify Upper Bound on Approximate Settling Time” on page 5-27

“Specify Piecewise-Linear Upper and Lower Bounds on Singular Values” on page 5-29

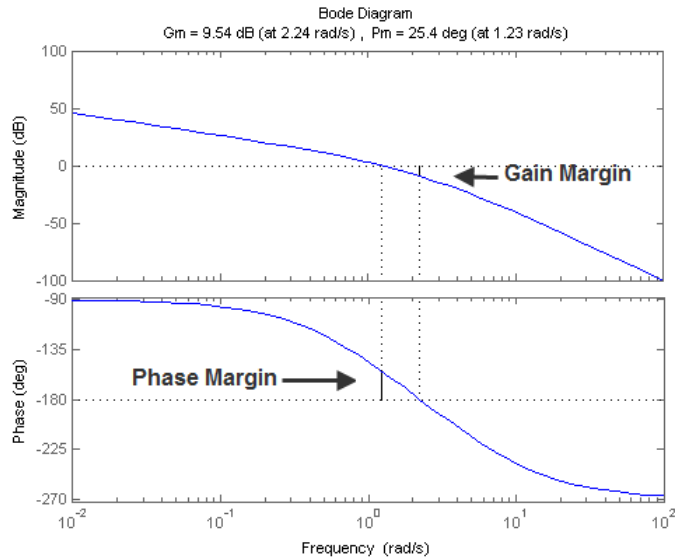
“Specify Step Response Characteristics” on page 5-32

“Specify Custom Requirements” on page 5-35

### Specify Lower Bounds on Gain and Phase Margin

To specify lower bounds on the gain and phase margin of a linear system:

- 1** In the Design Optimization tool, select **Gain and Phase Margin** in the **New** list. A window opens where you specify lower bounds on the gain and phase margin of your linear system.
- 2** Specify a requirement name in **Name**.
- 3** Specify bounds on the gain margin or phase margin, or both.



- **Gain margin** — Amount of gain increase or decrease required to make the loop gain unity at the frequency where the phase angle is  $-180^\circ$ .
- **Phase margin** — Amount of phase increase or decrease required to make the phase angle  $-180^\circ$  when the loop gain is 1.0

To specify a lower bound on the gain margin or phase margin, or both, select the corresponding check box and enter the lower bound value.


- 4** In the **Select Systems to Bound** section, select the linear systems to which this requirement applies.

Linear systems are defined by snapshot times at which the model is linearized and sets of linearization I/O points defining the system inputs and outputs.

- Specify the simulation time at which the model is linearized using the **Snapshot Times** box. For multiple simulation snapshot times, specify a vector.
- Select the linearization input/output set from the **Linearization I/O** area.



If you have already created a linearization input/output set, it will appear in the list. Select the corresponding check box.

If you have not created a linearization input/output set, click  to open the Create linearization I/O set dialog box.

For more information on using this dialog box, see “Create Linearization I/O Sets” on page 3-82.

For more information on linearization, see “What Is Linearization?”.

#### 5 Click **OK**.

A variable with the specified requirement name appears in the **Design Optimization Workspace**. A graphical display of the requirement also appears in the Design Optimization tool window.

#### 6 (Optional) In the graphical display, you can:

- “Move Constraints Graphically” on page 3-22
- “Position Constraints Exactly” on page 3-23


Alternatively, you can use the Check Gain and Phase Margins block to specify bounds on the gain and phase margin. (Requires Simulink Control Design.)

## Specify Piecewise-Linear Lower and Upper Bounds on Frequency Response

To specify upper or lower bounds on the magnitude of a system response:

- 1 In the Design Optimization tool, select **Bode Magnitude** in the **New** list. A window opens where you specify the lower or upper bounds on the magnitude of the system response.
- 2 Specify a requirement name in the **Name** box.
- 3 Specify the requirement type using the **Type** list.
- 4 Specify the edge start and end frequencies and corresponding magnitude in the **Frequency** and **Magnitude** columns.

**5** Insert or delete bound edges.

Click  to specify additional bound edges.


Select a row and click  to delete a bound edge.

**6** In the **Select Systems to Bound** section, select the linear systems to which this requirement applies.

Linear systems are defined by snapshot times at which the model is linearized and sets of linearization I/O points defining the system inputs and outputs.

- a** Specify the simulation time at which the model is linearized using the **Snapshot Times** box. For multiple simulation snapshot times, specify a vector.
- b** Select the linearization input/output set from the **Linearization I/O** area.

If you have already created a linearization input/output set, it will appear in the list. Select the corresponding check box.

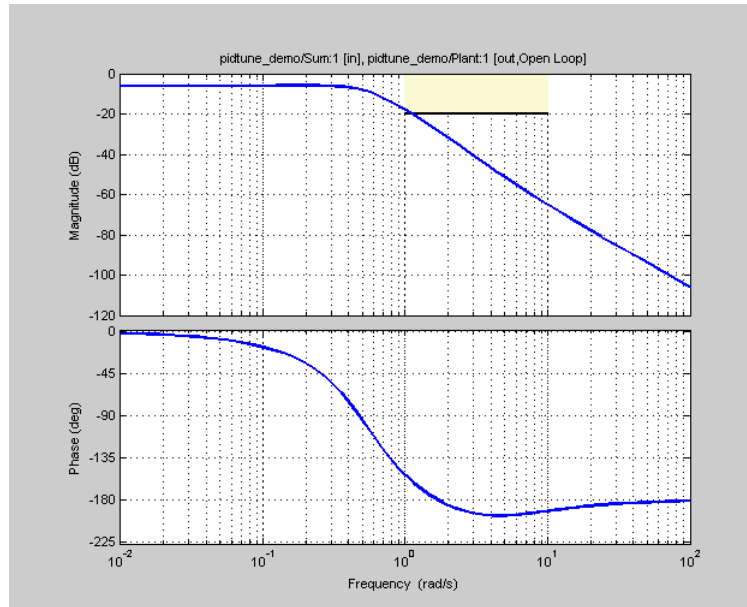
If you have not created a linearization input/output set, click  to open the Create linearization I/O set dialog box.

For more information on using this dialog box, see “Create Linearization I/O Sets” on page 3-82.

For more information on linearization, see “What Is Linearization?”.

**7** Click **OK**.

A new variable with the specified name appears in the **Design Optimization Workspace** of the Design Optimization tool window. A graphical display of the requirement also appears in the Design Optimization tool window.



**8** (Optional) In the graphical display, you can:

- “Move Constraints Graphically” on page 3-22
- “Position Constraints Exactly” on page 3-23

Alternatively, you can use the Check Bode Characteristics block to specify bounds on the magnitude of the system response. (Requires Simulink Control Design.)

## Specify Bound on Closed-Loop Peak Gain

To specify an upper bound on the closed-loop peak response of a system:


- 1** In the Design Optimization tool, select **Closed-Loop Peak Gain** in the **New** list. A window opens where you specify an upper bound on the closed-loop peak gain of the system.
- 2** Specify a requirement name in the **Name** box.

- 3** Specify the upper bound on the closed-loop peak gain in the **Closed-Loop peak gain** box.
- 4** In the **Select Systems to Bound** section, select the linear systems to which this requirement applies.

Linear systems are defined by snapshot times at which the model is linearized and sets of linearization I/O points defining the system inputs and outputs.

- a** Specify the simulation time at which the model is linearized using the **Snapshot Times** box. For multiple simulation snapshot times, specify a vector.
- b** Select the linearization input/output set from the **Linearization I/O** area.

If you have already created a linearization input/output set, it will appear in the list. Select the corresponding check box.

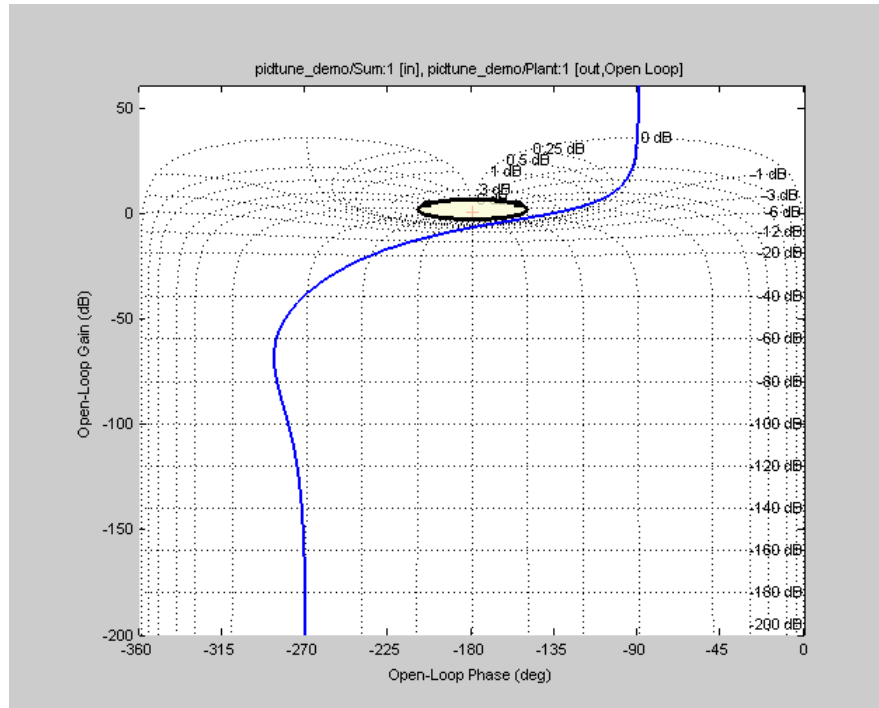
If you have not created a linearization input/output set, click  to open the Create linearization I/O set dialog box.

For more information on using this dialog box, see “Create Linearization I/O Sets” on page 3-82.

For more information on linearization, see “What Is Linearization?”.

- 5** Click **OK**.

A new variable with the specified name appears in the **Design Optimization Workspace** of the Design Optimization tool window. A graphical display of the requirement also appears in the Design Optimization tool window.



6 (Optional) In the graphical display, you can:

- “Move Constraints Graphically” on page 3-22
- “Position Constraints Exactly” on page 3-23

Alternatively, you can use the Check Nichols Characteristics block to specify bounds on the magnitude of the system response. (Requires Simulink Control Design.)

## Specify Lower Bound on Damping Ratio

To specify a lower bound on the damping ratio of the system:


- 1 In the Design Optimization tool, select **Damping Ratio** in the **New** list. A window opens where you specify an upper bound on the damping ratio of the system.

- 2 Specify a requirement name in the **Name** box.
- 3 Specify the lower bound on the damping ratio in the **Damping ratio** box.
- 4 In the **Select Systems to Bound** section, select the linear systems to which this requirement applies.

Linear systems are defined by snapshot times at which the model is linearized and sets of linearization I/O points defining the system inputs and outputs.

- a Specify the simulation time at which the model is linearized using the **Snapshot Times** box. For multiple simulation snapshot times, specify a vector.
- b Select the linearization input/output set from the **Linearization I/O** area.

If you have already created a linearization input/output set, it will appear in the list. Select the corresponding check box.

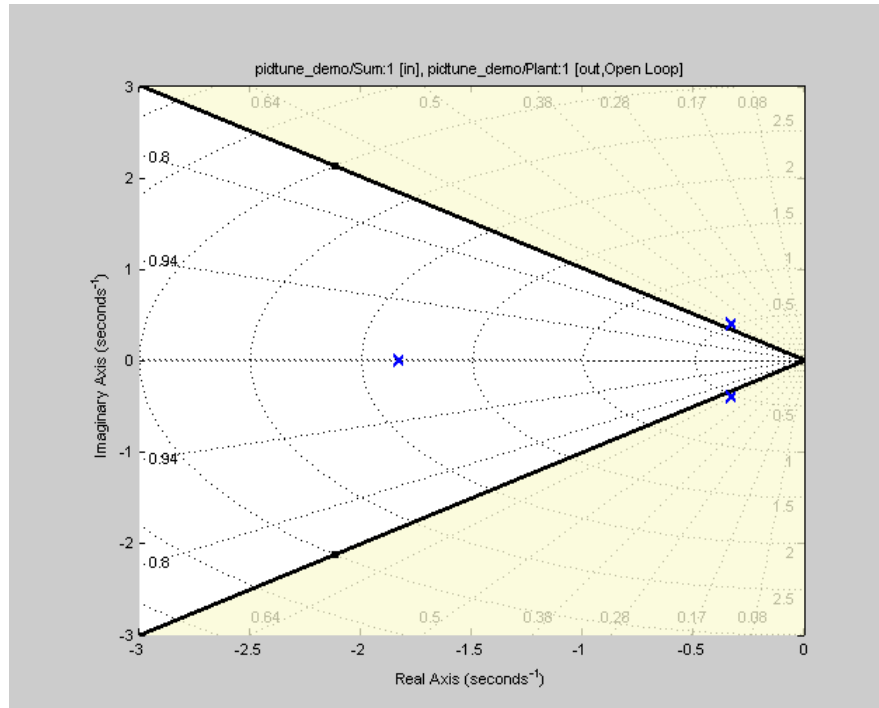
If you have not created a linearization input/output set, click  to open the Create linearization I/O set dialog box.

For more information on using this dialog box, see “Create Linearization I/O Sets” on page 3-82.

For more information on linearization, see “What Is Linearization?”.

- 5 Click **OK**.

A new variable with the specified name appears in the **Design Optimization Workspace** of the Design Optimization tool. A graphical display of the requirement also appears in the Design Optimization tool window.



**6** (Optional) In the graphical display, you can:

- “Move Constraints Graphically” on page 3-22
- “Position Constraints Exactly” on page 3-23

Alternatively, you can use the Check Pole-Zero Characteristics block to specify a bound on the damping ratio. (Requires Simulink Control Design.)

## Specify Upper and Lower Bounds on Natural Frequency

To specify a bound on the natural frequency of the system:


- 1** In the Design Optimization tool, select **Natural Frequency** in the **New** list. A window opens where you specify a bound on the natural frequency of the system.

- 2 Specify a requirement name in the **Name** box.
- 3 Specify a lower or upper bound on the natural frequency in the **Natural frequency** box.
- 4 In the **Select Systems to Bound** section, select the linear systems to which this requirement applies.

Linear systems are defined by snapshot times at which the model is linearized and sets of linearization I/O points defining the system inputs and outputs.

- a Specify the simulation time at which the model is linearized using the **Snapshot Times** box. For multiple simulation snapshot times, specify a vector.
- b Select the linearization input/output set from the **Linearization I/O** area.

If you have already created a linearization input/output set, it will appear in the list. Select the corresponding check box.

If you have not created a linearization input/output set, click  to open the Create linearization I/O set dialog box.

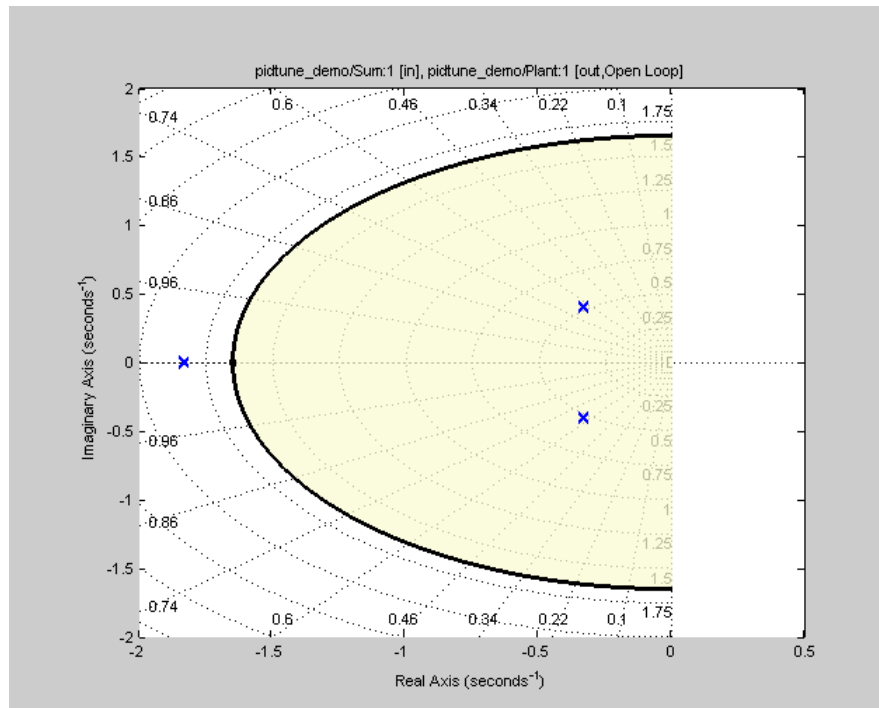
For more information on using this dialog box, see “Create Linearization I/O Sets” on page 3-82.

For more information on linearization, see “What Is Linearization?”.

- 5 Click **OK**.

A new variable with the specified name appears in the **Design Optimization Workspace** of the Design Optimization tool. A graphical display of the requirement also appears in the Design Optimization tool window.





**6** (Optional) In the graphical display, you can:

- “Move Constraints Graphically” on page 3-22
- “Position Constraints Exactly” on page 3-23

Alternatively, you can use the Check Pole-Zero Characteristics block to specify a bound on the natural frequency. (Requires Simulink Control Design.)

## Specify Upper Bound on Approximate Settling Time

To specify an upper bound on the approximate settling time of the system:

- 1** In the Design Optimization tool, select **Settling Time** in the **New** list. A window opens where you specify an upper bound on the approximate settling time of the system.
- 2** Specify a requirement name in the **Name** box.


**3** Specify the upper bound on the approximate settling time in the **Settling time** box.

**4** In the **Select Systems to Bound** section, select the linear systems to which this requirement applies.

Linear systems are defined by snapshot times at which the model is linearized and sets of linearization I/O points defining the system inputs and outputs.

- a** Specify the simulation time at which the model is linearized using the **Snapshot Times** box. For multiple simulation snapshot times, specify a vector.
- b** Select the linearization input/output set from the **Linearization I/O** area.

If you have already created a linearization input/output set, it will appear in the list. Select the corresponding check box.

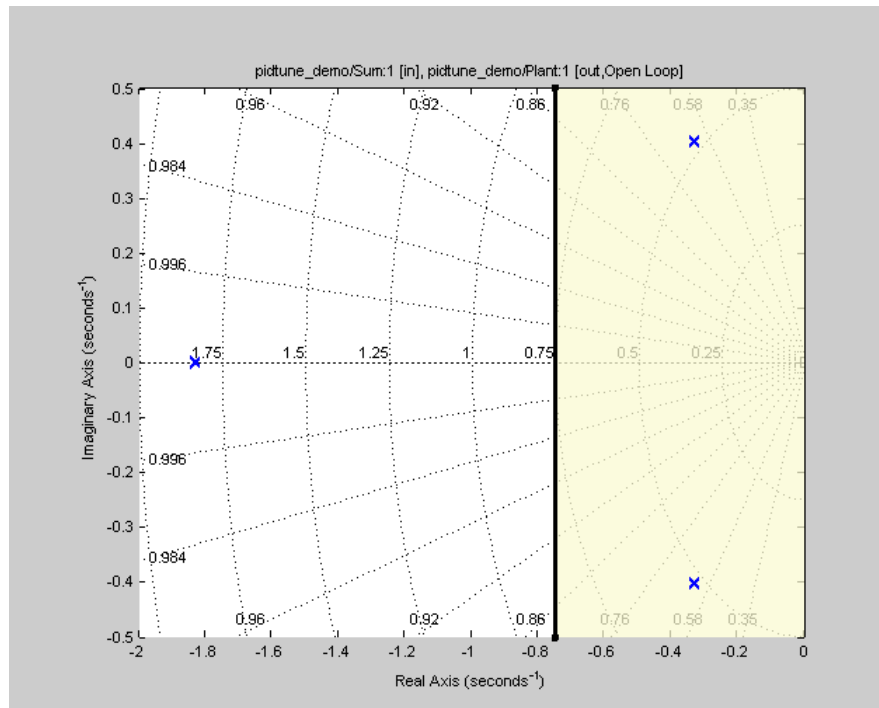
If you have not created a linearization input/output set, click  to open the Create linearization I/O set dialog box.

For more information on using this dialog box, see “Create Linearization I/O Sets” on page 3-82.

For more information on linearization, see “What Is Linearization?”.

**5** Click **OK**.

A new variable with the specified name appears in the **Design Optimization Workspace** of the Design Optimization tool. A graphical display of the requirement also appears in the Design Optimization tool window.



6 (Optional) In the graphical display, you can:


- “Move Constraints Graphically” on page 3-22
- “Position Constraints Exactly” on page 3-23

Alternatively, you can use the Check Pole-Zero Characteristics block to specify the approximate settling time. (Requires Simulink Control Design.)

## Specify Piecewise-Linear Upper and Lower Bounds on Singular Values

To specify piecewise-linear upper and lower bounds on the singular values of a system:

- 1 In the Design Optimization tool, select **Singular Values** in the **New** list. A window opens where you specify the lower or upper bounds on the singular values of the system.
- 2 Specify a requirement name in the **Name** box.
- 3 Specify the requirement type using the **Type** list.
- 4 Specify the edge start and end frequencies and corresponding magnitude in the **Frequency** and **Magnitude** columns, respectively.
- 5 Insert or delete bound edges.

Click  to specify additional bound edges.


Select a row and click  to delete a bound edge.

- 6 In the **Select Systems to Bound** section, select the linear systems to which this requirement applies.

Linear systems are defined by snapshot times at which the model is linearized and sets of linearization I/O points defining the system inputs and outputs.

- a Specify the simulation time at which the model is linearized using the **Snapshot Times** box. For multiple simulation snapshot times, specify a vector.
- b Select the linearization input/output set from the **Linearization I/O** area.

If you have already created a linearization input/output set, it will appear in the list. Select the corresponding check box.

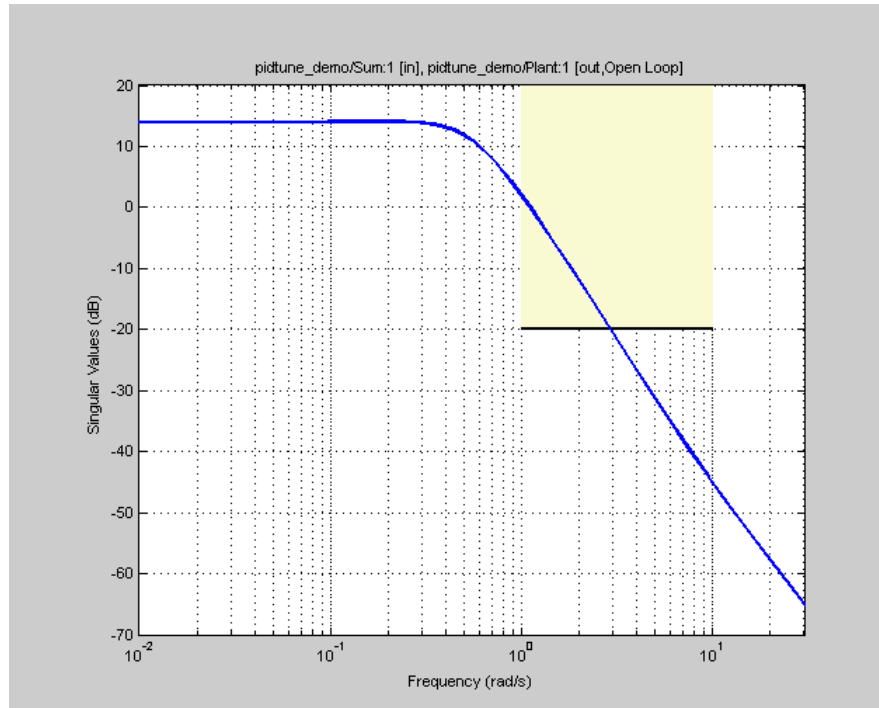
If you have not created a linearization input/output set, click  to open the Create linearization I/O set dialog box.

For more information on using this dialog box, see “Create Linearization I/O Sets” on page 3-82.

For more information on linearization, see “What Is Linearization?”.

**7** Click **OK**.

A new variable with the specified name appears in the **Design Optimization Workspace** of the Design Optimization tool. A graphical display of the requirement also appears in the Design Optimization tool window.

**8** (Optional) In the graphical display, you can:

- “Move Constraints Graphically” on page 3-22
- “Position Constraints Exactly” on page 3-23

Alternatively, you can use the Check Singular Value Characteristics block to specify bounds on the singular value. (Requires Simulink Control Design.)

## Specify Step Response Characteristics

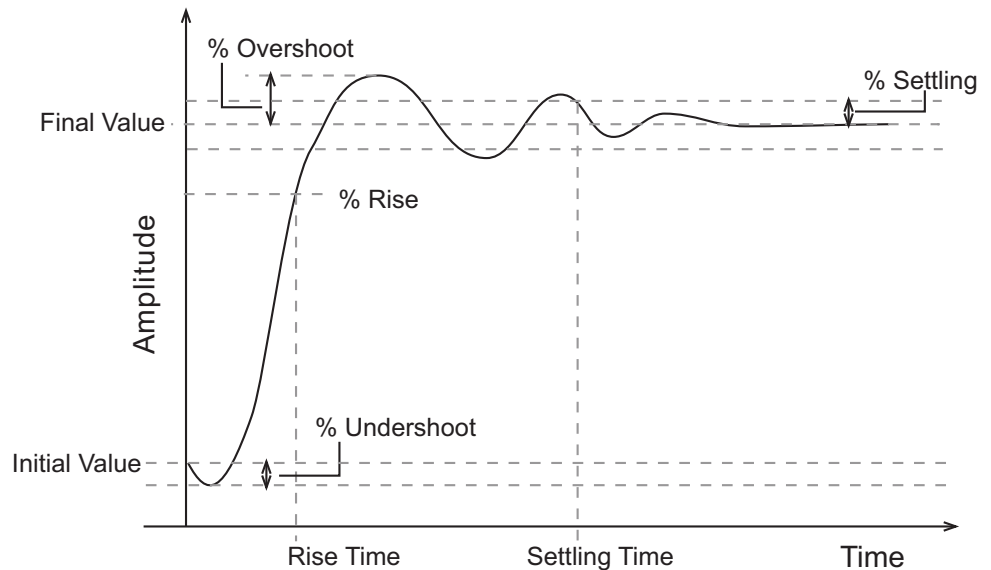
To specify step response characteristics:

- 1 You can apply this requirement to either a signal or a linearization of your model.

In the Design Optimization Tool, click **New**. To apply this requirement to a signal, select the **Step Response Envelope** entry in the **New Time Domain Requirement** section of the **New** list. To apply this requirement to a linearization of your model, select the **Step Response Envelope** entry in the **New Frequency Domain Requirement** section of the **New** list. The latter option requires Simulink Control Design software.

A window opens where you specify the step response requirements on a signal, or system.

- 2 Specify a requirement name in the **Name** box.
- 3 Specify the step response characteristics:



- **Initial value:** Input level before the step occurs
- **Step time:** Time at which the step takes place
- **Final value:** Input level after the step occurs
- **Rise time:** The time taken for the response signal to reach a specified percentage of the step's range. The step's range is the difference between the final and initial values.
- **% Rise:** The percentage used in the rise time.
- **Settling time:** The time taken until the response signal settles within a specified region around the final value. This settling region is defined as the final step value plus or minus the specified percentage of the final value.
- **% Settling:** The percentage used in the settling time.
- **% Overshoot:** The amount by which the response signal can exceed the final value. This amount is specified as a percentage of the step's range. The step's range is the difference between the final and initial values.
- **% Undershoot:** The amount by which the response signal can undershoot the initial value. This amount is specified as a percentage of the step's range. The step's range is the difference between the final and initial values.

#### 4 Specify the signals or systems to be bound.


You can apply this requirement to a model signal or to a linearization of your Simulink model (requires Simulink Control Design software).

- Apply this requirement to a model signal:

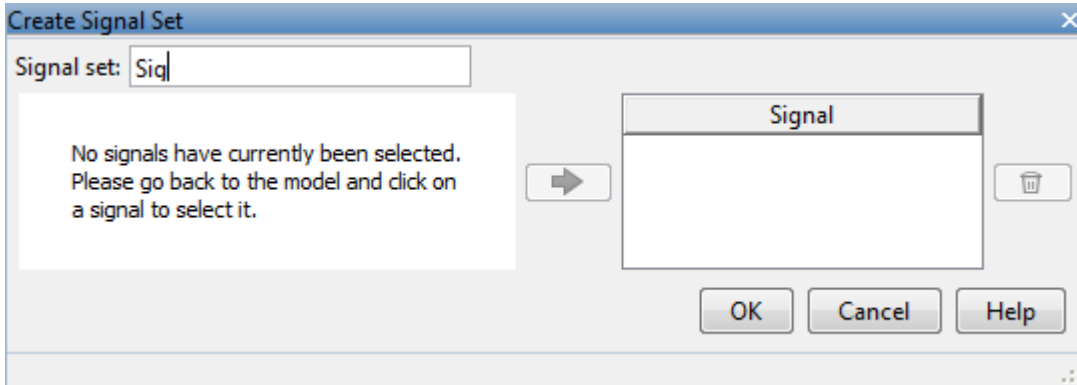
In the **Select Signals to Bound** area, select a logged signal to which you will apply the requirement.

If you have already selected a signal to log, as described in “Specify Signals to Log” on page 3-13, it appears in the list. Select the corresponding check-box.


If you haven't selected a signal to log:

- Click . A window opens where you specify the logged signal.

- b In the Simulink model window, click the signal to which you want to add a requirement.



The window updates and displays the name of the block and the port number where the selected signal is located.

- c Select the signal and click  to add it to the signal set.
- d In the **Signal set** box, enter a name for the selected signal set.

Click **OK**. A new variable, with the specified name, appears in the **Design Optimization Workspace** of the Design Optimization tool window.


- Apply this requirement to a linear system.

Linear systems are defined by snapshot times at which the model is linearized and sets of linearization I/O points defining the system inputs and outputs.

- a Specify the simulation time at which the model is linearized using the **Snapshot Times** box. For multiple simulation snapshot times, specify a vector.
- b Select the linearization input/output set from the **Linearization I/O** area.

If you have already created a linearization input/output set, it will appear in the list. Select the corresponding check box.



If you have not created a linearization input/output set, click  to open the Create linearization I/O set dialog box.

For more information on using this dialog box, see “Create Linearization I/O Sets” on page 3-82.

For more information on linearization, see “What Is Linearization?”.

#### 5 Click **OK**.

A variable with the specified requirement name appears in the **Design Optimization Workspace**. A graphical display of the requirement also appears in the Design Optimization tool window.


Alternatively, you can use the Check Step Response Characteristics block to specify step response bounds for a signal.


#### See Also

“Design Optimization to Meet Step Response Requirements (GUI)”

## Specify Custom Requirements

To specify custom requirements, such as minimizing system energy:

- 1 In the Design Optimization tool, select **Custom Requirement** in the **New** list. A window opens where you specify the custom requirement.
- 2 Specify a requirement name in the **Name** box.
- 3 Specify the requirement type using the **Type** list.
- 4 Specify the name of the function that contains the custom requirement in the **Function** box. The field must be specified as a function handle using @. The function must be on the MATLAB path. Click  to review or edit the function.

If the function does not exist, clicking  opens a template MATLAB file. Use this file to implement the custom requirement. The default function name is myCustomRequirement.

- 5** (Optional) If you want to prevent the solver from considering specific parameter combinations, select the **Error if constraint is violated** check box. Use this option for parameter-only constraints.

During an optimization iteration, the solver evaluates requirements with this option selected first.

- If the constraint is violated, the solver skips evaluating any remaining requirements and proceeds to the next iterate.
- If the constraint is *not* violated, the solver evaluates the remaining requirements for the current iterate. If any of the remaining requirements bound signals or systems, then the solver simulates the model .

For more information, see “Skip Model Simulation Based on Parameter Constraint Violation (GUI)” on page 3-152.

---

**Note** If you select this check box, then do not specify signals or systems to bound. If you *do* specify signals or systems, then this check box is ignored.

---

- 6** (Optional) Specify the signal or system, or both, to be bound.

You can apply this requirement to model signals, or a linearization of your Simulink model (requires Simulink Control Design software), or both.


Click **Select Signals and Systems to Bound (Optional)** to view the signal and linearization I/O selection area.

- Apply this requirement to a model signal:

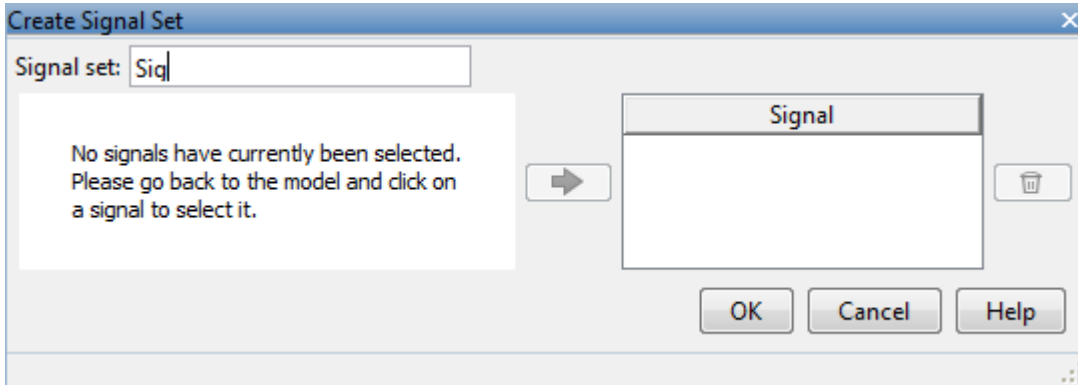
In the **Signal** area, select a logged signal to which you will apply the requirement.

If you have already selected a signal to log, as described in “Specify Signals to Log” on page 3-13, it appears in the list. Select the corresponding check box.


If you have not selected a signal to log:

- Click . A window opens where you specify the logged signal.

- b In the Simulink model window, click the signal to which you want to add a requirement.



The window updates and displays the name of the block and the port number where the selected signal is located.

- c Select the signal and click  to add it to the signal set.
- d In the **Signal set** box, enter a name for the selected signal set.


Click **OK**. A new variable, with the specified name, appears in the **Design Optimization Workspace** of the Design Optimization tool window.

- Apply this requirement to a linear system.

Linear systems are defined by snapshot times at which the model is linearized and sets of linearization I/O points defining the system inputs and outputs.

- a Specify the simulation time at which the model is linearized using the **Snapshot Times** box. For multiple simulation snapshot times, specify a vector.
- b Select the linearization input/output set from the **Linearization I/O** area.

If you have already created a linearization input/output set, it will appear in the list. Select the corresponding check box.

If you have not created a linearization input/output set, click  to open the Create linearization I/O set dialog box. For more information on using this dialog box, see “Create Linearization I/O Sets” on page 3-82.

For more information on linearization, see “What Is Linearization?”.

### 7 Click **OK**.

A new variable, with the specified name, appears in the **Design Optimization Workspace** of the Design Optimization tool. A graphical display of the requirement also appears in the Design Optimization tool window.

### **See Also**

- “Design Optimization to Meet a Custom Objective (GUI)” on page 3-105
- “Design Optimization to Meet Custom Signal Requirements (GUI)” on page 3-122

## Specify Design Variables

Before running the optimization, you must define the model parameters to optimize. These parameters form the *design variables set* for optimization. By tuning these parameters, Simulink Design Optimization software attempts to make the signals meet the requirements.

Simulink Design Optimization software optimizes the response signals of the model by varying the tuned parameters so that the response signals lie within the constraint bound segments or closely match a specified reference signal. The design variables can be scalar, vector, matrix, or an expression that evaluates to one of these values.

To specify the parameters to be tuned using the Design Optimization tool:

- 1 In the **Design Variables Set** list, select **New**.

A window opens where you specify design variables. All model parameters are displayed in this window.

- 2 Select one or more parameter names and click



to add the selected parameters to a design variables set.

---

**Note** You can add the same parameter to multiple design variable sets.

---

- 3 (Optional) Specify design variable settings.

Setting	Description	Default
Variable	The name of the parameter.	Not an editable field
Value	Value of the model parameter. This value is used by the optimization method as the initial value and is modified during optimization.	Current value of the parameter in the model. If you edit this column, click <b>Update model variable values</b> to update the values in the model.

Setting	Description	Default
Minimum	The minimum value or lower bound for the parameter. You can edit this field to provide an alternate minimum value.	- Inf
Maximum	The maximum value or upper bound for the parameter. You can edit this field to provide an alternate maximum value.	Inf
Scale	During optimization, the design variables are scaled, or normalized, by dividing their current value by a scale value. You can edit this field to provide an alternate scaling factor.	1

The check-box indicates whether the parameter is selected as an design variable in the set. Select it if you want this parameter to be tuned during the optimization. Unselect if you do not want this parameter to be tuned during the optimization but you would like to keep it on the list of tuned parameters (for a subsequent optimization).

Expand **Variable Detail** to see the block in the model that contains this parameter.

**4** Click **OK** to create a design variable set.

### Related Examples

- “Specify Independent Parameters to Optimize” on page 3-67
- “Optimize Parameters for Robustness (GUI)” on page 3-162
- “Update Model with Design Variables Set” on page 3-71
- “Export Design Variable Values for Specific Iteration” on page 3-98

## Specify Independent Parameters to Optimize

This example shows how to specify independent parameters, that do not appear explicitly in the model, as optimization parameters.

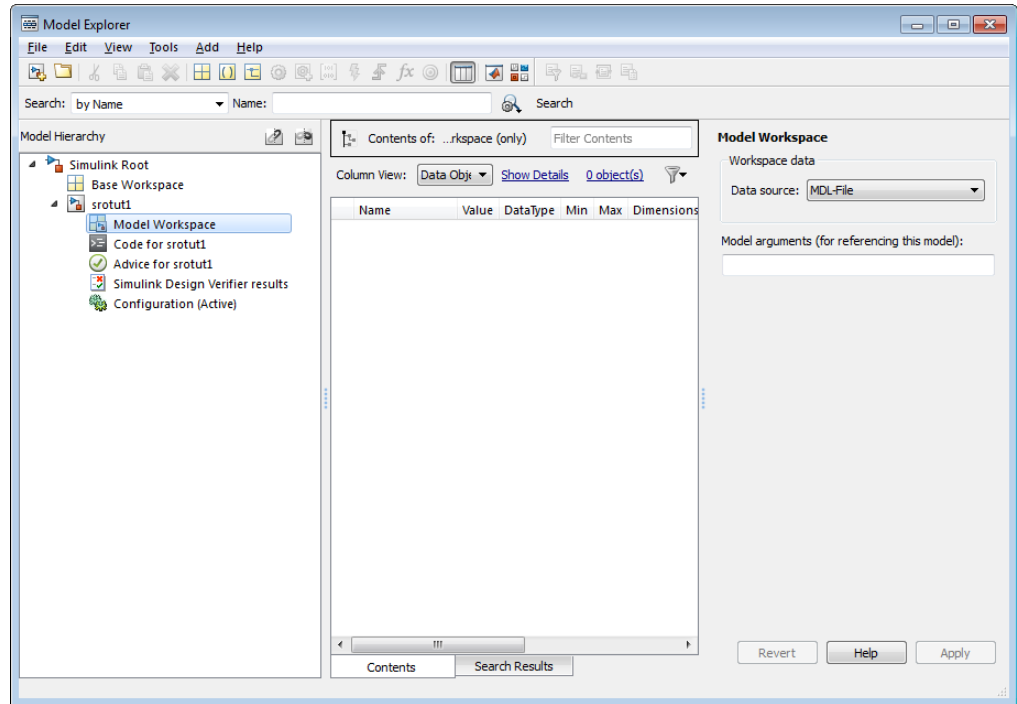
Assume that the parameter `Kint` in the model `srotut1` is related to the parameters `x` and `y` according to the relationship  $Kint=x+y$ . Also assume that the initial values of `x` and `y` are 1 and -0.7, respectively. To tune `x` and `y` instead of `Kint`, first define these parameters in the model workspace. To do this,

**1** Open the Simulink model.

```
open_system('srotut1')
```

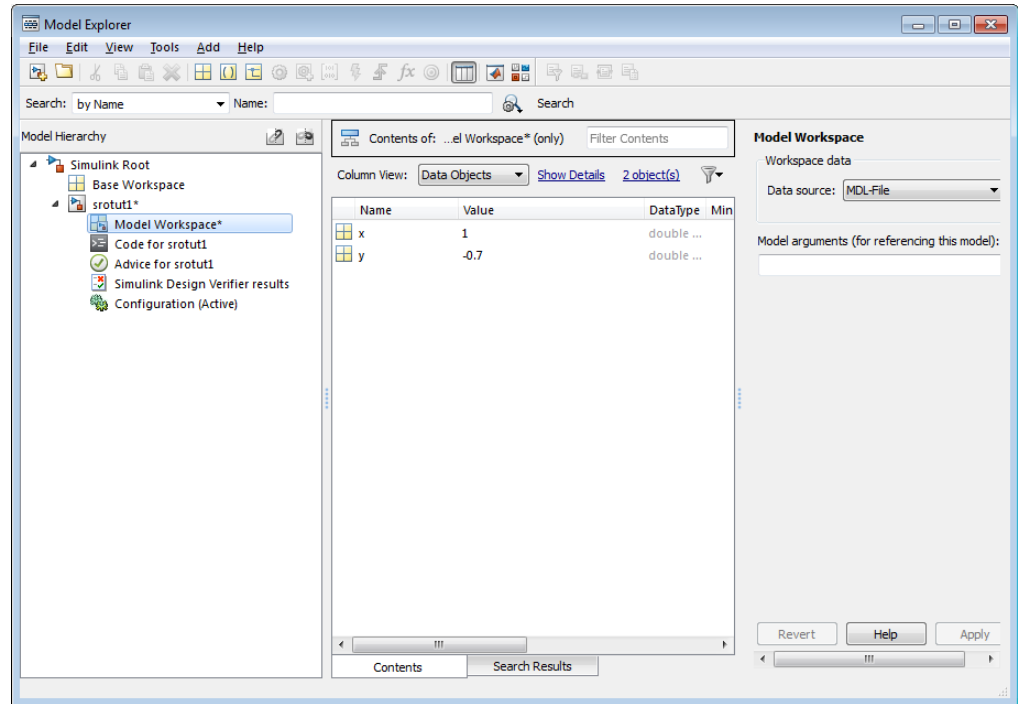
**2** Add the independent parameters to the model workspace, along with their initial values.

- Select **View > Model Explorer** from the `srotut1` window to open the Model Explorer window.
- In the Model Hierarchy tree, select `srotut1 > Model Workspace`.



- Select **Add > MATLAB Variable** to add a new variable to the model workspace. A new variable with a default name Var appears in the **Name** column.
  - Double-click Var to make it editable and change the variable name to x. Edit the initial **Value** to 1.
  - Repeat steps 3 and 4 to add a variable y with an initial value of -0.7.
- The Model Explorer window resembles the following figure.





**3** Define a Simulation Start function that runs before each simulation of the model. This Simulation Start function defines the relationship between the dependent parameters in the model and the independent parameters in the model workspace.

- In the srotut1 model window, select **File > Model Properties > Model Properties**.
- In the Model Properties window, click the **Callbacks** tab.
- To enter a Simulation start function, select **StartFcn**, and type the name of a new function. For example, type `srotut1_start` in the **Simulation start function** panel. Then, click **OK**.
- Create a MATLAB file named `srotut1_start`.

The content of the file defines the relationship between the parameters in the model and the parameters in the workspace. For this example, the content resembles the following:

```
wks = get_param(gcs, 'ModelWorkspace')
x = wks.evalin('x')
y = wks.evalin('y')
Kint = x+y;
```

---

**Note** You must first use `get_param` to get the variables independent variables, `x` and `y`, from the model workspace. Then define the dependent variable, `Kint`, in terms of the independent variables.

---

When you add a new design or uncertain parameter, `x` and `y` appear in the dialog box.

---

**Caution** Avoid adding independent parameters together with their corresponding dependent parameters to the lists of tuned and uncertain parameters. Otherwise, the optimization could give incorrect results. For example, when a parameter `c` depends on the parameters `a` and `b` avoid adding all three parameters to the lists.

---

### Related Examples

- “Specify Design Variables” on page 3-65

## Update Model with Design Variables Set

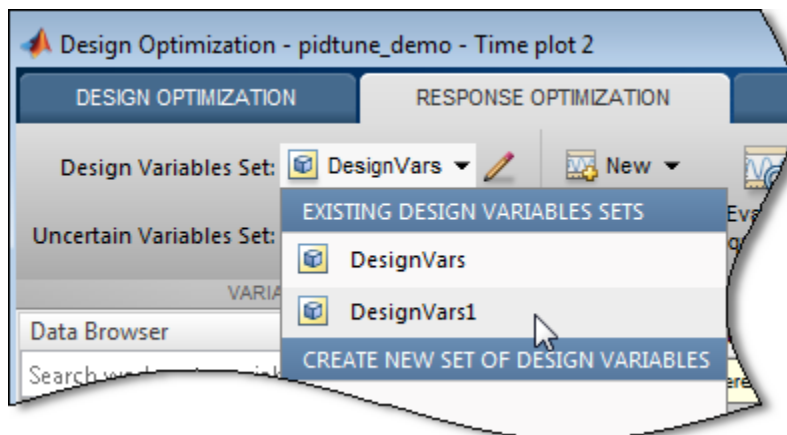
This example shows how to update a model with a set of design variables.

Open the Simulink model and load the preconfigured Design Optimization tool session.

```
load('pidtune_demo_sdoession_update_dv.mat')
sdotool(SDOSessionData)
```

The Design Optimization tool opens and loads the preconfigured session. In the **Design Optimization Workspace**, DesignVars1 is a set of tuned design variables.

In the **Design Variables Set** list, select the design variable set, DesignVars1.

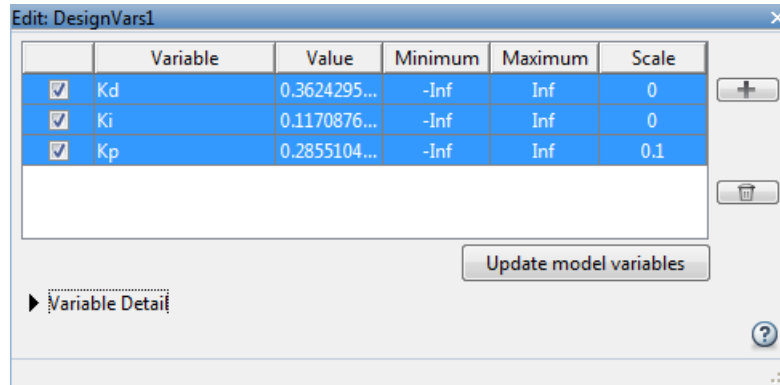


Open the Edit dialog box.

Click  for the **Design Variable Set** list.

Select the variables you want to update in the model.

For this example, select Kd, Ki, and Kp.



Click **Update model variables**.

Plot the model response.

In the **Response Optimization** tab, click **Plot Current Response**.

## Related Examples

- “Export Design Variable Values for Specific Iteration” on page 3-98

## General Options

### In this section...

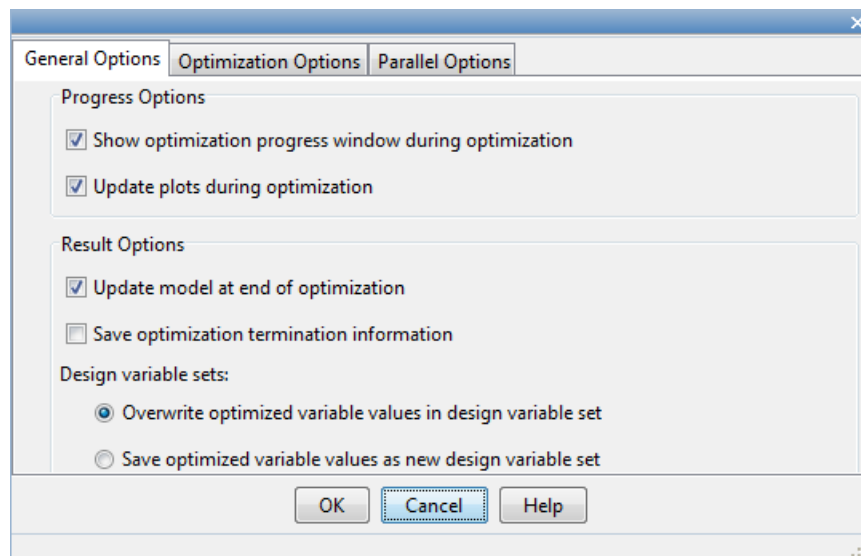
“Accessing General Options” on page 3-73

“Progress Options” on page 3-73

“Result Options” on page 3-74

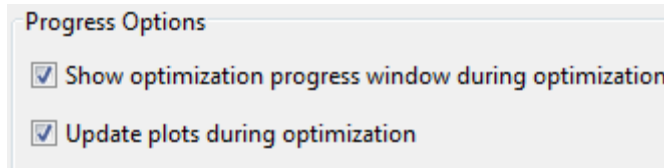
## Accessing General Options

You can set optimization progress and result options. To set these options, click **Options** in the Design Optimization tool. A window opens. Select the **General Options** tab.



## Progress Options

You can specify options related to optimization progress using the options in the **Progress Options** area.



- **Show optimization progress window during optimization**

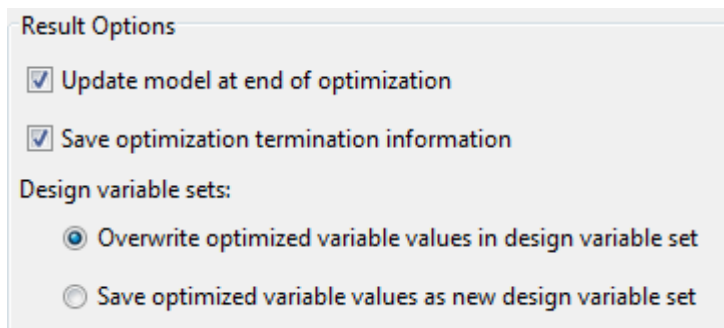
Opens an optimization progress window during optimization. The window displays information such as constraint violations and cost function if **Display level** is **Iteration**. The window is updated at the end of the optimization with the termination information such as whether the optimization converged.

- **Update plots during optimization**

Updates model response and design variable plots at each optimization iteration.

## Result Options

You can specify options for optimization results in the **Result Options** area.



- **Update model at end of optimization**

Updates optimized parameter values in the Simulink model after the optimization terminates.

- **Save optimization termination information**

Saves termination information returned by the optimization solver as a variable named `info` in the **Design Optimization Workspace**. `info` is a structure with one or more of the following fields:

- `F` — Optimized cost (objective) value.
- `Cleq` — Optimized nonlinear inequality constraint violations.  
The field appears if the optimization problem includes a nonlinear inequality constraint.  
The value is a  $m \times 1$  vector. Positive values indicate that the constraint has not been satisfied. Check `exitflag` to confirm that the optimization succeeded.
- `Ceq` — Optimized nonlinear equality constraint violations.  
The field appears if the optimization problem includes a nonlinear equality constraint.  
The value is a double  $r \times 1$  vector. Any nonzero values indicate that the constraint has not been satisfied. Check `exitflag` to confirm that the optimization succeeded.
- `Gradients` — Cost and constraint gradients at the optimized parameter values. See “How the Optimization Algorithm Formulates Minimization Problems” on page 3-3 on how the solver computes gradients.  
This field appears if the solver specified in the `Method` property of `sdo.OptimizeOptions` computes gradients.  
The value is a structure.
- `exitflag` — Integer identifying the reason the algorithm terminated. See `fmincon`, `patternsearch` and `fminsearch` for a list of the values and the corresponding termination reasons.
- `iterations` — Number of optimization iterations
- `SolverOutput` — A structure with solver-specific output information. The fields of this structure depends on the optimization solver specified in the `Method` property of `sdo.OptimizeOptions`. See `fmincon`, `patternsearch` and `fminsearch` for a list of solver outputs and their description.

- **Stats** — A structure that contains statistics collected during optimization, such as start and end times, number of function evaluations and restarts.
- **Design variable sets**
  - **Overwrite optimized variable values in design variable set**


Overwrites the optimized model parameter values in the design variable set variable used in the optimization. You can see the updated values in the Value field.

```
▼ Design Optimization Workspace
Name ▲      Value
DesignVars  <3x1 para...

▼ Variable Preview

DesignVars(1,1) =
    Name: 'Kd'
    Value: 0
    Minimum: 0
    Maximum: Inf
    Free: 1
    Scale: 1
    Info: [1x1 struct]
```

- **Save optimized variable values as new design variable set**

Creates a new variable in the **Design Optimization Workspace** that contains the optimized parameter values. To update the model with the optimized parameter values, select the variable in the **Design Variables Set** list. Open the Edit dialog box by clicking . Select the parameters of interest and click **Update model variables**.



## Optimization Options

### In this section...

“Accessing Optimization Options” on page 3-77

“Selecting Optimization Methods” on page 3-78

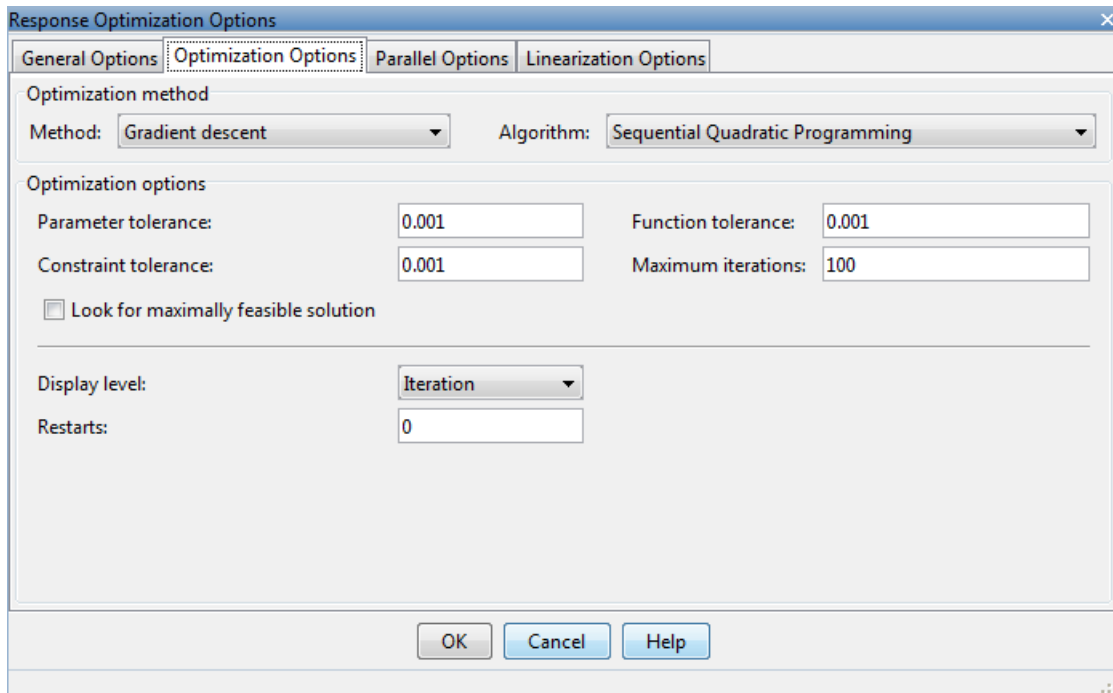
“Selecting Optimization Termination Options” on page 3-79

“Selecting Additional Optimization Options” on page 3-80

## Accessing Optimization Options

You can set several options for the optimization. These options include the optimization methods and the tolerances the methods use.

To set optimization options, click **Options** in the Design Optimization tool. A window opens. Select the **Optimization Options** tab.



## Selecting Optimization Methods

Both the **Method** and **Algorithm** options in the **Optimization method** area define the optimization method.

The screenshot shows a dialog box titled "Optimization method". It contains two dropdown menus. The first is labeled "Method:" and is set to "Gradient descent". The second is labeled "Algorithm:" and is set to "Sequential Quadratic Programming".

The choices for the **Method** option are:

- **Gradient descent** (default) — Uses the Optimization Toolbox function `fmincon` to optimize the response signal subject to the constraints.

The **Algorithm** options for **Gradient descent** are:

Algorithm Option	Learn More
Sequential Quadratic Programming (default)	“fmincon SQP Algorithm” in the Optimization Toolbox documentation.
Active-Set	“fmincon Active Set Algorithm” in the Optimization Toolbox documentation.
Interior-Point	“fmincon Interior Point Algorithm” in the Optimization Toolbox documentation.
Trust-Region-Reflective	“fmincon Trust Region Reflective Algorithm” in the Optimization Toolbox documentation.

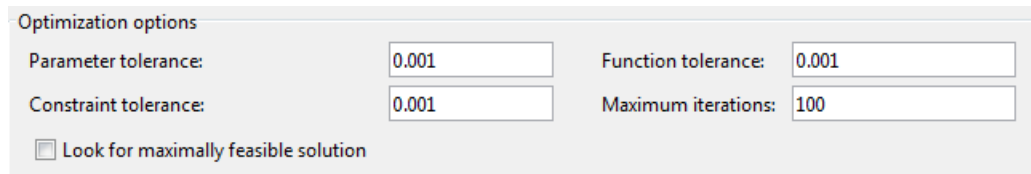
- **Pattern search** — Uses the Global Optimization Toolbox function `patternsearch`, an advanced direct search method, to optimize the response. This option requires the Global Optimization Toolbox.
- **Simplex search** — Uses the Optimization Toolbox function `fminsearch`, a direct search method, to optimize the response. **Simplex search** is

most useful for simple problems and is sometimes faster than Gradient descent for models that contain discontinuities.

For more information on the problem formulations for each optimization method, see “How the Optimization Algorithm Formulates Minimization Problems” on page 3-3.

## Selecting Optimization Termination Options

Use the **Optimization options** panel to specify when you want the optimization to terminate.



The screenshot shows a panel titled "Optimization options" with the following settings:

Parameter tolerance:	0.001	Function tolerance:	0.001
Constraint tolerance:	0.001	Maximum iterations:	100

Look for maximally feasible solution

- **Parameter tolerance:** The optimization terminates when successive parameter values change by less than this number. For more details, refer to the discussion of the parameter TolX in the reference page for the Optimization Toolbox function `fmincon`.
- **Constraint tolerance:** This number determines the maximum limit by which the constraints can be violated, and still allow a successful convergence.
- **Function tolerance:** The optimization terminates when successive function values are less than this value. Changing the default **Function tolerance** value is only useful when you are tracking a reference signal or using the Simplex search method. For more details, refer to the discussion of the parameter TolFun in the reference page for the Optimization Toolbox function `fmincon`.
- **Maximum iterations:** The maximum number of iterations allowed. The optimization terminates when the number of iterations exceeds this number.
- **Look for maximally feasible solution:** When selected, the optimization continues after it has found an initial, feasible solution, until it finds a maximally feasible, optimal solution. When this option is unselected, the

optimization terminates as soon as it finds a solution that satisfies the constraints and the resulting response signal sometimes lies very close to the constraint segment. In contrast, a maximally feasible solution is typically located further inside the constraint region.

---

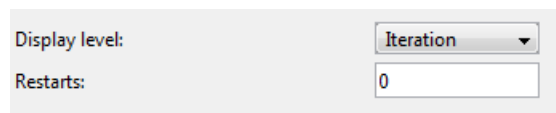
**Note** If selected, the software ignores this option when tracking a reference signal.

---

By varying these parameters you can force the optimization to continue searching for a solution or to continue searching for a more accurate solution.

## Selecting Additional Optimization Options

At the bottom of the **Optimization Options** panel is a group of additional optimization options.



The screenshot shows a light gray panel with two controls. The first control is labeled 'Display level:' and has a dropdown menu with 'Iteration' selected. The second control is labeled 'Restarts:' and has a text input field containing the number '0'.

- “Display Level” on page 3-80
- “Restarts” on page 3-81

## Display Level

The **Display level** option specifies the form of the output that appears in the Optimization Progress window. The options are:

- **Iterations** (default) — Displays information after each iteration
- **Off** — Turns off all output display
- **Notify** — Displays output only if the function does not converge
- **Final** — Displays only the final output

For more information on the type of iterative output that appears for the method you selected in **Method**, see the discussion of output for the corresponding function.

<b>Method</b>	<b>Function</b>	<b>Output Information</b>
Gradient descent	fmincon	fmincon section of “Function-Specific Headings” in the Optimization Toolbox documentation
Simplex search	fminsearch	fminsearch section of “Function-Specific Headings” in the Optimization Toolbox documentation
Pattern search	patternsearch	“Display to Command Window Options” in the Global Optimization Toolbox documentation

### **Restarts**

In some optimizations, the Hessian may become ill-conditioned and the optimization does not converge. In these cases, it is sometimes useful to restart the optimization after it stops, using the endpoint of the previous optimization as the starting point for the next one. To automatically restart the optimization, indicate the number of times you want to restart in this field.

## Create Linearization I/O Sets

This example shows how to create a linearization input/output set using the Design Optimization Tool.

You create a linearization input/output set using the Create Linearization I/O Set dialog box. This dialog box may be accessed in two ways:

- In the Design Optimization tool, select **Linearization I/Os** in the **New** drop-down list.
- In a requirement dialog box, in the **Select Systems to Bound** area, click

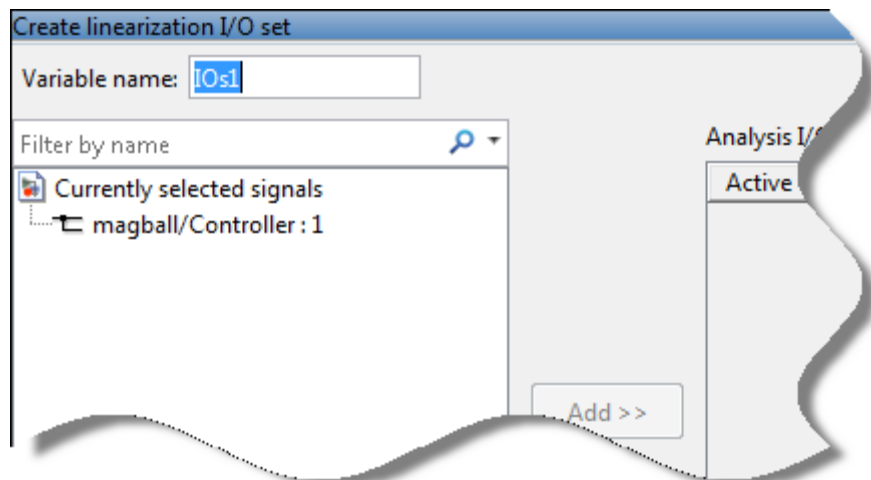


### Create Linearization I/O Set

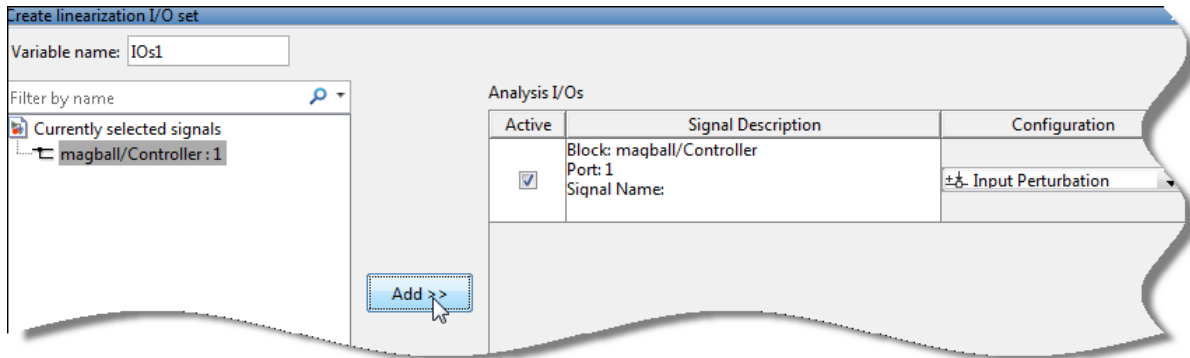
To create a new linearization I/O set:

- 1 In your Simulink model, select a signal that you want to define as a linearization input or output point.

The selected signal appears in the Create linearization I/O set dialog box under **Currently selected signals**.



- 2 In the Create linearization I/O set dialog box, click the signal name under Currently selected signals.
- 3 Click **Add**. The signal appears in the list of Analysis I/Os.



- 4 Select the linearization point type from the **Configuration** drop-down list. For example:
  - If you want the selected signal to be a linearization output point, select **Output Measurement**.
  - If you want the signal to be an open-loop output point, select **Open-loop Output**.
- 5 Repeat steps 1–4 for any other signals you want to define as linearization I/O points.

---

**Tip** To highlight in the Simulink model the blocks that are included in the linearization specified by the current list of Analysis I/Os, click **Highlight**.

---

- 6 After you define all the signals for the I/O set, enter a name for the I/O set in the **Variable name** field located at the top-left of the window.
- 7 Click **OK**.

## Linearization Options

### In this section...

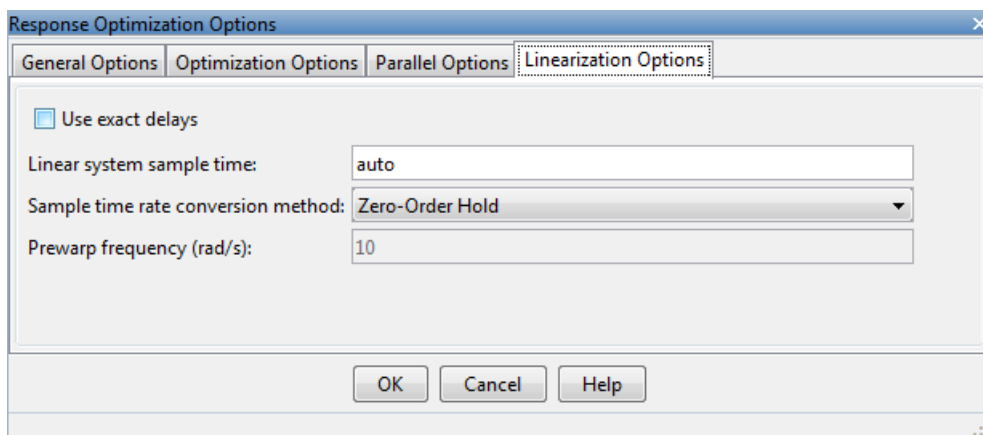
“Accessing Linearization Options” on page 3-84

“Configuring Linearization Options” on page 3-84

### Accessing Linearization Options

If you have Simulink Control Design, you can set several options for linearization. These options include the linearization methods and the sample time of the linear systems.

To set linearization options, click **Options** in the Design Optimization tool. A window opens. Select the **Linearization Options** tab.



### Configuring Linearization Options

#### Models with Time Delays

Simulink Control Design lets you choose whether to linearize models using exact representation or Pade approximation of continuous time delays. How you treat time delays during linearization depends on your nonlinear model.



Simulink blocks that model time delays are:

- Transport Delay block
- Variable Time Delay block
- Variable Transport Delay block
- Delay block
- Unit Delay block

By default, linearization uses Pade approximation for representing time delays in your linear model.

Use Pade approximation to represent time delays when:

- Applying more advanced control design techniques to your linear plant, such as LQR or H-infinity control design.
- Minimizing the time to compute a linear model.

Specify to linearize with exact time delays for:

- Minimizing errors that result from approximating time delays
- PID tuning or loop-shaping control design methods in Simulink Control Design
- Discrete-time models (to avoid introducing additional states to the model)

The software treats discrete-time delays as internal delays in the linearized model. Such delays do not appear as additional states in the linearized model.

**Specify How Delays are Treated.** To specify whether the linearization should approximate delays or use them exactly, set the **Use exact delays** check box appropriately.

### Linearization Sampling Time

To specify the sampling time of the linearized model, use the **Linear system sample time** box. By default, the software chooses the slowest applicable sampling time. Use 0 to specify a continuous-time linear model.

### Linearization Rate Conversion Method

When you linearize models with multiple sample times, such as a discrete controller with a continuous plant, a rate conversion algorithm generates a single-rate linear model. The rate conversion algorithm affects linearization results.

Rate Conversion Method	When to Use
Zero-Order Hold	Use when you need exact discretization of continuous dynamics in the time-domain for staircase inputs.
Tustin	Use when you need good frequency-domain matching between a continuous-time system and the corresponding discretized system, or between an original system and the resampled system.
Tustin with Prewarping	Use when you need good frequency domain matching at a particular frequency between the continuous-time system and the corresponding discretized system, or between an original system and the resampled system.
Upsampling when possible (Zero-Order Hold, Tustin, and Tustin with Prewarping)	Upsample discrete states when possible to ensure gain and phase matching of upsampled dynamics. You can only upsample when the new sample time is an integer multiple of the sampling time of the original system. Otherwise, the software uses an alternate rate conversion method.

## Plots in the Design Optimization Tool

### In this section...

“Adding Plots in Design Optimization Tool” on page 3-87

“Plotting Current Response” on page 3-87

“Plotting Intermediate Steps” on page 3-87

“Modifying Plot Properties” on page 3-88

“Plot Types” on page 3-89

“Export Design Variables and Requirement Values for an Iteration” on page 3-92

### Adding Plots in Design Optimization Tool

To create a new plot or to add to an existing plot in the Design Optimization Tool, choose the variable to plot in the **Data to Plot** list. Then select the plot type using the **Add Plot** list. The **Add Plot** list has entries for the supported plot types for the given plot variable.

### Plotting Current Response

To display the current response, click **Plot Current Response** in the **Response Optimization** tab or the **Figure** tab of the Design Optimization tool. The current response appears as a thick line.

### Plotting Intermediate Steps

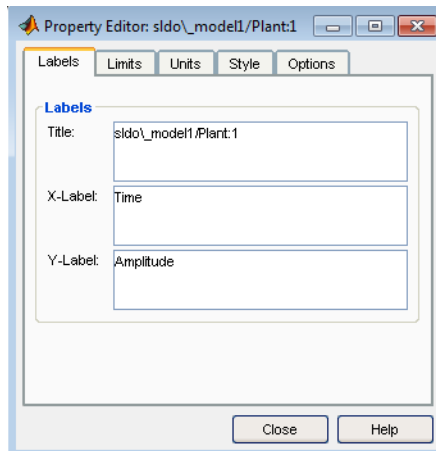
To turn on, or off, the display of the response signal at intermediate steps during the optimization, right-click within the white space in the plot and select **Responses > Show Iteration Responses**. The response at an intermediate step is based on parameter values at that intermediate point in the optimization.

## Modifying Plot Properties

### Modifying Properties of Response Plots

Right-click the white space in a plot and select **Axes Properties** to open the Property Editor dialog box.

This figure shows the Property Editor dialog box for a step response.



In general, you can change the following properties of response plots.

- **Labels** — Titles and X- and Y-labels

To specify new text for plot titles and axis labels, type the new string in the field next to the label you want to change. The label changes immediately as you type, so you can see how the new text looks as you are typing.

- **Limits** — Numerical ranges of the  $x$ - and  $y$ - axes

Default values for the axes limits make sure that the maximum and minimum  $x$  and  $y$  values are displayed. If you want to override the default settings, change the values in the **Limits** pane fields. The **Auto-Scale** check box automatically clears if you click a different field. The new limits appear immediately in the response plot.

To reestablish the default values, select the **Auto-Scale** check box again.

- **Units** — Units where applicable (e.g., rad/s to Hertz). If you cannot customize units, the Property Editor displays that no units are available for the selected plot.
- **Style** — Show a grid, adjust font properties, such as font size, bold and italics, and change the axes foreground color
- **Options** — Change options where applicable. These include peak response, settling time, phase and gain margins, etc. Plot options change with each plot response type. The Property Editor displays only the options that make sense for the selected response plot. For example, phase and gain margins are not available for step responses.

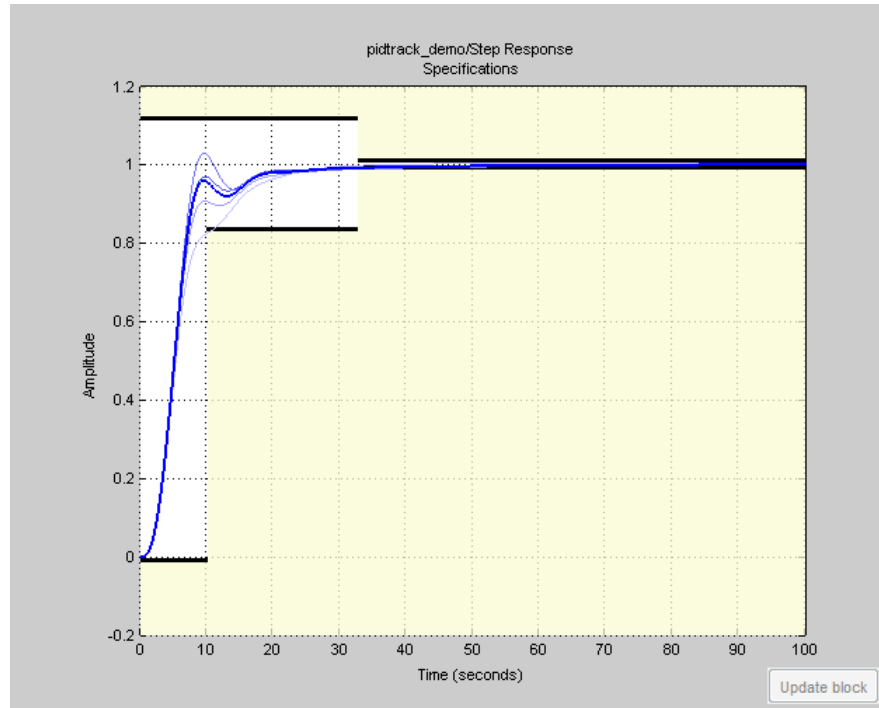
## Plot Types

- “Response Plots” on page 3-89
- “Spider Plots” on page 3-90
- “Iteration Plots” on page 3-91

## Response Plots

You can view model signals and the requirements applied to the signal using a response plot. You can also plot the frequency response of a system (requires Simulink Control Design).

The response plot shows the system response as it varies during optimization. You can also view the uncertain system responses in the plot.



---

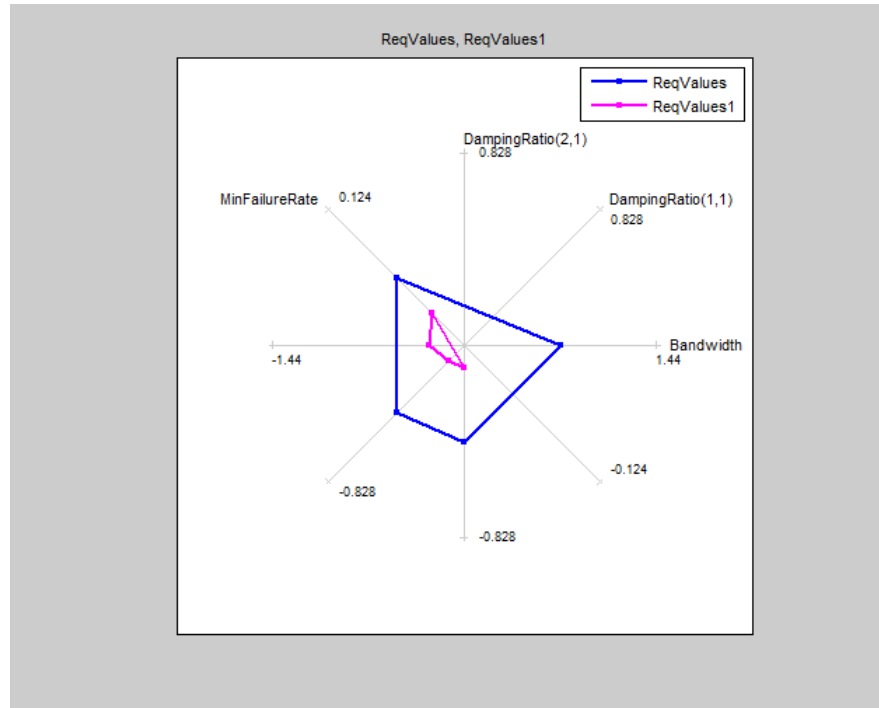
**Tip** To select the responses and systems displayed in a given plot, right-click on the plot and use the **Systems** and **Responses** menu.

---

### Spider Plots

You can compare the values of design variable sets or evaluated requirements using a spider plot.

Spider plots depict multivariate data using an axis for each variable. The various axes are arranged clockwise and have a common intersecting point, as this example shows:




---

**Tip** To view only some of the requirement values in a given plot, right-click on the plot and select the requirements in the **Show** list.

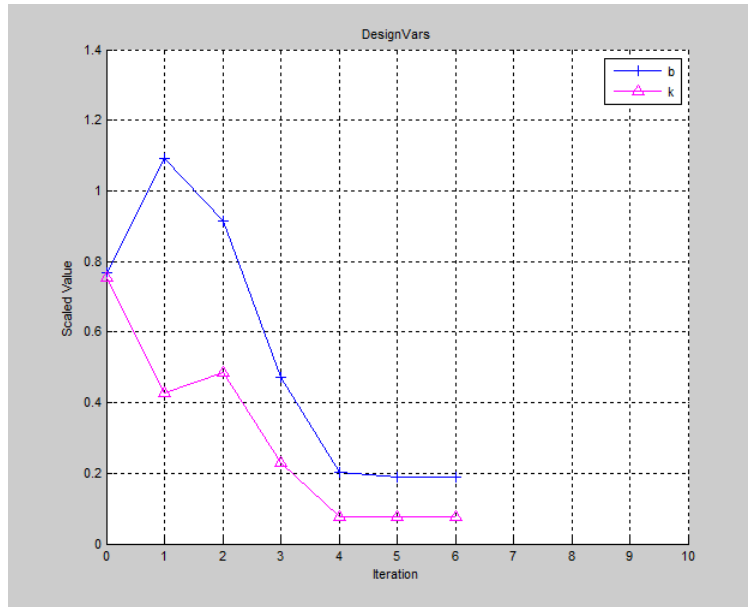
---

For information on using a spider plot to compare design variables sets or evaluated requirements, see “Compare Requirements and Design Variables Using Spider Plot” on page 3-94

### Iteration Plots

You can plot the values of design variables and requirements as they vary during optimization using an iteration plot.

Iteration plots depict the value of the plot variable(s) for each iteration. The x-axis represents the iteration number, as this example shows:



You can export the values of a plotted variable for a given iteration. For more information, see “Export Design Variables and Requirement Values for an Iteration” on page 3-92.

---

**Tip** To view scaled values of the plotted variable(s), right-click on the plot and select **Show scaled values**.

---

## Export Design Variables and Requirement Values for an Iteration

To export the values of design variables or requirements:

- 1 Open the Export Iteration Data dialog box.

Right-click on the iteration plot and select **Export**.

- 2 Specify the plotted variable that you want to export using the **Data to export** list.



- 3 Specify the iteration for which you want to export data in the **Iteration(s) to export** box.

To specify multiple iterations, use a vector of integers. For example, [0 2 5].

- 4 Specify the variable name for the exported data using the **Export to a variable named** box.

- 5 Export the data to the Design Optimization Workspace.

Click **OK**. The exported data variable appears in the **Design Optimization Workspace**.

---

**Note** The iteration number is added as a suffix to the exported data variable name.

---

## Compare Requirements and Design Variables Using Spider Plot

This example shows how to use a spider plot to compare requirement evaluations before and after optimizing the response. You can use a similar procedure to compare the values of sets of design variables.

**Open the Simulink model and load the pre-configured Design Optimization Tool session.**

For this example, which uses a distillation column model, the step response requirements are preconfigured and loaded in the model workspace.

**1** Open the distillation model.

```
sys = 'distillation_demo';  
open_system(sys)
```

**2** Open the Design Optimization Tool.

In the Simulink model window, select **Analysis > Response Optimization**.

Alternatively, click the Response Optimization GUI with preloaded data block in the model and skip the next step.

**3** Load the preconfigured Design Optimization Tool session.

Click the **Design Optimization** tab. In the **Open** drop-down list, select **Open from model workspace**. A window opens where you select the Design Optimization Tool session to load. Select `distillation_optim` and click **OK**.

The preconfigured step response requirements are loaded in the Design Optimization Tool.

**Evaluate the requirement before optimization.**

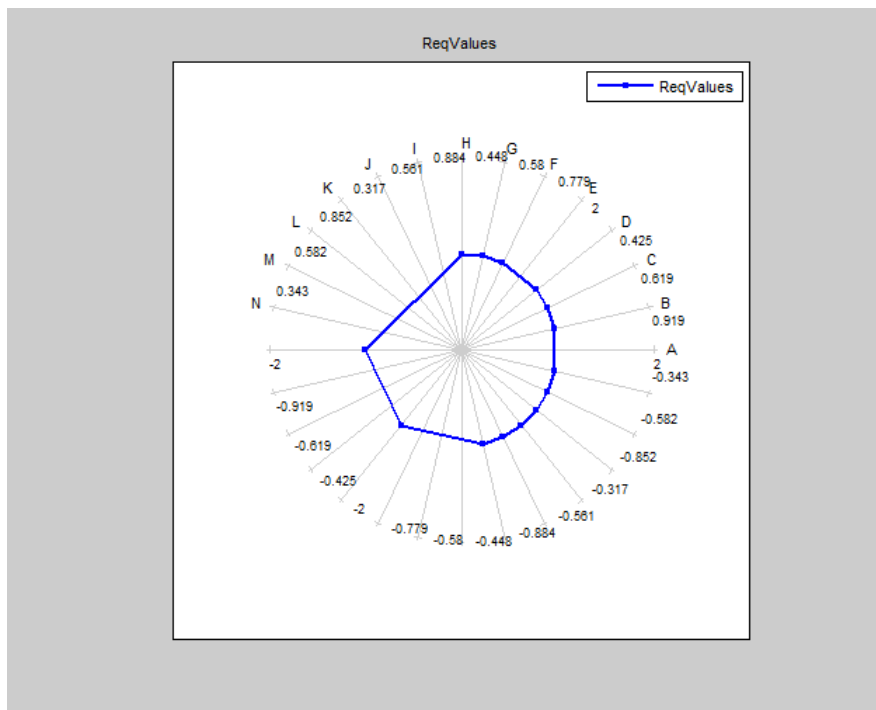
In the **Response Optimization** tab, click **Evaluate Requirements**.

A new variable, ReqValues, containing the evaluation of the requirements appears in the **Design Optimization Workspace**.

When optimizing the model response, you create a set of requirements that it must satisfy. If the requirements are violated, meaning that they evaluate to nonnegative values, the design variables must be optimized. After the optimization, you can compare the original requirement value with the requirement evaluated using the optimized design variable values.

**Plot the requirement value before optimization.**

- 1** In the **Data to Plot** list, select ReqValues.
- 2** In the **Add Plot** list, select Spider plot.



The plot has an axis for each edge-and-signal combination defined in the `distillation_demo/Desired Step Response` check block. Points on each

axis represent the violation for that signal-edge combination and the plot connects these points to form a closed polygon representing the initial design. Note that some points are negative, representing satisfied constraints, and some positive, representing violated constraints.

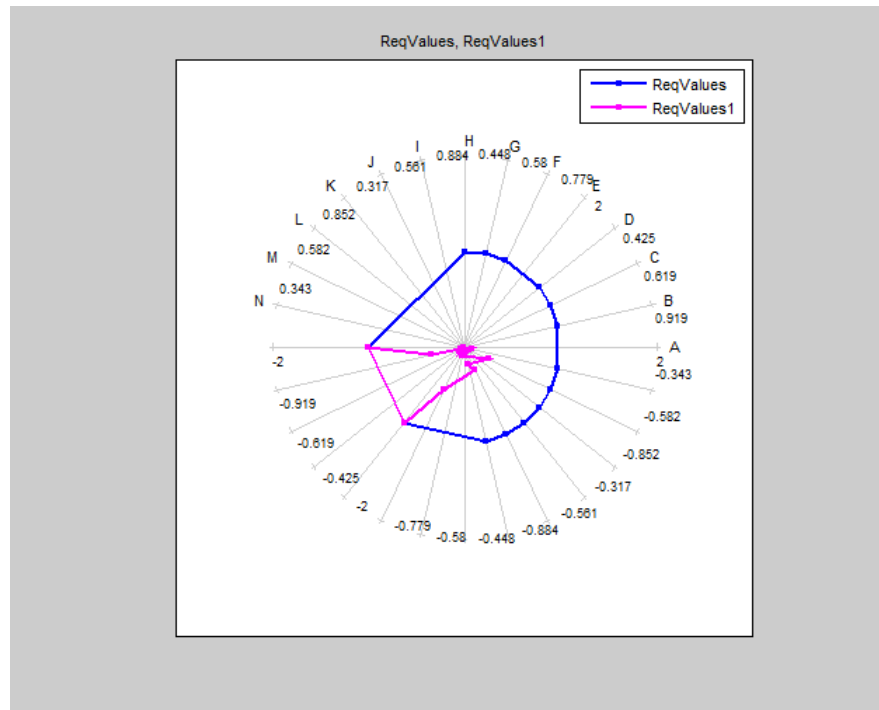
### **Optimize the model.**

Click **Optimize**.

A new variable, ReqValues1, containing the evaluation of the requirements using the optimized design variables appears in the **Design Optimization Workspace**.

### **Compare the requirement values before and after optimization.**

- 1** In the **Data to Plot** list, select ReqValues1.
- 2** In the **Add Plot** list, select Spider plot 1.



The optimized requirement values, ReqValues1, are all negative or zero, indicating that all the constraints are satisfied.

## Concepts

- “Export Design Variable Values for Specific Iteration” on page 3-98

## Export Design Variable Values for Specific Iteration

This example shows how to export the design variable values for a specific optimization iteration.

During optimization, the optimization solver simulates the model using a different set of design variables at each iteration. After the optimization completes, you can export the values for an iteration from the iteration plot of the design variable set.

For this example, load a preconfigured Design Optimization tool session. Optimize the model, and export the design variable set values for the third iteration.

Open the Simulink model and load the preconfigured Design Optimization tool session.

```
load('distillation_demo_sdoession_export_iter_dv.mat')
sdotool(SDOSessionData)
```

The Design Optimization tool opens and loads the preconfigured session. **Iteration Plot 1** is configured to plot the values of DesignVars for each optimization iteration.

Click **Optimize**.

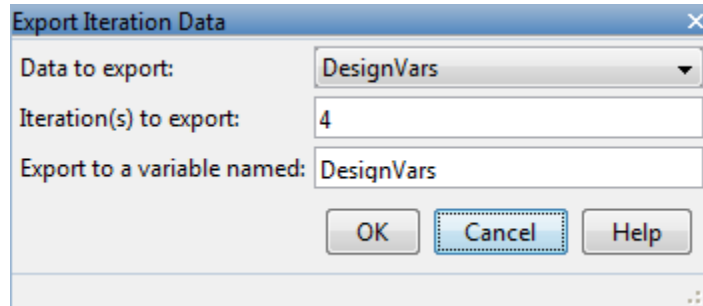
The optimization completes after four iterations.

Select the iteration plot of the design variable set.

Click **Iteration plot 1**.

Open the Export Iteration Data dialog box.

Right-click on the iteration plot, and select **Export**.



Specify details regarding exporting the design variable set data:

- In the **Data to export** list, select **DesignVars**.
- In the **Iteration(s) to export** box, enter **3**.  
To specify multiple iterations, use a vector of integers. For example, [0 2 5].
- In the **Export to a variable named** box, enter **DesignVars\_iter**.

Export the design variable values set to the Design Optimization Workspace.

Click **OK**. The exported data variable, **DesignVars\_iter\_3**, appears in the **Design Optimization Workspace**.

---

**Note** You will see the iteration number suffixed to the exported data variable name.

---

## Related Examples

- “Update Model with Design Variables Set” on page 3-71
- “Compare Requirements and Design Variables Using Spider Plot” on page 3-94

## Concepts

- “Iteration Plots” on page 3-91

## Design Optimization to Meet Time- and Frequency-Domain Requirements (GUI)

This example shows how to tune a controller to satisfy time- and frequency-domain design requirements using the Design Optimization tool.

The example requires Simulink® Control Design™.

### Aircraft Longitudinal Flight Control Model

Open the Simulink model.

```
sys = 'sdoAircraft';  
open_system(sys);
```

The aircraft model is based on the Simulink `slexAircraftExample` model. The model includes:

- Subsystems to model aircraft dynamics (Aircraft Dynamics Model), wind gusts (Dryden Wind Gust Models), and pilot G-forces (Pilot G-force calculation).
- A step change applied to the aircraft joystick at 1 second into the simulation that causes the aircraft to pitch upward.

### Controller Design Problem

You tune the controller gains to meet the following time- and frequency-domain design requirements:

- Angle-of-attack  $\alpha$  response to a step change in the joystick has a rise time of less than 1 second, less than 1% overshoot, and settles to within 1% of steady state within less than 5 seconds
- Pitch-rate control loop has good tracking below 1 rad/s and 20db noise rejection above 100 rad/s



- Closed loop response from joystick to pilot G-Force is below 0db above 5 rad/s.

These requirements reduce the high frequency G-forces experienced by the pilot in response to joystick changes while still maintaining flight performance.

The model includes the following blocks (from Simulink® Design Optimization™ and Simulink Control Design Model Verification libraries):

- **Alpha Response** specifies the alpha step response requirement.
  
- **Pitch Rate Loop** specifies the pitch-rate performance requirement.

The linearization inputs/outputs are already selected in the **Linearizations** tab. The pitch-rate loop starts from the input of the controller (the controller error signal) and ends at the output of the pitch-rate sensor. The angle-of-attack loop is opened signal so that the block only computes the pitch-rate loop response. The linear system is computed at a simulation time of 0.

The **Bounds** tab specifies the following pitch-rate loop shape requirements:

- Greater than 20db over the range 0.01 rad/s to 0.1 rad/s
- Greater than 0db over the range 0.1 rad/s to 1 rad/s
- Less than -20db over the range 100 rad/s to 1000 rad/s
  
- **Pilot G Response** specifies the G-force requirement.

The linearization inputs/outputs are already selected in the **Linearizations** tab. The linear system is computed at a simulation time of 0.

The **Bounds** tab specifies the G-force requirements of less than 0db over the range 5 rad/s 100 rad/s.

### Open the Design Optimization Tool

Open the Design Optimization tool to configure and run design optimization problems interactively. Click **Response Optimization** on the Block Parameters dialog of Alpha Response, Pitch Rate Loop or Pilot G Response block. Alternatively, type `sdotool('sdoAircraft')`. To show multiple requirement plots at the same time, use the plot layout widgets at the top-right of the tool.

The tool detects the requirements specified in the Model Verification blocks and automatically includes them as requirements to satisfy.

### Specify Design Variables

Specify the following model parameters as design variables for optimization:

- Controller gains  $K_i$  and  $K_f$
- Pitch-rate sensor gain  $K_q$
- Alpha sensor gain  $K_a$

In the **Design Variables Set** drop-down list, select **New**. A dialog to select model parameters for optimization opens.

Select  $K_i$ ,  $K_f$ ,  $K_q$  and  $K_a$ . Click << to add the selected parameters to the design variables set.

Specify minimum and maximum gain values, the  $K_i$  and  $K_f$  values must remain negative while  $K_a$  and  $K_q$  must remain positive.

Press **Enter** after you enter the values.

Click **OK**. A new variable `DesignVars` appears in the **SDOTOOL Workspace**.

#### **Evaluate the Initial Design**

Click **Plot Current Response** to simulate the model and check how well the initial design satisfies the design requirements.

The plots indicate that the current design does not satisfy the pilot G-force requirement and the alpha step response overshoot requirement is violated.

#### **Optimize the Design**

Create a plot to display how the controller variables are modified during the optimization. In the **Add plot** drop-down list, select **DesignVars**, which contains the optimization design variables  $K_i$ ,  $K_f$ ,  $K_q$  and  $K_a$ .

Click **Optimize**.

To load a pre-configured file and run the optimization, click **Open** in the **Design Optimization** tab and select `sdoAircraft_sdoession.mat`. Alternatively load the project by typing:

```
>> load sdoAircraft_sdoession
```

```
>> sdotool(SDOSessionData)
```

The optimization progress window updates at each iteration and shows that the optimization converged after 5 iterations.

The Alpha Response and Pilot G Response plots indicate that the design requirements are satisfied. The DesignVars plot shows that the controller gains converged to new values.

To view the optimized design variable values, click **DesignVars** in the **SDOTOOL Workspace**. The optimized values of the design variables are automatically updated in the Simulink model.

```
% Close the model  
bdclose('sdoAircraft')
```

## Design Optimization to Meet a Custom Objective (GUI)

This example shows how to optimize a design to meet a custom objective using the Design Optimization tool. You optimize the cylinder parameters to minimize the cylinder geometry and satisfy design requirements.

### Hydraulic Cylinder Model

The hydraulic cylinder model is based on the Simulink model `sldemo_hydcyl`. The model includes:

- Pump and Cylinder Assembly subsystems. For more information on the subsystems, see "Single Hydraulic Cylinder Simulation".
- A step change applied to the cylinder control valve orifice area that causes the cylinder piston position to change.

### Hydraulic Cylinder Design Problem

You tune the cylinder cross-sectional area and piston spring constant to meet the following design requirements:

- Ensure that the piston position has a step response rise time of less than 0.04 seconds and setting time of less than 0.05 seconds.
- Limit the maximum cylinder pressures to  $1.75e6$  N/m.
- Minimize the cylinder cross-sectional area.

### Open the Design Optimization Tool

Open the Design Optimization tool to configure and run design optimization problems interactively.

```
sdotool('sdoHydraulicCylinder')
```

### Specify Design Variables

Specify the following model parameters as design variables for optimization:

- Cylinder cross-sectional area  $A_c$
- Piston spring constant  $K$

In the **Design Variables Set** drop-down list, select **New**. A dialog to select model parameters for optimization opens.

Select  $A_c$  and  $K$ . Click <- to add the selected parameters to the design variables set.

Limit the cylinder cross-sectional area to circular area with radius between 1 and 2 centimeters and the piston spring constant to a range of  $1e4$  to  $10e4$  N/m. To do so, specify the maximum and minimum for the corresponding variable in the **Maximum** and **Minimum** columns.

Because the variable values are different orders of magnitude, scale  $A_c$  by  $1e-3$  and  $K$  by  $1e5$ .

Press **Enter** after you specify the values.

Click **OK**. A new variable **DesignVars** appears in the **SDOTOOL Workspace**.

### Specify Design Requirements

The design requirements require logged model signals. During optimization, the model is simulated using the current value of the design variables and the logged signal is used to evaluate the design requirements.

Log the cylinder pressures, which is the first output port of the **Cylinder Assembly** block.

In the **New** drop-down list, select **Signal**. A dialog to select model signals to log opens.

Enter **Pressures** as the signal name in the **Signal set** field. Then, in the Simulink model, click the first output port of the **Cylinder Assembly** block named **Pressure**. The dialog updates to display the selected signal.

Select the signal in the dialog and click **->** to add it to the signal set.

Click **OK**. A new variable **Pressures** appears in the **SDOTOOL Workspace**.

Similarly, log the piston position, which is the second output of the **Cylinder Assembly** block, in a variable named **PistonPosition**.

Specify the maximum cylinder pressure requirement of less than  $1.75e6$  N/m.

In the **New** drop-down list, select **Signal Bound**. A dialog to create a signal bound requirement opens.

In the **Amplitude** columns, enter the maximum pressure requirement of  $1.75e6$  N/m and **Requirement Name** as **MaxPressure**. In the **Select Model Signals** area, select **Pressures**, the signal on which this requirement applies.

Click **OK**.

- A new `MaxPressure` variable appears in the **SDOTOOL Workspace**.
- A graphical view of the maximum pressure requirement is automatically created.

Specify the piston position step response requirement of rise time of less than 0.04 seconds and a settling time of less than 0.05 seconds.

In the **New** drop-down list of the **Response Optimization** tab, select **Step Response Envelope**. A dialog to create a step response requirement opens.

Specify a requirement name `PistonResponse`, the required rise and settling time bounds. Select `PistonPosition` as the signal to apply the step response requirement to.

Click **OK**.

### **Specify Custom Objective**

The custom objective is to minimize the cylinder cross-sectional area.

In the **New** drop-down list, select **Custom Requirement**. A dialog to create custom requirement opens.

Specify a function to call during optimization in the **Requirement function** field. At each optimization iteration, the software calls the



function and passes the current design variable values. You can also optionally pass logged signals to the custom requirement. Here, you use `sdoHydraulicCylinder_customObjective` as the custom requirement function, which returns the value of the cylinder cross-sectional area.

In the **Requirement type** drop-down list, specify whether the requirement is an objective to minimize (min), an inequality constraint ( $\leq$ ), or an equality constraint ( $=$ ).

```
type sdoHydraulicCylinder_customObjective
```

```
function objective = sdoHydraulicCylinder_customObjective(data)
%SDOHYDRAULICCYLINDER_CUSTOMOBJECTIVE
%
% The sdoHydraulicCylinder_customObjective function is used to define a
% custom requirement that can be used in the graphical SDTOOL environment.
%
% The |data| input argument is a structure with fields containing the
% design variable values chosen by the optimizer.
%
% The |objective| return argument is the objective value to be minimized by
% the SDOTool optimization solver.
%
% Copyright 2011 The MathWorks, Inc.

%For the cylinder design problem we want to minimize the cylinder
%cross-sectional area so return the cylinder cross-sectional area as an
%objective value.
Ac = data.DesignVars(1);
objective = Ac.Value;
end
```

### Evaluate the Initial Design

Click **Plot Current Response** to simulate the model and check how well the initial design satisfies the design requirements. To show both requirement plots at the same time, use the plot layout widgets at the top-right of the tool.

From the plots, see that the maximum pressure requirement is satisfied but the piston position step response requirement is not satisfied.

### **Optimize the Design**

Create a plot to display how the cylinder cross-sectional area and piston spring constant are modified during optimization.

In the **Add plot** drop-down list, select **DesignVars**, which contains the optimization design variables *Ac* and *K*.

Click **Optimize**.

The optimization progress window updates at each iteration and shows that the optimization converged after 5 iterations.

The *Pressures* and *PistonPosition* plots indicate that the design requirements are satisfied. The *DesignVars* plot shows that the cylinder cross-sectional area *Ac* is minimized.

To view the optimized design variable values, click the variable name in the **SDOTOOL Workspace**. The optimized values of the design variables are automatically updated in the Simulink model.

**Related Examples**

To learn how to optimize the cylinder design using the `sdo.optimize` command, see "Design Optimization to Meet Custom Objective (Code)".

```
% Close the model
delete(sdotool('sdoHydraulicCylinder'))
bdclose('sdoHydraulicCylinder')
```

## Design Optimization to Meet a Custom Objective (Code)

This example shows how to optimize a design to meet custom objective using `sdo.optimize`. You optimize the cylinder parameters to minimize the cylinder geometry and satisfy design requirements.

### Hydraulic Cylinder Model

Open the Simulink model.

```
sys = 'sdoHydraulicCylinder';  
open_system(sys);
```

The hydraulic cylinder model is based on the Simulink model `sldemo_hydcyl`. The model includes:

- Pump and Cylinder Assembly subsystems. For more information on the subsystems, see "Single Hydraulic Cylinder Simulation".
- A step change applied to the cylinder control valve orifice area that causes the cylinder piston position to change.

### Hydraulic Cylinder Design Problem

You tune the cylinder cross-sectional area and piston spring constant to meet the following design requirements:

- Ensure that the piston position has a step response rise time of less than 0.04 seconds and setting time of less than 0.05 seconds.
- Limit the maximum cylinder pressures to  $1.75e6$  N/m.
- Minimize the cylinder cross-sectional area.

### Specify Design Variables

Select the following model parameters as design variables for optimization:

- Cylinder cross-sectional area  $A_c$
- Piston spring constant  $K$

```
Ac = sdo.getParameterFromModel('sdoHydraulicCylinder','Ac');
K = sdo.getParameterFromModel('sdoHydraulicCylinder','K');
```

Limit the cylinder cross-sectional area to a circular area with radius between 1 and 2 centimeters.

```
Ac.Minimum = pi*1e-2^2; % m^2
Ac.Maximum = pi*2e-2^2; % m^2
```

Limit the piston spring constant to a range of  $1e4$  to  $10e4$  N/m.

```
K.Minimum = 1e4; % N/m
K.Maximum = 10e4; % N/m
```

### Specify Design Requirements

The design requirements require logged model signals. During optimization, the model is simulated using the current value of the design variables and the logged signal is used to evaluate the design requirements.

Log the following signals:

- Cylinder pressures, available at the first output port of the Cylinder Assembly block

```
Pressures = Simulink.SimulationData.SignalLoggingInfo;
Pressures.BlockPath = 'sdoHydraulicCylinder/Cylinder Assembly';
Pressures.OutputPortIndex = 1;
```

- Piston position, available at the second output port of the Cylinder Assembly block

```
PistonPosition = Simulink.SimulationData.SignalLoggingInfo;
PistonPosition.BlockPath = 'sdoHydraulicCylinder/Cylinder Assembly';
PistonPosition.OutputPortIndex = 2;
```

Create an object to store the logging information and use later to simulate the model

```
simulator = sdo.SimulationTest('sdoHydraulicCylinder');  
simulator.LoggingInfo.Signals = [PistonPosition,Pressures];
```

Specify the piston position step response requirement of rise time of less than 0.04 seconds and settling time less than of 0.05 seconds.

```
PistonResponse = sdo.requirements.StepResponseEnvelope;  
set(PistonResponse, ...  
    'RiseTime',      0.04, ...  
    'FinalValue',   0.04, ...  
    'SettlingTime', 0.05, ...  
    'PercentSettling', 1);
```

Specify the maximum cylinder pressure requirement of less than 1.75e6 N/m.

```
MaxPressure = sdo.requirements.SignalBound;  
set(MaxPressure, ...  
    'BoundTimes',    [0 0.1], ...  
    'BoundMagnitudes', [1.75e6 1.75e6], ...  
    'Type',          '<=');
```

For convenience, collect the performance requirements into a single structure to use later.

```
requirements = struct(...  
    'PistonResponse', PistonResponse, ...  
    'MaxPressure',    MaxPressure);
```

### **Create Objective/Constraint Function**

To optimize the cylinder cross-sectional area and piston spring constant, create a function to evaluate the cylinder design. This function is called at each optimization iteration.

Here, use an anonymous function with one argument that calls the `sdoHydraulicCylinder_design` function.

```
evalDesign = @(p) sdoHydraulicCylinder_design(p,simulator,requirements);
```

The function:

- Has one input argument that specifies the cylinder cross-sectional area and piston spring constant values.
- Returns the optimization objective value and optimization constraint violation values.

The optimization solver minimizes the objective value and attempts to keep the optimization constraint violation values negative. Type `help sdoExampleCostFunction` for more details on how to write the objective/constraint function.

The `sdoHydraulicCylinder_design` function uses the `simulator` and `requirements` objects to evaluate the design. Type `edit sdoHydraulicCylinder_design` to examine the function in more detail.

```

type sdoHydraulicCylinder_design

function design = sdoHydraulicCylinder_design(p,simulator,requirements)
%SDOHYDRAULICCYLINDER_DESIGN
%
% The sdoHydraulicCylinder_design function is used to evaluate a cylinder
% design.
%
% The |p| input argument is the vector of cylinder design parameters.
%
% The |simulator| input argument is a sdo.SimulinkTest object used to
% simulate the |sdoHydraulicCylinder| model and log simulation signals
%
% The |requirements| input argument contains the design requirements used
% to evaluate the cylinder design
%
% The |design| return argument contains information about the design
% evaluation that can be used by the |sdo.optimize| function to optimize
% the design.
%
% see also sdo.optimize, sdoExampleCostFunction

```

```
% Copyright 2011 The MathWorks, Inc.

%% Simulate the model
%
% Use the simulator input argument to simulate the model and log model
% signals.
%
% First ensure that we simulate the model with the parameter values chosen
% by the optimizer.
%
simulator.Parameters = p;
% Simulate the model and log signals.
%
simulator = sim(simulator);
% Get the simulation signal log, the simulation log name is defined by the
% model |SignalLoggingName| property
%
logName = get_param('sdoHydraulicCylinder','SignalLoggingName');
simLog = get(simulator.LoggedData,logName);

%% Evaluate the design requirements
%
% Use the requirements input argument to evaluate the design requirements
%
% Check the PistonPosition signal against the stepresponse requirement
%
PistonPosition = get(simLog,'PistonPosition');
cPiston = evalRequirement(requirements.PistonResponse,PistonPosition.Values);
% Check the Pressure signals against the maximum requirement
%
Pressures = find(simLog,'Pressures');
cPressure = evalRequirement(requirements.MaxPressure,Pressures.Values);
% Use the PistonResponse and MaxPressure requirements as non-linear
% constraints for optimization.
design.Cleq = [cPiston(:);cPressure(:)];
% Add design objective to minimize the Cylinder cross-sectional area
Ac = p(1); %Since we called sdo.optimize(evalDesign,[Ac;K])
design.F = Ac.Value;
end
```



### Evaluate the Initial Design

Call the objective function with the initial cylinder cross-sectional area and initial piston spring constant.

```
initDesign = evalDesign([Ac;K]);
```

The function simulates the model and evaluates the design requirements. The scope shows that the maximum pressure requirement is satisfied but the piston position step response requirement is not satisfied.

`initDesign` is a structure with the following fields:

- `Cleq` shows that some of the inequality constraints are positive indicating they are not satisfied by the initial design.

```
initDesign.Cleq
```

```
ans =
```

```
-0.3839  
-0.1861  
-0.1836  
-1.0000  
0.3033  
0.2909  
0.1671  
0.2326  
-0.0480  
-0.0480
```

- `F` shows the optimization objective value (in this case the cylinder cross-sectional area). The initial design cross-sectional area, as expected, has the same value as the initial cross-sectional area parameter `Ac`.

```
initDesign.F
```

```
ans =  
  
1.0000e-03
```

#### Optimize the Design

Pass the objective function, initial cross-sectional area and piston spring constant values to `sdo.optimize`.

```
[pOpt,optInfo] = sdo.optimize(evalDesign,[Ac;K]);
```

```
Optimization started 18-Jan-2014 17:27:18
```

Iter	F-count	f(x)	max constraint	Step-size	First-order optimality
0	5	0.001	0.3033		
1	11	0.00057281	0.07293	0.48	85.4
2	17	0.000391755	0	0.128	28
3	22	0.000388463	0	0.00232	0.00409
4	27	0.000382784	0	0.00401	0.00231
5	32	0.000378554	0	0.00299	0.000545

```
Local minimum found that satisfies the constraints.
```

```
Optimization completed because the objective function is non-decreasing in  
feasible directions, to within the selected value of the function tolerance  
and constraints are satisfied to within the selected value of the constraint
```

The optimization repeatedly evaluates the cylinder design by adjusting the cross-sectional area and piston spring constant to meet the design requirements. From the scope, see that the maximum pressure and piston response requirements are met.

The `sdo.optimize` function returns:

- `pOpt` shows the optimized cross-sectional area and piston spring constant values.

pOpt

pOpt(1,1) =

```
Name: 'Ac'  
Value: 3.7855e-04  
Minimum: 3.1416e-04  
Maximum: 0.0013  
Free: 1  
Scale: 0.0020  
Info: [1x1 struct]
```

pOpt(2,1) =

```
Name: 'K'  
Value: 1.5816e+04  
Minimum: 10000  
Maximum: 100000  
Free: 1  
Scale: 65536  
Info: [1x1 struct]
```

2x1 param.Continuous

- **optInfo** is a structure that contains optimization termination information such as number of optimization iterations and the optimized design.

**optInfo**

optInfo =

```
Cleq: [10x1 double]  
F: 3.7855e-04  
Gradients: [1x1 struct]  
exitflag: 1
```

```
iterations: 5
SolverOutput: [1x1 struct]
Stats: [1x1 struct]
```

For example, the `Cleq` field shows the optimized non-linear inequality constraints are all non-positive to within optimization tolerances, indicating that the maximum pressure and piston response requirements are satisfied.

`optInfo.Cleq`

```
ans =

-0.0968
-0.0126
-0.0126
-1.0000
-0.2067
-0.0052
-0.0074
-0.0004
-0.0476
-0.0476
```

The `F` field contains the optimized cross-sectional area. The optimized cross-sectional area value is nearly 50% less than the initial value.

`optInfo.F`

```
ans =

3.7855e-04
```

**Update the Model Variable Values**

By default, the model variables `Ac` and `K` are not updated at the end of optimization. Use the `setValueInModel` command to update the model variable values.

```
sdo.setValueInModel('sdoHydraulicCylinder',pOpt)
```

### **Related Examples**

To learn how to optimize the cylinder design using the Design Optimization tool, see "Design Optimization to Meet Custom Objective (GUI)".

```
% Close the model  
bdclose('sdoHydraulicCylinder')
```

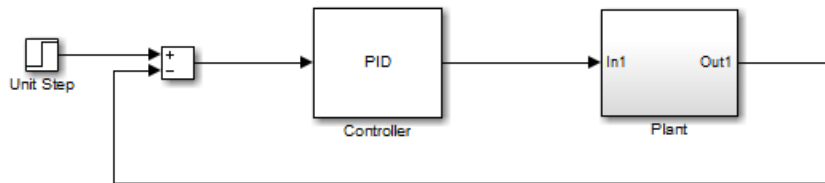
## Design Optimization to Meet Custom Signal Requirements (GUI)

This example shows how to optimize a design to meet a custom signal requirement. You optimize the controller parameters to minimize the plant actuation signal energy while satisfying step response requirements.

- 1 Load a saved Design Optimization tool session.

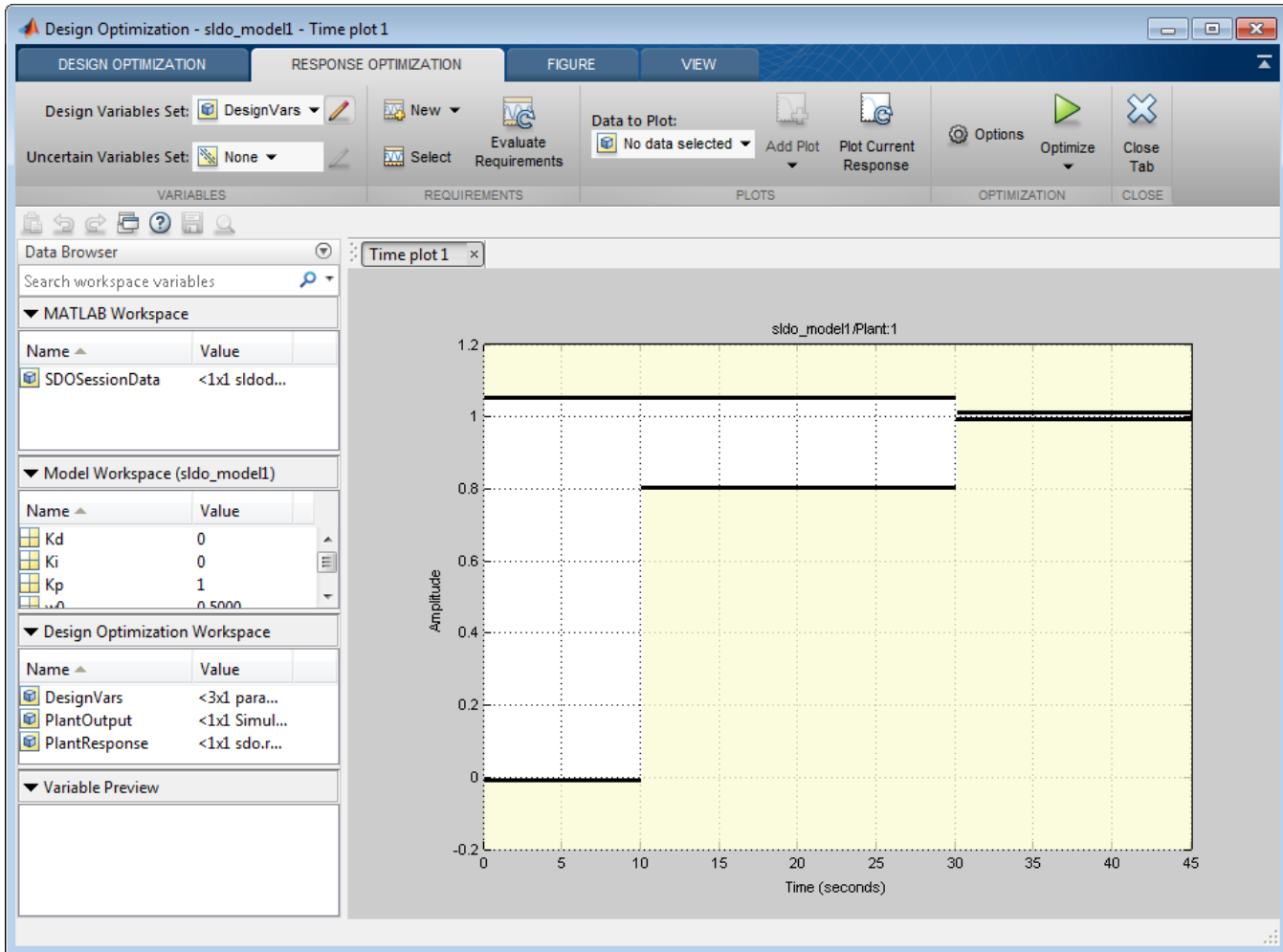
```
load sldo_model1_custom_signal_session
sdotool(SDOSessionData);
```

The following Simulink model opens.



The Design Optimization tool, configured with the following settings, also opens:

- Step response characteristics, specified on the output of the Plant block, that the model output must satisfy:
  - Maximum overshoot of 5%
  - Maximum rise time of 10 seconds
  - Maximum settling time of 30 seconds
- Design variable set with the controller parameters  $K_p$ ,  $K_i$  and  $K_d$ . These parameters have a minimum value of 0.
- The variables for step requirements (PlantResponse), logged signal (PlantOutput) and design variables (DesignVars) which appear in the **Design Optimization Workspace**.




**2** Specify a signal to log. You apply the custom requirement on this logged signal.

**a** Select **New > Signal**.

A window opens where you select a signal to log.

**b** In the Simulink model window, click the output of the Controller block.

The window updates to display the selected signal.

- c Select the signal and click  to add it to the signal set.
- d In **Signal set**, enter PlantActuator.

Click **OK**. A new variable PlantActuator appears in the **Design Optimization Workspace**.

### 3 Specify the custom requirement to apply to the signal.

The custom requirement calls the objective function `sldo_model11_minimize_energy` which returns the energy in the PlantActuator signal. The signal energy is minimized. This function accepts:

- An input argument `data` which is a structure with fields for the design variables in the **Design Optimization Workspace**. Signals are logged for the nominal and uncertain parameter values if there are any.
- Returns the objective value to be minimized.

---

**Tip** To see the contents of this function, type `edit sldo_model11_minimize_energy`.

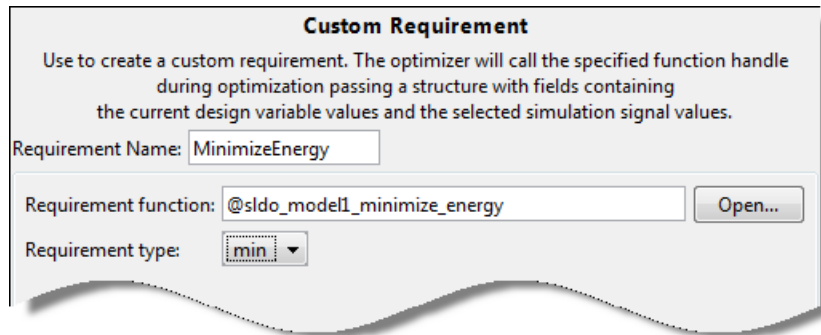
---

#### a Select **New > Custom Requirement**.

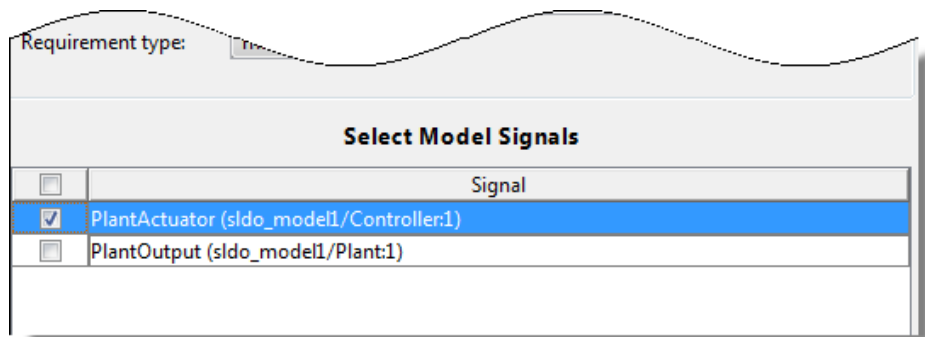
A window opens where you specify the custom requirement.

- b Specify `MinimizeEnergy` as the **Requirement Name**.
- c Specify `@sldo_model11_minimize_energy` as the **Requirement function**.
- d Select `min` as the **Requirement type**.



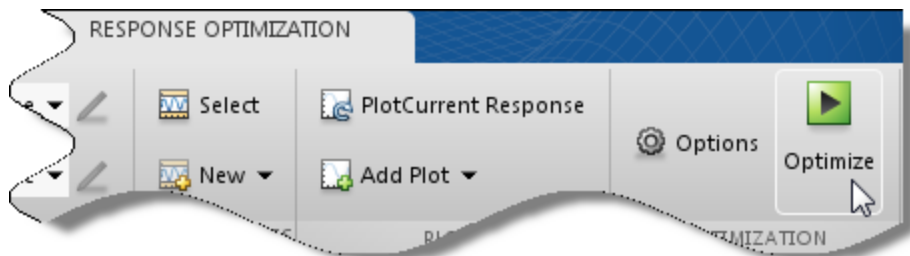


- 4** In the **Select Model Signals** area, select the **PlantActuator** check box to associate the custom requirement with that signal.

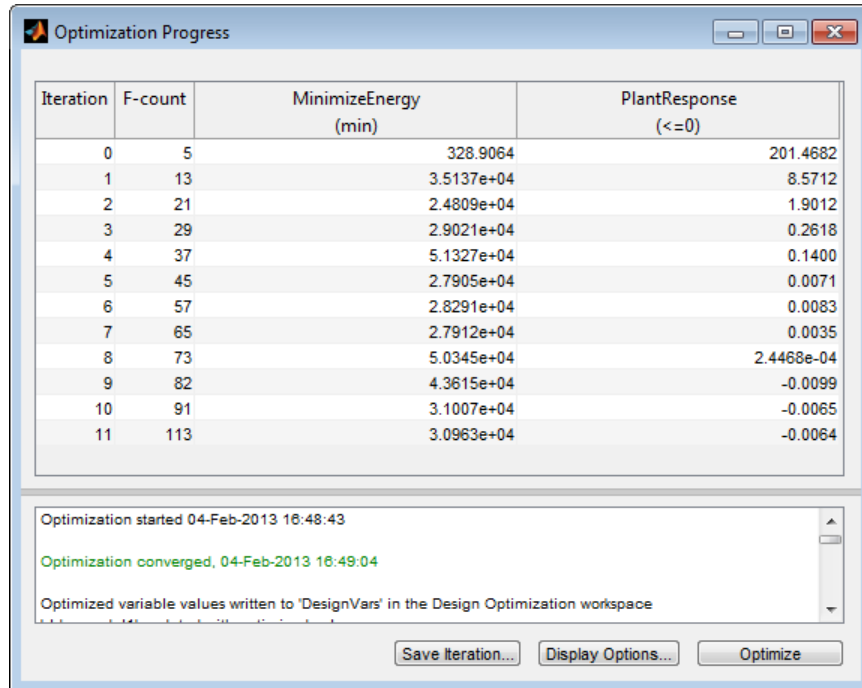


Click **OK**. A new variable appears in the **Design Optimization Workspace**. The window also updates to graphically display the custom signal requirement.

- 5** Click **Optimize**.



After a few iterations, the optimization converges to meet both the custom signal and step response requirements.



The screenshot shows a window titled "Optimization Progress" with a table of results and a log area. The table has four columns: Iteration, F-count, MinimizeEnergy (min), and PlantResponse (<=0). The log area shows the start and convergence of the optimization process.

Iteration	F-count	MinimizeEnergy (min)	PlantResponse (<=0)
0	5	328.9064	201.4682
1	13	3.5137e+04	8.5712
2	21	2.4809e+04	1.9012
3	29	2.9021e+04	0.2618
4	37	5.1327e+04	0.1400
5	45	2.7905e+04	0.0071
6	57	2.8291e+04	0.0083
7	65	2.7912e+04	0.0035
8	73	5.0345e+04	2.4468e-04
9	82	4.3615e+04	-0.0099
10	91	3.1007e+04	-0.0065
11	113	3.0963e+04	-0.0064

Optimization started 04-Feb-2013 16:48:43  
Optimization converged, 04-Feb-2013 16:49:04  
Optimized variable values written to 'DesignVars' in the Design Optimization workspace

Buttons: Save Iteration..., Display Options..., Optimize

6 Close the model.

```
setOption(sdotool('sldo_model11'),'NoPromptClose',true)  
bdclose('sldo_model11')
```

## Design Optimization to Meet Frequency-Domain Requirements (GUI)

This example shows how to tune model parameters to meet frequency-domain requirements using the Design Optimization tool.

The example requires Simulink® Control Design™

### Suspension Model

Open the Simulink Model.

```
open_system('sdoSimpleSuspension')
```

Mass-spring-damper models represent simple suspension systems and for this example we tune the system to meet typical suspension requirements. The model implements the second order system representing a mass-spring-damper using Simulink blocks and includes:

- a Mass gain block parameterized by the total suspended mass,  $m_0+m_{load}$ . The total mass is the sum of a nominal mass  $m_0$  and a variable load mass  $m_{Load}$ .
- a Damper gain block parameterized by the damping coefficient,  $b$ .
- a Spring gain block parameterized by the spring constant,  $k$ .
- two integrator blocks to compute the mass velocity and position.
- a Band-Limited Disturbance Force block applying a disturbance force to the Mass. The disturbance force is assumed to be band-limited white noise.

Simulate the model to view the system response to the applied disturbance force.

### Design Problem

The initial system has a bandwidth that is too high. This can be seen from the spiky position signal. You tune the spring and damper values to meet the following requirements:

- The -3dB system bandwidth must not exceed 10 rad/s.
- The damping ratio of the system must be less than  $1/\sqrt{2}$ . This ensures that no frequencies in pass band are amplified by the system.
- Minimize the expected failure rate of the system. The expected failure rate is described by a Weibull distribution dependent on the mass, spring, and damper values.
- These requirements must all be satisfied as the load mass ranges from 0 to 20.

### Open the Design Optimization Tool

In the Simulink model **Analysis** menu, select **Response Optimization**.

### Specify Design Variables

In the **Design Variables Set** list, select **New**. Add the b and k model variables to the design variable set.

- Specify the **Minimum** and **Maximum** values for the b variable as 100 and 10000 respectively.
- Specify the **Minimum** and **Maximum** values for the k variable as 10000 and 100000 respectively.

Click **OK**. A new variable, DesignVars, appears in the **Design Optimization Workspace**.

In the **Uncertain Variables Set** list, select **New**. Add the `mLoad` variable to the uncertain variables set.

- Specify the **Uncertain Values** value for the `mLoad` variable as [10 15 20]

Click **OK**. A new variable, `UncVars`, appears in the **Design Optimization Workspace**.

### **Specify Linear Analysis Input/Output Points**

Specify the input/output points defining the linear system used to compute the bandwidth and damping ratio.

To specify the input/output points:

- In the **New** list, select **Linearization I/Os**.
- In the Simulink model, click the signal at the output of the **Band-Limited Disturbance Force** block. The **Create linearization I/O set** dialog box is updated and the chosen signal appears in it.
- In the **Create linearization I/O** dialog box, select the signal and click **Add**.
- In the **Configuration** list for the selected signal, choose **Input Perturbation** to specify it as an input signal.
- Similarly, add the **pos** signal from the Simulink model. Specify this signal as an output. In the **Configuration** list, select **Output Measurement**.

- Click **OK**. A new variable, I0s, appears in the **Design Optimization Workspace**.

#### **Add Bandwidth and Damping-Ratio Requirements**

Tune the spring and damper values to satisfy bandwidth and damping ratio requirements.

To specify the bandwidth requirement:

- Open a dialog to specify bounds on the Bode magnitude. In the **New** list, select **Bode Magnitude**.
- Specify the requirement name as **Bandwidth**.
- Specify the edge start frequency and magnitude as 10 rad/s and -3db, respectively.
- Specify the edge end frequency and magnitude as 100 rad/s and -3db, respectively.
- Specify the input/output set to which the requirement applies by clicking **Select Systems to Bound**. Select the I0s check box .

- Click **OK**. A new requirement, **Bandwidth**, appears in the **Design Optimization Workspace** and a graphical view of the bandwidth requirement is automatically created.

To specify the damping ratio requirement:

- Open a dialog to specify bounds on the damping ratio. In the **New** list, select **Damping Ratio**.
- Specify the damping ratio bound value as 0.7071.
- Specify the input/output set to which the requirement applies by clicking **Select Systems to Bound**. Select the I0s check box .

- Click **OK**. A new requirement, `DampingRatio`, appears in the **Design Optimization Workspace** and a graphical view of the damping ratio requirement is automatically created.

### Add a Reliability Requirement

Tune the spring and damper values to minimize the expected failure rate over a lifetime of 100e3 miles. The failure rate is computed using a Weibull distribution on the damping ratio of the system. As the damping ratio increases the failure rate is expected to increase.

Specify the reliability requirement as a custom requirement:

- Open a dialog box to specify the custom requirements. In the **New** list, select **Custom Requirement**.
- Specify the custom requirement name as `MinFailureRate`.
- In the **Specify Function** area, select **Minimize the function output** from the **Type** list.
- Specify the function as `@sdoSuspension_FailureRate`.
  
- Click **OK**. A new requirement, `MinFailureRate`, appears in the **Design Optimization Workspace** and a graphical view of the custom requirement is automatically created.

The `@sdoSuspension_FailureRate` function returns expected failure rate for a lifetime of 100e3 miles.

```
type sdoSuspension_FailureRate
```

```
function pFailure = sdoSuspension_FailureRate(data)
```

```
%SDOSUSPENSION_FAILURERATE
%
% The sdoSuspension_FailureRate function is used to define a custom
% requirement that can be used in the graphical SDTOOL environment.
%
% The |data| input argument is a structure with fields containing the
% design variable values chosen by the optimizer.
%
% The |pFailure| return argument is the failure rate to be minimized by the
% SDTOOL optimization solver. The failure rate is given by a Weibull
% distribution that is a function of the mass, spring and damper values.
% The design minimizes the failure rate for a 100e3 mile lifetime.
%

% Copyright 2012 The MathWorks, Inc.

%Get the spring and damper design values
allVarNames = {data.DesignVars.Name};
idx          = strcmp(allVarNames,'k');
k            = data.DesignVars(idx).Value;
idx          = strcmp(allVarNames,'b');
b            = data.DesignVars(idx).Value;

%Get the nominal mass from the model workspace
wksp = get_param('sdoSimpleSuspension','ModelWorkspace');
m     = evalin(wksp,'m0');

%The expected failure rate is defined by the Weibull cumulative
%distribution function, 1-exp(-(x/l)^k), where k=3, l is a function of the
%mass, spring and damper values, and x the lifetime.
d     = b/2/sqrt(m*k);
pFailure = 1-exp(-(100e3*d/250e3)^3);
end
```

### **Optimize the Design**

Before running the optimization be sure to have completed the earlier steps. Alternatively, you can load the `sdoSimpleSuspension_sdoession` from the model workspace into the Design Optimization tool.



To save the initial design variable values and later compare them with the optimized values configure the optimization.

- Click **Options**.
- Select the **Save optimized variable values as new design variable set** option.

To study how the design variable values change during optimization:

- In the **Data to Plot** list, select **DesignVars**.
- In the **Add Plot** list, and select **Iteration Plot**.
- View the design variables in an appropriately scaled manner. Right-click on the **DesignVars** plot and select **Show scaled values**.

To evaluate the requirements at the initial design point, click **Evaluate Requirements** . The requirement plots are updated and a **ReqValues** variable is added to the **Design Optimization Workspace**.

To optimize the design, click **Optimize**. The plots are updated during optimization. At the end of optimization, the optimal design values are written to the **DesignVars1** variable. The requirement values for the optimized design are written to the **ReqValues1** variable.

### **Analyze the Design**

To compare design variables before and after optimization:

- In the **Data to Plot** list, select **DesignVars**.

- In the **Add Plot** list, select **Spider Plot**.
- To add the optimized design variables to the same plot, select **DesignVars1** in the **Design Optimization Workspace** and drag it onto the Spider plot. Alternatively, in the **Data to Plot** list, select **DesignVars1**. Then, in the **Add Plot** list, select **Spider plot 1** from the **Add to Existing Plot** section.

The plot shows that the optimizer reduced both the k and b values for the optimal design.

To compare requirements before and after optimization:

- In the **Data to Plot** list, select **ReqValues**.
- In the **Add Plot** list, select **Spider Plot**.
- To add the optimized requirement values to the same plot, select **ReqValues1** in the **Design Optimization Workspace** and drag it onto the Spider plot. Alternatively, in the **Data to Plot** list, select **ReqValues1**. Then, in the **Add Plot** list, select **Spider plot 2** from the **Add to Existing Plot** section.

The plot shows that the optimal design has a lower failure rate (the **MinFailureRate** axis) and better satisfies the bandwidth requirement. The value plotted on the bandwidth axis is the difference between the bandwidth bound and the bandwidth value. The optimization satisfies the bound by keeping this value negative; a more negative value indicates better satisfaction of the bound.

The improved reliability and bandwidth are achieved by pushing the damping ratio closer to the damping ratio bound. The plot has two axes for the damping ratio requirement, one for each system pole, and the plotted values are the difference between the damping ratio bound and the damping ratio value. The optimization satisfies the bound by keeping this value negative.

Finally the simulated mass position is smoother than the initial position response (indication of a lower bandwidth as required) at the expense of larger position deflection.

```
% Close the model  
bdclose('sdoSimpleSuspension')
```

## Specify Custom Signal Objective with Uncertain Variable (GUI)

This example shows how to specify a custom objective function for a model signal. You calculate the objective function value using a variable that models parameter uncertainty.

### Competitive Population Dynamics Model

The Simulink model `sdoPopulation` models a simple two-organism ecology using the competitive Lotka-Volterra equations:

- is the population size of the n-th organism.
- is the inherent per capita growth rate of each organism.
- is the competitive delay for each organism.
- is the carrying capacity of the organism environment.
- is the proximity of the two populations and how strongly they affect each other.

The model uses normalized units.

Open the model.

```
open_system('sdoPopulation')
```

The two-dimensional signal, P, models the population sizes for P1 (first element) and P2 (second element). The model is initially configured with one organism, P1, dominating the ecology. The Population scope shows the P1 population oscillating between high and low values, while P2 is constant at 0.1. The Population Phase Portrait block shows the population sizes of the two organisms in relation to each other.

### **Population Stabilization Design Problem**

Tune the  $\mu$ ,  $\sigma$ , and  $\gamma$  values to meet the following design requirements:

- Minimize the population range, that is, the maximum difference between P1 and P2.
- Stabilize P1 and P2, that is, ensure that neither organism population dies off or grows extremely large.

You must tune the parameters for different values of the carrying capacity,  $K$ . This ensures robustness to environment carrying-capacity uncertainty.

### **Open Design Optimization Tool**

Double-click the Open Optimization Tool block in the model to open a pre configured Design Optimization tool session. The session specifies the following variables:

- DesignVars - Design variables set for the  $\mu$ ,  $\sigma$ , and  $\gamma$  model parameters.
- K\_unc - Uncertain parameter modeling the carrying capacity of the organism environment ( $K$ ). K\_unc specifies the nominal value and two sample values.
- P1 and P2 - Logged signals representing the populations of the two organisms.

### **Specify Custom Signal Objective Function**

Specify a custom requirement to minimize the maximum difference between the two population sizes. Apply this requirement to the P1 and P2 model signals.

- 1 Open the Create Requirement dialog box. In the **New** list, select **Custom Requirement**.
- 2 Specify the following in the Create Requirement dialog box:
  - **Name** - Enter PopulationRange.
  - **Type** - Select **Minimize the function output** from the list.
  - **Function** - Enter @sdoPopulation\_PopRange. For more information about this function, see **Custom Signal Objective Function Details**.
  - **Select Signals and Systems to Bound (Optional)** - Select the P1 and P2 check boxes.
3. Click **OK**.

A new variable, PopulationRange, appears in the **Design Optimization Workspace**.

### **Custom Signal Objective Function Details**

PopulationRange uses the sdoPopulation\_PopRange function. This function computes the maximum difference between the populations, across different environment carrying capacity values. By minimizing this value, you can achieve both design goals. The function is called by the optimizer at each iteration step.

To view the function, type `edit sdoPopulation_PopRange`. The following discusses details of this function.

### **Input/Output**

The function accepts `data`, a structure with the following fields:

- `DesignVars` - Current iteration values of , and .
- `Nominal` - Logged signal data, obtained by simulating the model using parameter values specified by `data.DesignVars` and nominal values

for all other parameters. The `Nominal` field is itself a structure with fields for each logged signal. The field names are the logged signal names. The custom requirement uses the logged signals, `P1` and `P2`. Therefore, `data.Nominal.P1` and `data.Nominal.P2` are timeseries objects corresponding to `P1` and `P2`.

- **Uncertain** - Logged signal data, obtained by simulating the model using the sample values of the uncertain variable `K_unc`. The `Uncertain` field is a vector of `N` structures, where `N` is the number of sample values specified for `K_unc`. Each element of this vector is similar to `data.Nominal` and contains simulation results obtained from a corresponding sample value specified for `K_unc`.

The function returns the maximum difference between the population sizes across different carrying capacities. The following code snippet in the function performs this action:

```
val = max(maxP(1)-minP(2),maxP(2)-minP(1));
```

### Data Time Range

When computing the design goals, discard the initial population growth data to eliminate biases from the initial-condition. The following code snippet in the function performs this action:

```
%Get the population data
tMin = 5; %Ignore signal values prior to this time
iTime = data.Nominal.P1.Time > tMin;
sigData = [data.Nominal.P1.Data(iTime), data.Nominal.P2.Data(iTime)];
```

`iTime` represents the time interval of interest, and the columns of `sigData` contain `P1` and `P2` data for this interval.

### Optimization for Different Values of Carrying Capacity

The function includes the effects of varying the carrying capacity by iterating through the elements of `data.Uncertain`. The following code snippet in the function performs this action:

```
...
for ct=1:numel(data.Uncertain)
```

```
iTime = data.Uncertain(ct).P1.Time > tMin;
sigData = [data.Uncertain(ct).P1.Data(iTime), data.Uncertain(ct).P2.Data

maxP = max([maxP; max(sigData)]); %Update maximum if new signals are bi
minP = min([minP; min(sigData)]); %Update minimum if new signals are sm
end
...
```

The maximum and minimal populations are obtained across all the simulations contained in `data.Uncertain`.

#### **Optimize Design**

Click **Optimize**.

The optimization converges after a number of iterations.

The P1,P2 plot shows the population dynamics, with the first organism population in blue and the second organism population in green. The dotted lines indicate the population dynamics for different environment capacity values. The `PopulationRange` plot shows that the maximum difference between the two organism populations reduces over time.

The `Population Phase Portrait` block shows the populations initially varying, but they eventually converge to stable population sizes.

```
% Close the model
bdclose('sdoPopulation')
```



## Design Optimization with Uncertain Variables (Code)

This example shows how to optimize a design when there are uncertain variables. You optimize the dimensions of a Continuously Stirred Tank Reactor (CSTR) to minimize product concentration variation and production cost in case of varying, or uncertain, feed stock.

### Continuously Stirred Tank Reactor (CSTR) Model

Continuously Stirred Tank Reactors (CSTRs) are common in the process industry. The Simulink model, `sdnCSTR`, models a jacketed diabatic (i.e., non-adiabatic) tank reactor described in [1]. The CSTR is assumed to be perfectly mixed, with a single first-order exothermic and irreversible reaction,  $A \rightarrow B$ , the reactant, is converted to  $B$ , the product.

In this example, you use the following two-state CSTR model, which uses basic accounting and energy conservation principles:

- $C_A$ , and  $C_{A0}$  - Concentrations of A in the CSTR and in the feed [kgmol/m<sup>3</sup>]
- $T$ ,  $T_0$ , and  $T_c$  - CSTR, feed, and coolant temperatures [K]
- $Q$  and  $\rho$  - Volumetric flow rate [m<sup>3</sup>/h] and the density of the material in the CSTR [1/m<sup>3</sup>]
- $H$  and  $A_c$  - Height [m] and heated cross-sectional area [m<sup>2</sup>] of the CSTR.
- $k_0$  - Pre-exponential non-thermal factor for reaction [1/h]
- $E$  and  $Q_r$  - Activation energy and heat of reaction for  $A \rightarrow B$  [kcal/kgmol]
- $R$  - Boltzmann's gas constant [kcal/(kgmol \* K)]

- and - Heat capacity [kcal/K] and heat transfer coefficients [kcal/(m<sup>2</sup> \* K \* h)]

Open the Simulink model.

```
open_system('sdoCSTR');
```

The model includes a cascaded PID controller in the `Controller` subsystem. The controller regulates the reactor temperature, `T`, and reactor residual concentration, `C`.

### **CSTR Design Problem**

Assume that the CSTR is cylindrical, with the coolant applied to the base of the cylinder. Tune the CSTR cross-sectional area, `A`, and CSTR height, `H`, to meet the following design goals:

- Minimize the variation in residual concentration, `C`. Variations in the residual concentration negatively affect the quality of the CSTR product. Minimizing the variations also improves CSTR profit.
- Minimize the mean coolant temperature `T_c`. Heating or cooling the jacket coolant temperature is expensive. Minimizing the mean coolant temperature improves CSTR profit.

The design must allow for variations in the quality of supply feed concentration, `C_f`, and feed temperature, `T_f`. The CSTR is fed with feed from different suppliers. The quality of the feed differs from supplier to supplier and also varies within each supply batch.

### **Specify Design Variables**

Select the following model parameters as design variables for optimization:

- Cylinder cross-sectional area
- Cylinder height

```
p = sdo.getParameterFromModel('sdoCSTR',{ 'A', 'h' });
```

Limit the cross-sectional area to a range of [1 2] m<sup>2</sup>.

```
p(1).Minimum = 1;
p(1).Maximum = 2;
```

Limit the height to a range of [1 3] m.

```
p(2).Minimum = 1;
p(2).Maximum = 3;
```

### **Specify Uncertain Variables**

Select the feed concentration and feed temperature as uncertain variables. You evaluate the design using different values of feed temperature and concentration.

```
pUnc = sdo.getParameterFromModel('sdoCSTR',{'FeedCon0','FeedTemp0'});
```

Create a parameter space for the uncertain variables. Use normal distributions for both variables. Specify the mean as the current parameter value. Specify a variance of 5% of the mean for the feed concentration and 1% of the mean for the temperature.

```
uSpace = sdo.ParameterSpace(pUnc);
uSpace = setDistribution(uSpace,'FeedCon0',makedist('normal',pUnc(1).Value,
uSpace = setDistribution(uSpace,'FeedTemp0',makedist('normal',pUnc(2).Value
```

The feed concentration is inversely correlated with the feed temperature. Add this information to the parameter space.

```
%uSpace.RankCorrelation = [1 -0.6; -0.6 1];
```

The rank correlation matrix has a row and column for each parameter with the (i,j) entry specifying the correlation between the i and j parameters.

Sample the parameter space. The scatter plot shows the correlation between concentration and temperature.

```
rng('default'); %For reproducibility
```

```
uSmpl = sdo.sample(uSpace,60);  
sdo.scatterPlot(uSmpl)
```

Ideally you want to evaluate the design for every combination of points in the design and uncertain spaces, which implies  $30 \times 60 = 1800$  simulations. Each simulation takes around 0.5 sec. You can use parallel computing to speed up the evaluation. For this example you instead only use the samples that have maximum & minimum concentration and temperature values, reducing the evaluation time to around 1 min.

```
[~,iminC] = min(uSmpl.FeedCon0);  
[~,imaxC] = max(uSmpl.FeedCon0);  
[~,iminT] = min(uSmpl.FeedTemp0);  
[~,imaxT] = max(uSmpl.FeedTemp0);  
uSmpl = uSmpl(unique([iminC,imaxC,iminT,imaxT]) ,:);
```

#### **Specify Design Requirements**

The design requirements require logging model signals. During optimization, the model is simulated using the current value of the design variables. Logged signals are used to evaluate the design requirements.

Log the following signals:

- CSTR concentration, available at the second output port of the sdoCSTR/CSTR block

```
Conc = Simulink.SimulationData.SignalLoggingInfo;  
Conc.BlockPath = 'sdoCSTR/CSTR';  
Conc.OutputPortIndex = 2;  
Conc.LoggingInfo.NameMode = 1;  
Conc.LoggingInfo.LoggingName = 'Concentration';
```

- Coolant temperature, available at the first output of the sdoCSTR/Controller block

```
Coolant = Simulink.SimulationData.SignalLoggingInfo;  
Coolant.BlockPath = 'sdoCSTR/Controller';
```

```
Coolant.OutputPortIndex      = 1;  
Coolant.LoggingInfo.NameMode = 1;  
Coolant.LoggingInfo.LoggingName = 'Coolant';
```

Create and configure a simulation test object to log the required signals.

```
simulator = sdo.SimulationTest('sdoCSTR');  
simulator.LoggingInfo.Signals = [Conc,Coolant];
```

### **Create Objective/Constraint Function**

Create a function to evaluate the CSTR design. This function is called at each optimization iteration.

Use an anonymous function with one argument that calls the `sdoCSTR_design` function.

```
evalDesign = @(p) sdoCSTR_design(p,simulator,pUnc,uSmp1);
```

The `evalDesign` function:

- Has one input argument that specifies the CSTR dimensions
- Returns the optimization objective value

The `sdoCSTR_design` function uses a `for` loop that iterates through the sample values specified for the feed concentration. Within the loop, the function:

- Simulates the model using the current iterate, feed concentration, and feed temperature values
- Calculates the residual concentration variation and coolant temperature costs

To view the objective function, type `edit sdoCSTR_design`.

### **Evaluate Initial Design**

Call the `evalDesign` function with the initial CSTR dimensions.

```
dInit = evalDesign(p)
```

```
dInit =  
  
          F: 11.3358  
    costConc: 6.4387  
  costCoolant: 4.8971
```

Plot the model response for the initial design. Simulate the model using the sample feed concentration values. The plot shows the variation in the residual concentration and coolant temperature.

```
sdoCSTR_plotModelResponse(p,simulator,pUnc,uSmpl);
```

The `sdoCSTR_plotModelResponse` function plots the model response. To view this function, type `edit sdoCSTR_plotModelResponse`.

### **Optimize Design**

Pass the objective function and initial CSTR dimensions to `sdo.optimize`.

```
pOpt = sdo.optimize(evalDesign,p)
```

```
Optimization started 18-Jan-2014 17:27:48
```

Iter	F-count	f(x)	max constraint	Step-size	First-order optimality
0	4	5.17935	0		
1	8	3.81245	0	2.01	7.81
2	12	2.65827	0	0.574	3.06
3	16	2.53697	0	0.162	0.423
4	20	2.52022	0	0.0154	0.249
5	24	2.48533	0	0.072	0.163
6	28	2.47909	0	0.0285	0.107
7	37	2.47708	0	0.0019	0.143
8	42	2.46892	0	0.0477	0.452

9	50	2.46495	0	0.00891	0.397
10	65	2.46444	0	0.00127	0.351
11	72	2.46444	0	0.000801	0.351

Local minimum possible. Constraints satisfied.

fmincon stopped because the size of the current step is less than the selected value of the step size tolerance and constraints are satisfied to within the selected value of the constraint tolerance.

pOpt(1,1) =

```
Name: 'A'  
Value: 2  
Minimum: 1  
Maximum: 2  
Free: 1  
Scale: 0.5000  
Info: [1x1 struct]
```

pOpt(2,1) =

```
Name: 'h'  
Value: 2.2093  
Minimum: 1  
Maximum: 3  
Free: 1  
Scale: 2  
Info: [1x1 struct]
```

2x1 param.Continuous

### Evaluate Optimized Design

Call the evalDesign function with the optimized CSTR dimensions.

```
dFinal = evalDesign(pOpt)
```

```
dFinal =  
  
          F: 2.4644  
      costConc: 1.4454  
  costCoolant: 1.0191
```

Plot the model response for the optimized design. Simulate the model using the sample feed concentration values. The optimized design reduces the residual concentration variation and average coolant temperature for different feed stocks.

```
sdoCSTR_plotModelResponse(pOpt,simulator,pUnc,uSmp1);
```

#### **Related Examples**

To learn how to use sensitivity analysis to explore the CSTR design space and select an initial design for optimization, see "Design Optimization with Uncertain Variables (Code)".

#### **References**

[1] Bequette, B.W. *Process Dynamics: Modeling, Analysis and Simulation*. 1st ed. Upper Saddle River, NJ: Prentice Hall, 1998.

```
% Close the model  
bdclose('sdoCSTR')
```



## Generate MATLAB Code for Design Optimization Problems (GUI)

This example shows how to automatically generate a MATLAB function to solve a Design Optimization problem. You use the Design Optimization tool to define an optimization problem for a hydraulic cylinder design and generate MATLAB code to solve this optimization problem.

### Hydraulic Cylinder Design Problem

The "Design Optimization to Meet Custom Objective Using the Design Optimization Tool" example shows how to use the Design Optimization tool to optimize a cylinder design. In this example we load a pre-configured Design Optimization tool session based on that example.

```
load sdoHydraulicCylinder_sdoSession
sdotool(SDOSessionData)
```

### Generate MATLAB Code

From the **Optimize** list, select **Generate MATLAB Code**.

The generated code is added to the MATLAB editor as an unsaved MATLAB function.

Examine the generated code. Significant code portions are:

- **Specify Design Variables** - Definition of the model parameters being optimized.
- **Specify Design Requirements** - Definition of the design requirements.
- **Create Optimization Objective Function** - Creation of an anonymous function that calls the subfunction `sdoHydraulicCylinder_optFcn`, which evaluates the cylinder design. `sdo.optimize` calls the anonymous function at each iteration.
- **Evaluate custom parameter requirement functions** - Evaluates the custom requirement, `MinimizeAC`, that uses the `sdoHydraulicCylinder_customObjective` function.
- **Optimize the Design** - Optimization using the `sdo.optimize` command.

Select **Save** from the MATLAB editor to save the generated function.

### **Run Generated Code**

Run the generated function.

The first output argument, `pOpt`, contains the optimized parameter values and the second output argument, `optInfo`, contains optimization information.

### **Modify the Generated Code**

You can:

- Modify the generated `sdo_sdoHydraulicCylinder` function to include or exclude new design requirements or change the optimization options.
- Call the generated `sdo_sdoHydraulicCylinder` function with a different set of parameters to optimize.

For details on how to write an objective/constraint function to use with the `sdo.optimize` command, type `help sdoExampleCostFunction` at the MATLAB command prompt.

Close the model

```
delete(sdotool('sdoHydraulicCylinder'))  
bdclose('sdoHydraulicCylinder')
```

## Skip Model Simulation Based on Parameter Constraint Violation (GUI)

This example shows how to optimize a design and specify parameter-only constraints that prevent the model from being evaluated in an invalid solution space.

During optimization, the solver may try a design variable set that results in a model simulation error, which can be computationally expensive. If you can define a parameter-only constraint that identifies such a design variable set, then the solver can use the constraint to skip such sets. In other words, you can configure the optimization to be more efficient by disallowing design variable sets that lead to simulation errors.

In this example, you optimize thermostat settings to minimize temperature set-point deviations while satisfying some constraints. One of the constraints applies to the model parameters that define the thermostat switch on/switch off points. If the switch-off point is greater than the switch-on point, evaluating the model leads to a simulation error.

### Thermostat Model

Open the model.

```
open_system('sdoThermostat');
```

The model describes a simple heater & thermostat that regulate the temperature of a room. The room is subject to external temperature fluctuations. The room temperature is computed using a first-order heat-flow equation:

Where:

- is the room temperature (C).
- the external temperature (C).

- the heat supplied by the heater (W).
- the room thermal capacity (J/C).

The heater is controlled by a thermostat that turns on when the difference between the room temperature and temperature set-point exceeds a threshold. The heater turns off when the error drops below a threshold.

The heater operation is displayed in the `Heater` use scope. The upper axis is the delivered heat and the lower axis shows the times when the heater is switched on.

The room temperature is displayed in the `Temperature` scope.

### **Thermostat Design Problem**

You tune the thermostat turn-on and turn-off temperature thresholds, and also the heater power. The `Thermostat` switch block specifies the turn-on and turn-off thresholds using the variables `H_on` and `H_off`. The `Heater` block specifies the heater power using the variable `Hgain`.

The design requirements are:

- Minimize the difference between the room temperature and temperature set-point over a 24 hour period.
- The heater must not turn on more than 12 times during the 24 hour period.
- The thermostat turn-on temperature must be greater than the thermostat turn-off temperature. If this constraint is violated, the model is invalid and cannot be simulated or evaluated.

### **Open the Design Optimization Tool**

Open a pre-configured Design Optimization tool session.

```
load sdoThermostat_sdoession  
sdotool(SDOSessionData)
```

The pre-configured session specifies the following variables:

- **DesignVars** - Design variables set for the H\_on, H\_off, and Hgain model parameters.
- **Minimize\_T\_error** - Requirement to minimize the temperature deviation from the set-point.
- **LimitH\_on** - Requirement to limit the number of times the thermostat is turned on.
- **H\_on\_sig** and **T\_error** - Logged signals. H\_on\_sig represents when the heater is on. T\_error is the difference between the room temperature and the set-point.

#### **Specify Parameter Constraint**

The H\_on > H\_off requirement is not yet defined. Use a custom requirement to specify this constraint and configure the requirement to error if it is not satisfied.

In the **New** drop-down list, select **Custom Requirement**. The Create Requirement dialog opens.

In this dialog, specify the following:

- **Name** - SwitchConstraint.
- **Type** - Select Constrain the function output to be  $\geq 0$  from the **Type** list.

- **Function** - @sdoThermostat\_SwitchingConstraint.
- **Error if constraint is violated** - Select this check box.

The software calls the `sdoThermostat_SwitchingConstraint` function at each optimization iteration with a structure containing all the design variables. The output of the `sdoThermostat_SwitchingConstraint` function is the difference between the `H_on` and `H_off` values. This difference must be positive for the requirement to be satisfied.

The software evaluates custom requirements that test parameter-only constraints, such as `SwitchConstraint`, before simulating the model and evaluating the remaining requirements.

- If the constraint is violated while the **Error if constraint is violated** check box is *selected*, the software does not simulate the model to evaluate the remaining requirements. Instead, the solver assigns the cost function a NaN value for this iteration, evaluates the terminating conditions, and continues.
- If the constraint is violated while the **Error if constraint is violated** check box is *cleared*, the solver will attempt to simulate the model to evaluate the remaining requirements. Simulating the model may lead to a hard error; for example, simulating the thermostat model when `SwitchConstraint` is violated will lead to an error. In this case, the solver assigns the cost function a NaN value for this iteration, evaluates the terminating conditions, and continues.

To examine the constraint function, type `edit sdoThermostat_SwitchingConstraint`. The requirement that  $H_{on} > H_{off}$  is implemented as  $H_{on} - H_{off} > 0$

### **Optimize the Design**

Click **Optimize**.

The Optimization Progress window appears and updates at each iteration. The optimization successfully minimizes the temperature error while satisfying the switching constraints.

During this optimization, the `H_on` and `H_off` values never approach the `H_on > H_off` constraint boundary. So, there is never a danger of violating the constraint. However, changing the optimization algorithm may produce different behavior. For example, changing the optimization algorithm from the default, 'Sequential Quadratic Programming', to 'Active-Set' results in `H_on` and `H_off` values that are at the constraint boundary. This violation triggers the `SwitchConstraint` requirement and prevents model simulation for the relevant iterations.

### **View Optimized Model Response**

Simulate the model with the optimized thermostat settings. The optimized heater operation is displayed in the `Heater use` scope where the upper axis is the delivered heat and the lower axis the heater switch on times.

The optimized room temperature is displayed in the `Temperature` scope.

Close the model

```
delete(sdotool('sdoThermostat'))  
bdclose('sdoThermostat')
```



# Optimizing Parameters for Robustness

## In this section...

“What Is Robustness?” on page 3-157

“Sampling Methods for Uncertain Parameters” on page 3-158

“Optimize Parameters for Robustness (GUI)” on page 3-162

## What Is Robustness?

A design is *robust* when its response does not violate design requirements under model parameter variations. Your model may contain parameters whose values are not precisely known. Such parameters vary over a given range of values and are defined as *uncertain parameters*. You may know the nominal value and the range of values in which these uncertain parameters vary.

You can use Simulink Design Optimization software to incorporate the parameter uncertainty to test the robustness of your design. When you optimize parameters for robustness, the optimization solver uses the responses computed using all the uncertain parameter values to adjust the design variable values.

You can specify the same parameter both as a design *and* uncertain variable. However, you cannot use a parameter both as a design and uncertain variable in the same optimization run. Also, you cannot add uncertainty to controller or plant parameters during optimization-based control design in the SISO Design Tool.

The uncertain variables can be scalar, vector, matrix or an expression.

You can test and optimize parameters for model robustness in the following ways:

- **Before Optimization.** Specify the parameter uncertainty *before* you optimize the parameters to meet the design requirements. In this case, the optimization method optimizes the signals based on both nominal parameter values as well as the uncertain values. This mode requires more computational time.

- **After Optimization.** Specify the parameter uncertainty *after* you have optimized the model parameters to meet design requirements. You can then test the effect of the uncertain parameters by plotting the model's response. If the response violates the design requirements, you can optimize the parameters again by including the parameter uncertainty during the optimization.

**Related Examples**

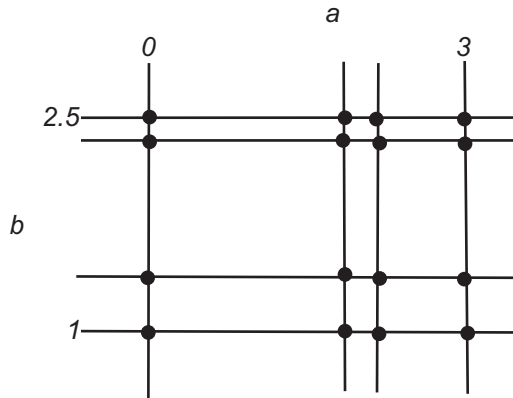
“Optimize Parameters for Robustness (GUI)” on page 3-162

**More About**

“Sampling Methods for Uncertain Parameters” on page 3-158

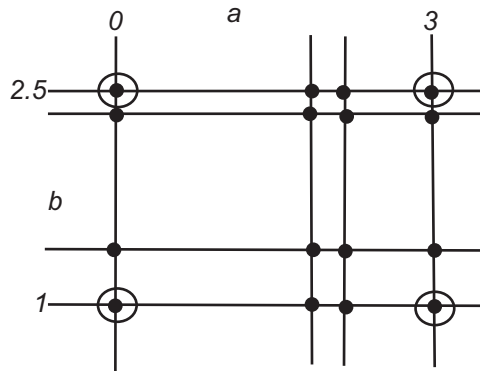
**Sampling Methods for Uncertain Parameters**

Sample values for uncertain parameters are a vector of numerical values. You can specify the vector yourself or generate a vector of random numbers using the software. The sample values you specify can be uniformly distributed or random. For example, four sample values for two uncertain parameters  $a$  and  $b$  in the range  $[0\ 3]$  and  $[1\ 2.5]$  may look like the following figure.



There are two methods to determine the number of sample values to use during optimization:

- Only the combination of minimum and maximum values (circled)



- Combination of the entire set of values (all solid dots in the previous figure)

---

**Tip** Using only the minimum and maximum values during optimization increases the computation speed when compared to using the entire set of values.

---

For the previous example, there are 4 combinations using the minimum and maximum values and 16 combinations if you use all sample values.

In the Design Optimization tool, you specify the sampling method using the options as shown in the following figure.

Create Uncertain Variables set:

<input checked="" type="checkbox"/>	Variable	Nominal Value	Uncertain Values
<input checked="" type="checkbox"/>	w0	0.5	[0.45 0.47 0.49 0.51 0.53 0.55]
<input type="checkbox"/>			

Sampling method

- Min and Max combinations only (2 combinations)
- All combinations (6 combinations)

### **Related Examples**

“Optimize Parameters for Robustness (GUI)” on page 3-162

### **More About**

- “What Is Robustness?” on page 3-157

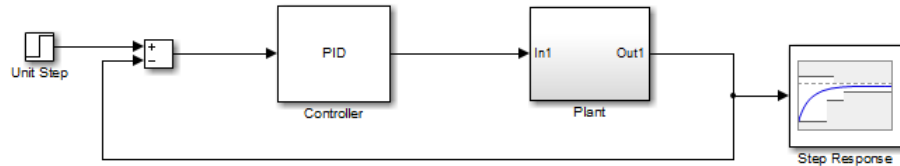
## Optimize Parameters for Robustness (GUI)

This example shows how to optimize parameters for model robustness.

1 Load a saved Design Optimization tool session.

```
load sldo_model1_desreq_optim_sdoession;  
sdotool(SDOSessionData);
```

The `sdotool` command opens the following Simulink model and a saved Design Optimization tool session.

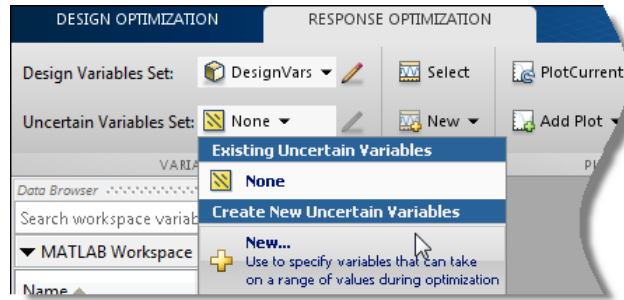


The parameters of this model,  $K_p$ ,  $K_i$  and  $K_d$ , have already been optimized to meet the following step response requirements:

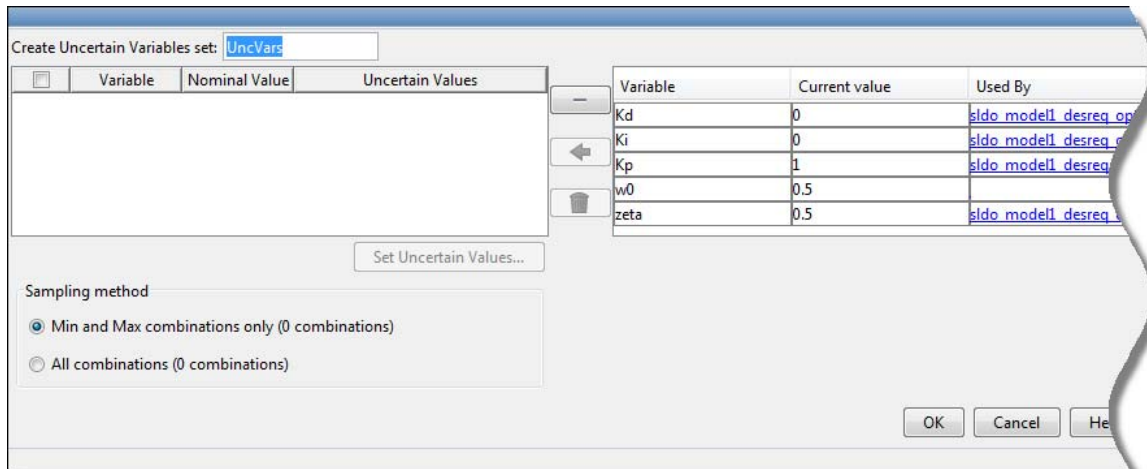
- Maximum overshoot of 5%
- Maximum rise time of 10 seconds
- Maximum settling time of 30 seconds

## 2 Specify parameter uncertainty.


- a In the **Uncertain Variables Set** drop-down list, select **New**.

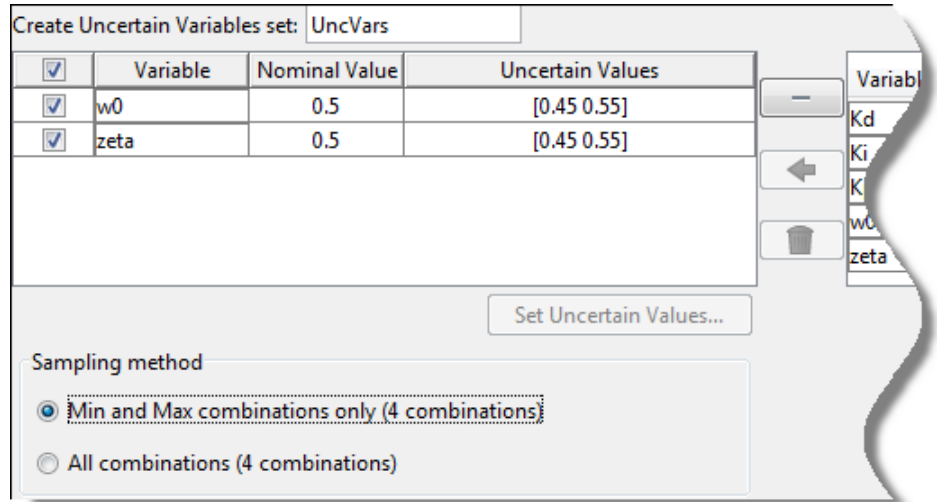


A window opens where you specify uncertain variables.



- b Click **w0** and **zeta** to select them.

- c Click  to add the selected parameters to an uncertain variables set.



The software displays the following parameter settings:

- **Variable** — Parameter name
- **Nominal Value** — Nominal value of the parameters as specified in the Simulink model
- **Uncertain Values** — Values that the uncertain parameter can take. By default, the maximum and minimum values vary by 10% of the nominal value.

The total number of sample values to use during optimization is a combination of the maximum and minimum values of the uncertain parameters.

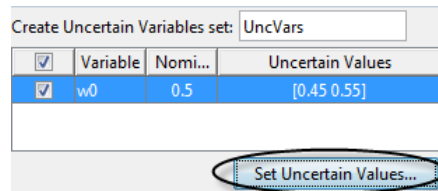
The check-box indicates that the parameter is included in the uncertain variable set. The default uncertain variable set name is `UncVars`.

Click **OK**. A new variable `UncVars` appears in **Design Optimization Workspace** of the Design Optimization tool.

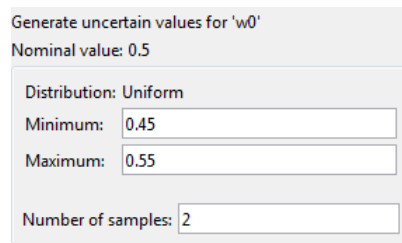


## Specify Random Values

Instead of specifying sample values, you can auto-generate random values in a specific range. Select a parameter and click **Set Uncertain Values**.



A window opens where you specify the range and the number of samples.

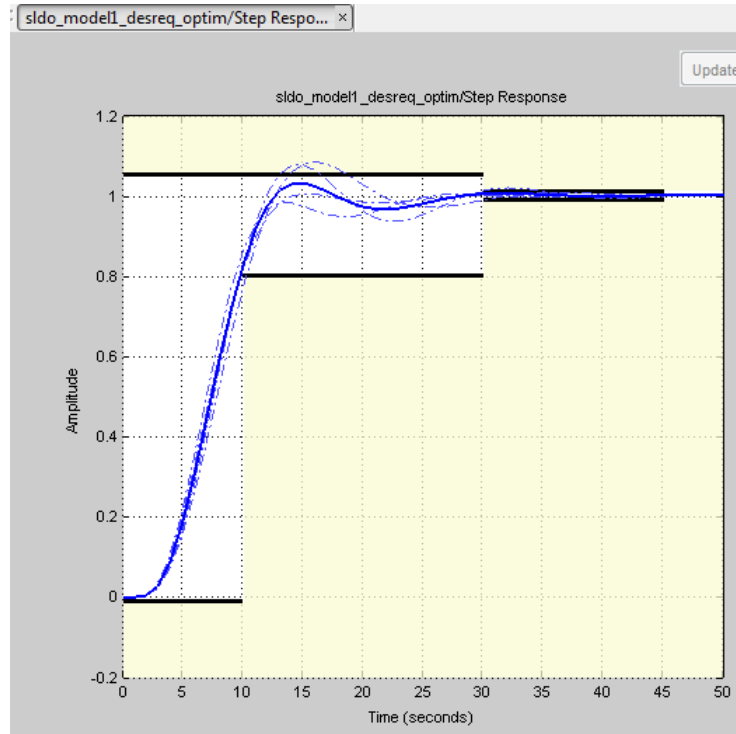


**3** Test the model robustness to the uncertain parameters.

**a** Click **Plot Current Response**.



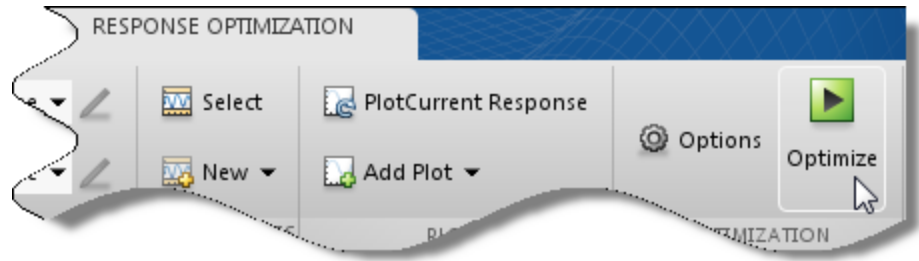
The step response plot, displaying the requirements, updates.



- The solid curve corresponds to the model response computed using the optimized parameters and nominal values of the uncertain parameter.
- The four dashed curves correspond to the model response with the minimum and maximum values of the uncertain parameters.

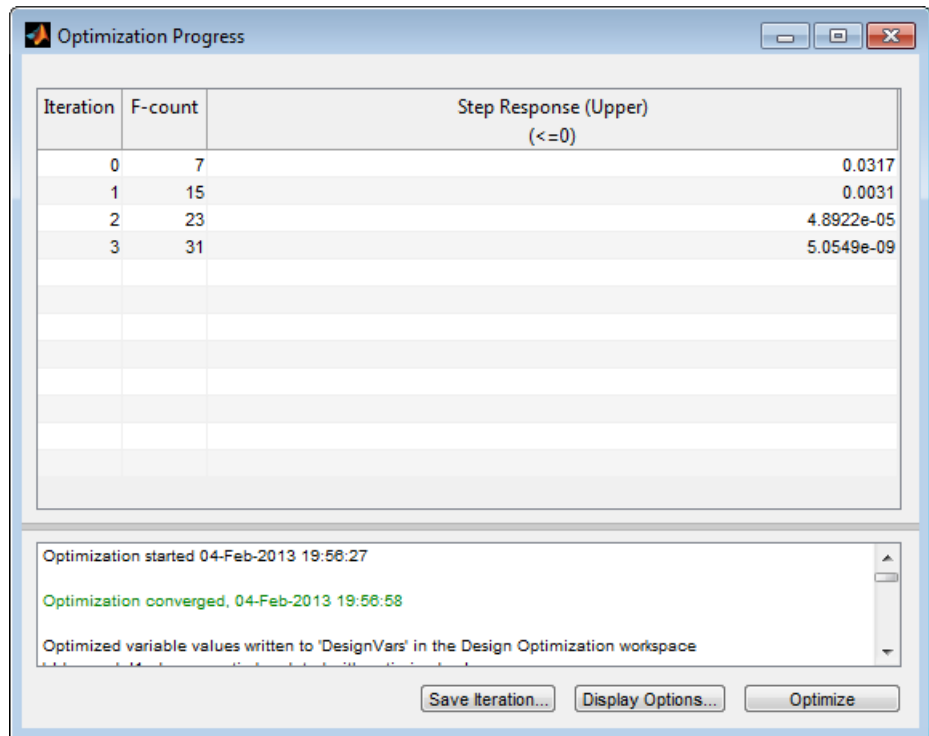
The dashed plot lines show that the response during the period of 10 to 20 seconds violates the design requirements.

**4** Optimize the parameters for model robustness. Click **Optimize**.



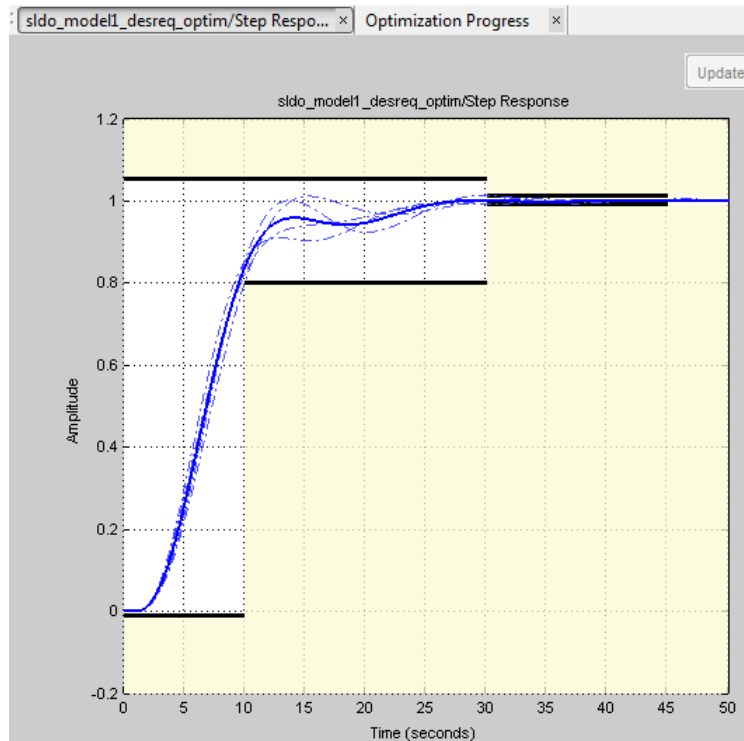
The Optimization Progress window opens which displays the optimization iterations.

After the optimization completes, the message **Optimization converged** indicates that the final model response computed by varying the uncertain parameters meets the specified design requirements.



#### 5 Examine the responses.

**Tip** To view only the final responses of the model, right-click the white area in the plot and uncheck **Responses > Show Iteration Responses**.



The final responses appear as the thick solid and dashed curves. The nominal and uncertain responses with parameter variations now meet the design requirements.

#### More About

- “What Is Robustness?” on page 3-157
- “Sampling Methods for Uncertain Parameters” on page 3-158

## **Related Examples**

- “Design Optimization with Uncertain Variables (Code)” on page 3-141

## Accelerating Model Simulations During Optimization

In this section...
“About Accelerating Optimization” on page 3-170
“Limitations” on page 3-170
“Setting Accelerator Mode for Response Optimization” on page 3-170

### About Accelerating Optimization

You can accelerate the response optimization computations by changing the simulation mode of your Simulink model. Simulink Design Optimization software supports `Normal` and `Accelerator` simulation modes. For more information about these modes, see “How Acceleration Modes Work” in the Simulink documentation.

The default simulation mode is `Normal`. In this mode, Simulink uses interpreted code, rather than compiled C code during simulations.

In the `Accelerator` mode, Simulink Design Optimization software runs simulations during optimization with compiled C code. Using compiled C code speeds up the simulations and reduces the time to optimize the model response signals.

### Limitations

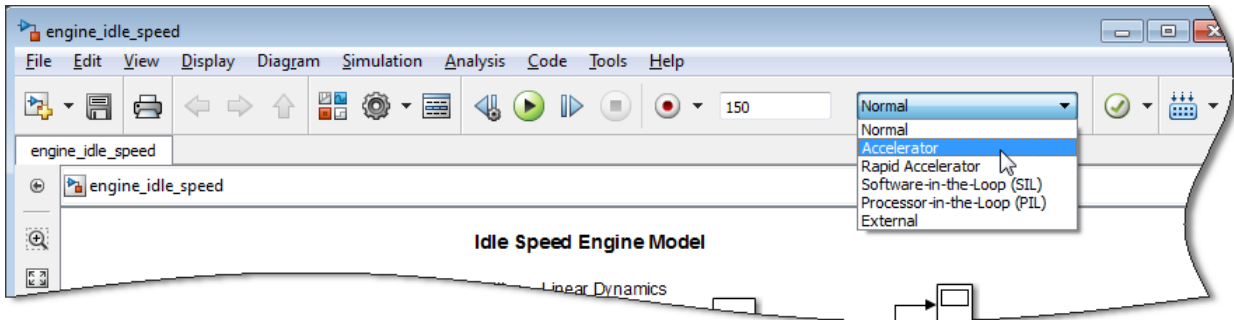
You cannot use the `Accelerator` mode if your model contains algebraic loops. If the model contains MATLAB function blocks, you must either remove them or replace them with `Fcn` blocks.

If the model structure changes during optimization, the model is compiled to regenerate the C code for each iteration. Using the `Accelerator` mode increases the computation time. To learn more about code regeneration, see “Code Regeneration in Accelerated Models” in the Simulink documentation.

### Setting Accelerator Mode for Response Optimization

To set the simulation mode to `Accelerator`, open the Simulink model window and perform one of the following actions:

- Select under **Simulation > Mode > Accelerator**.
- Choose Accelerator from the drop-down list as shown in the next figure.



---

**Tip** To obtain the maximum performance from the Accelerator mode, close all Scope blocks in your model.

---

## Speedup Using Parallel Computing

<b>In this section...</b>
“When to Use Parallel Computing for Response Optimization” on page 3-172
“How Parallel Computing Speeds Up Optimization” on page 3-173

### When to Use Parallel Computing for Response Optimization

You can use Simulink Design Optimization software with Parallel Computing Toolbox software to speed up the response optimization of a Simulink model. Using parallel computing may reduce model optimization time in the following cases:

- The model contains a large number of tuned parameters, and the Gradient descent method is selected for optimization.
- The Pattern search method is selected for optimization.
- The model contains a large number of uncertain parameters and uncertain parameter values.
- The model is complex and takes a long time to simulate.

When you use parallel computing, the software distributes independent simulations to run them in parallel on multiple MATLAB sessions, also known as *workers*. Distributing the simulations significantly reduces the optimization time because the time required to simulate the model dominates the total optimization time.

For information on how the software distributes the simulations and the expected speedup, see “How Parallel Computing Speeds Up Optimization” on page 3-173.

For information on configuring your system and using parallel computing, see “How to Use Parallel Computing” on page 3-177.



## How Parallel Computing Speeds Up Optimization

You can enable parallel computing with the `Gradient descent` and `Pattern search` optimization methods. When you enable parallel computing, the software distributes independent simulations during optimization on multiple MATLAB sessions. The following topics describe which simulations are distributed and the potential speedup using parallel computing:

- “Parallel Computing with the Gradient Descent Method” on page 3-173
- “Parallel Computing with the Pattern Search Method” on page 3-174

### Parallel Computing with the Gradient Descent Method

When you select `Gradient descent` as the optimization method, the model is simulated during the following computations:

- Constraint and objective value computation — One simulation per iteration
- Constraint and objective gradient computations — Two simulations for every tuned parameter per iteration
- Line search computations — Multiple simulations per iteration

The total time,  $T_{total}$ , taken per iteration to perform these simulations is given by the following equation:

$$T_{total} = T + (N_p \times 2 \times T) + (N_{ls} \times T) = T \times (1 + (2 \times N_p) + N_{ls})$$

where  $T$  is the time taken to simulate the model and is assumed to be equal for all simulations,  $N_p$  is the number of tuned parameters, and  $N_{ls}$  is the number of line searches.  $N_{ls}$  is difficult to estimate and you generally assume it to be equal to one, two, or three.

When you use parallel computing, the software distributes the simulations required for constraint and objective gradient computations. The simulation time taken per iteration when the gradient computations are performed in parallel,  $T_{totalP}$ , is approximately given by the following equation:

$$T_{totalP} = T + (\text{ceil}\left(\frac{N_p}{N_w}\right) \times 2 \times T) + (N_{ls} \times T) = T \times (1 + 2 \times \text{ceil}\left(\frac{N_p}{N_w}\right) + N_{ls})$$

where  $N_w$  is the number of MATLAB workers.

---

**Note** The equation does not include the time overheads associated with configuring the system for parallel computing and loading Simulink software on the remote MATLAB workers.

---

The expected speedup for the total optimization time is given by the following equation:

$$\frac{T_{totalP}}{T_{total}} = \frac{1 + 2 \times \text{ceil}\left(\frac{N_p}{N_w}\right) + N_{ls}}{1 + (2 \times N_p) + N_{ls}}$$

For example, for a model with  $N_p=3$ ,  $N_w=4$ , and  $N_{ls}=3$ , the expected speedup

$$\text{equals } \frac{1 + 2 \times \text{ceil}\left(\frac{3}{4}\right) + 3}{1 + (2 \times 3) + 3} = 0.6 .$$

For an example of the performance improvement achieved with the Gradient descent method, see Improving Optimization Performance Using Parallel Computing.

### **Parallel Computing with the Pattern Search Method**

The Pattern search optimization method uses search and poll sets to create and compute a set of candidate solutions at each optimization iteration.

The total time,  $T_{total}$ , taken per iteration to perform these simulations, is given by the following equation:

$$T_{total} = (T \times N_p \times N_{ss}) + (T \times N_p \times N_{ps}) = T \times N_p \times (N_{ss} + N_{ps})$$

where  $T$  is the time taken to simulate the model and is assumed to be equal for all simulations,  $N_p$  is the number of tuned parameters,  $N_{ss}$  is a factor for the search set size, and  $N_{ps}$  is a factor for the poll set size.  $N_{ss}$  and  $N_{ps}$  are typically proportional to  $N_p$ .

When you use parallel computing, Simulink Design Optimization software distributes the simulations required for the search and poll set computations, which are evaluated in separate parfor loops. The simulation time taken per iteration when the search and poll sets are computed in parallel,  $T_{totalP}$ , is given by the following equation:

$$\begin{aligned} T_{totalP} &= (T \times \text{ceil}(N_p \times \frac{N_{ss}}{N_w})) + (T \times \text{ceil}(N_p \times \frac{N_{ps}}{N_w})) \\ &= T \times (\text{ceil}(N_p \times \frac{N_{ss}}{N_w}) + \text{ceil}(N_p \times \frac{N_{ps}}{N_w})) \end{aligned}$$

where  $N_w$  is the number of MATLAB workers.

---

**Note** The equation does not include the time overheads associated with configuring the system for parallel computing and loading Simulink software on the remote MATLAB workers.

---

The expected speed up for the total optimization time is given by the following equation:

$$\frac{T_{totalP}}{T_{total}} = \frac{\text{ceil}(N_p \times \frac{N_{ss}}{N_w}) + \text{ceil}(N_p \times \frac{N_{ps}}{N_w})}{N_p \times (N_{ss} + N_{ps})}$$

For example, for a model with  $N_p=3$ ,  $N_w=4$ ,  $N_{ss}=15$ , and  $N_{ps}=2$ , the expected

$$\text{speedup equals } \frac{\text{ceil}(3 \times \frac{15}{4}) + \text{ceil}(3 \times \frac{2}{4})}{3 \times (15 + 2)} = 0.27 .$$

---

**Note** Using the Pattern search method with parallel computing may not speed up the optimization time. To learn more, see “Why do I not see the optimization speedup I expected using parallel computing?” on page 3-192

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For an example of the performance improvement achieved with the `Pattern` search method, see `Improving Optimization Performance Using Parallel Computing`.

### **Related Examples**

- “How to Use Parallel Computing” on page 3-177

# How to Use Parallel Computing

## In this section...

“Configure Your System for Parallel Computing” on page 3-177

“Model Dependencies” on page 3-177

“Optimize Design Using Parallel Computing (GUI)” on page 3-179

“Optimize Design Using Parallel Computing (Code)” on page 3-182

“Troubleshooting” on page 3-183

## Configure Your System for Parallel Computing

You can speed up model optimization using parallel computing on multicore processors or multiprocessor networks. You can use parallel computing with the Design Optimization tool and `sdo.optimize`. When you optimize the model using parallel computing, the software uses the available parallel pool. If no parallel pool is available and **Automatically create a parallel pool** is selected in your Parallel Computing Toolbox preferences, then the software starts a parallel pool using the settings in those preferences.

When you begin the optimization, the software automatically detects model dependencies and temporarily adds them to the parallel pool workers. However, to ensure that workers are able to access the undetected file and path dependencies, create a cluster profile that specifies the same. The parallel pool used to optimize the model must be associated with this cluster profile. For information regarding creating a cluster profile, see “Create and Modify Cluster Profiles” in the Parallel Computing Toolbox documentation.

To manually open a parallel pool that uses a specific cluster profile, use:

```
parpool(MyProfile);
```

`MyProfile` is the name of a cluster profile.

## Model Dependencies

*Model dependencies* are any referenced models, data (model variables etc.), S-functions, and additional files necessary to run the model. Before starting

the optimization, you must verify that all the remote workers can access the model dependencies. Otherwise, you may get unexpected results.

### **Making File Dependencies Accessible to Remote Workers**

When you use parallel computing, the Simulink Design Optimization software helps you identify model path dependencies. To do so, the software uses the Simulink Manifest Tools. However, the dependency analysis may not find all the files required by your model. For example, folders containing code for your model or block callbacks may not be detected. To learn more, see “Scope of Dependency Analysis” in the Simulink documentation.

If your model has undetected file dependencies, then specify them in the Files and Folders section of the cluster profile.

If your model has path dependencies that are undetected or inaccessible by the remote workers, then add them to the list of model path dependencies. For more information, see:

- “Optimize Design Using Parallel Computing (GUI)” on page 3-179
- “Optimize Design Using Parallel Computing (Code)” on page 3-182

### **Making Data Dependencies Accessible to Remote Workers**

You can check whether a model has access to all its data dependencies, such as variables required for model initialization. On your local machine, complete the following steps:

- 1 Close the model, and clear the MATLAB workspace.
- 2 Load the model. Verify that only the specified dependencies are accessible to the model.
- 3 Simulate the model. If the model errors, a dependency is missing. For example, if a simulation error occurs because a variable is not defined, you can correct the problem in one of the following ways:
  - Add the variable to the model workspace.

- Create a MATLAB script that creates the variable, and add the file to the list of dependencies. Modify the `PreLoadFcn` callback of the model to add a call to the MATLAB script.

## Optimize Design Using Parallel Computing (GUI)

To optimize a model response using parallel computing in the Design Optimization tool:

- 1** Ensure that the software can access parallel pool workers that use the appropriate cluster profile.

For more information, see “Configure Your System for Parallel Computing” on page 3-177.

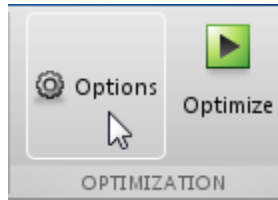
- 2** Open the Design Optimization tool for the model.

- 3** Configure the design variables, design requirements, and, optionally, optimization settings.

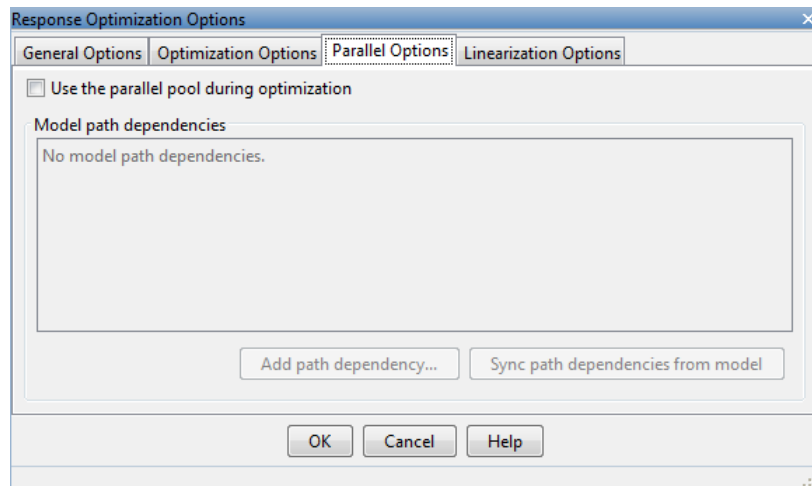
For more information, see “Specify Design Variables” on page 3-65, “Specify Time-Domain Design Requirements” on page 3-25, “Specify Frequency-Domain Design Requirements” on page 3-43, and “Optimization Options” on page 3-77.

**4** Open the **Parallel Options** tab.

**a** In the Design Optimization tool, click **Options**.



**b** Click the **Parallel Options** tab.



**5** Select the **Use the parallel pool during optimization** check box.

This option checks for model path dependencies in your Simulink model and displays them in the **Model path dependencies** list box.

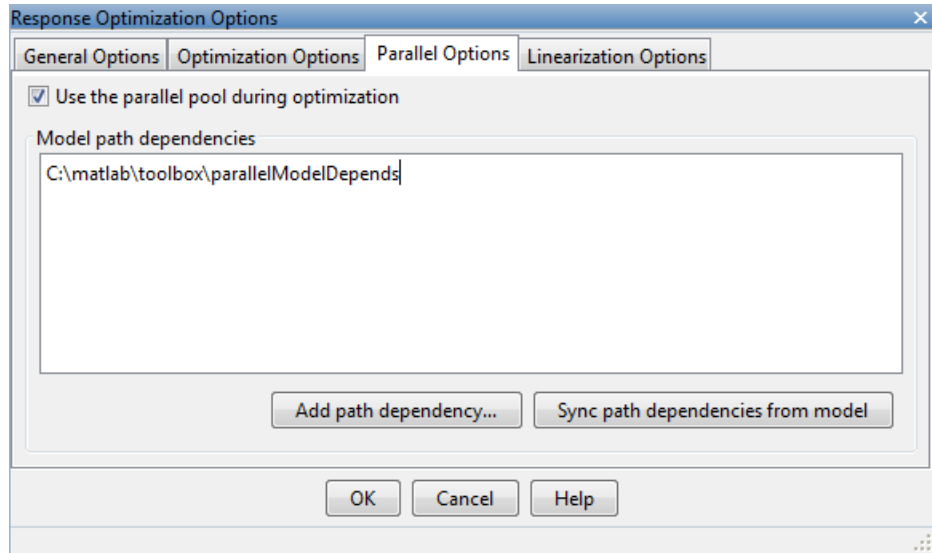
---

**Note** The automatic path dependencies check may not detect all the path dependencies in your model.

For more information, see “Model Dependencies” on page 3-177.

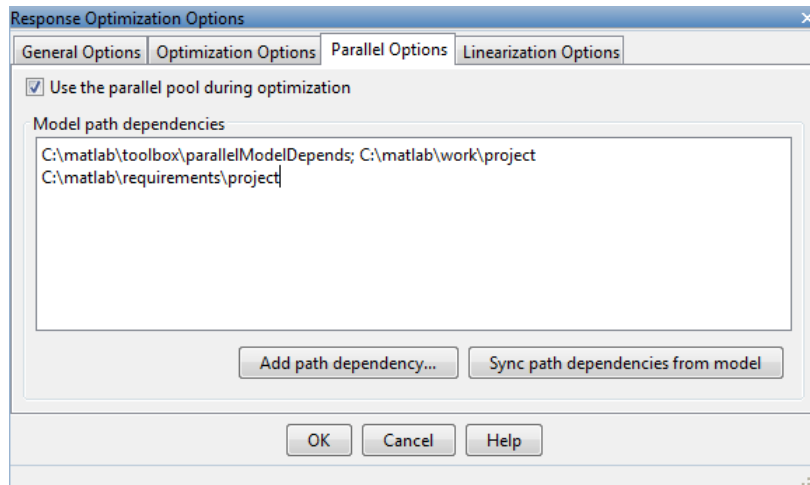
---





- 6 (Optional) Add the path dependencies that the automatic check does not detect.

Specify the paths in the **Model path dependencies** list box. You can specify the paths separated with a semicolon or on a new line.



Alternatively, you can click **Add path dependency** to open a dialog box, and select the folder to add.

- 7** (Optional) In the **Model path dependencies** list box, update the paths on local drives to make them accessible to remote workers. For example, change `C:\` to `\\\\hostname\C$\`.
- 8** (Optional) If you modify the Simulink model such that it introduces a new path dependency, then you must resync the path dependencies. Click **Sync path dependencies from model** in the **Parallel Options** tab to rerun the automatic dependency check for your model.  
  
This action updates the **Model path dependencies** list box with any new path dependency found in the model.
- 9** Click **OK**.
- 10** In the Design Optimization tool, click **Optimize** to optimize the model response using parallel computing.

For information on troubleshooting problems related to optimization using parallel computing, see “Troubleshooting” on page 3-183.

## Optimize Design Using Parallel Computing (Code)

To optimize a model response using parallel computing at the command line:

- 1** Ensure that the software can access parallel pool workers that use the appropriate cluster profile.

For more information, see “Configure Your System for Parallel Computing” on page 3-177.

- 2** Open the model.
- 3** Specify design requirements and design variables.
- 4** Enable parallel computing using an optimization option set, `opt`.

```
opt = sdo.OptimizeOptions;  
opt.UseParallel = 'always';
```

- 5 Find the model path dependencies.

```
dirs = sdo.getModelDependencies(modelname)
```

---

**Note** `sdo.getModelDependencies` may not detect all the path dependencies in your model.

For more information, see “Model Dependencies” on page 3-177.

---

- 6 (Optional) Modify `dirs` to include the path dependencies that `sdo.getModelDependencies` does not detect.

```
dirs = vertcat(dirs, '\\hostname\C$\matlab\work')
```

- 7 (Optional) Modify `dirs` to make paths on local drives accessible to remote workers.

```
dirs = regexprep(dirs, 'C:/', '\\\hostname\C$\')
```

- 8 Add the path dependencies for optimization.

```
opt.ParallelPathDependencies = dirs;
```

- 9 Run the optimization.

```
[pOpt,opt_info] = sdo.optimize(opt_fcn,param,opt);
```

For information on troubleshooting problems related to optimization using parallel computing, see “Troubleshooting” on page 3-183.

## Troubleshooting

- “Why are the optimization results with and without using parallel computing different?” on page 3-184
- “Why do I not see the optimization speedup I expected using parallel computing?” on page 3-184
- “Why does the optimization using parallel computing not make any progress?” on page 3-185

- “Why does the optimization using parallel computing not stop when I click the **Stop optimization** button?” on page 3-185

#### **Why are the optimization results with and without using parallel computing different?**

- Different numerical precision on the client and worker machines can produce marginally different simulation results. Thus, the optimization method can take a completely different solution path and produce a different result.
- The client and worker machines must have models in identical states. For example, you must verify that the model running on the client uses exactly the same variable values as the workers. You must also verify that the client and workers are accessing model dependencies in identical states.
- When you use parallel computing with the `Pattern search` method, the search is more comprehensive and can result in a different solution.

To learn more, see “Parallel Computing with the Pattern Search Method” on page 3-174.

#### **Why do I not see the optimization speedup I expected using parallel computing?**

- When you optimize a model that does not have a large number of parameters or does not take long to simulate, you might not see a speedup in the optimization time. In such cases, the overhead associated with creating and distributing the parallel tasks outweighs the benefits of running the optimization in parallel.
- Using the `Pattern search` method with parallel computing might not speed up the optimization time. Without parallel computing, the method stops the search at each iteration when it finds a solution better than the current solution. The candidate solution search is more comprehensive when you use parallel computing. Although the number of iterations might be larger, the optimization without using parallel computing might be faster.

To learn more about the expected speedup, see “Parallel Computing with the Pattern Search Method” on page 3-174.

## Why does the optimization using parallel computing not make any progress?

In some cases, the gradient computations on the remote worker machines may silently error out when you use parallel computing. In such cases, the Optimization Progress window shows that the  $f(x)$  and `max constraint` values do not change, and the optimization terminates after two iterations with the message `Unable to satisfy constraints`. To troubleshoot the problem:

- 1 Run the optimization for a few iterations without parallel computing to see if the optimization progresses.
- 2 Check whether the remote workers have access to all model dependencies. Model dependencies include data variables and files required by the model to run.

To learn more, see “Model Dependencies” on page 3-177.

## Why does the optimization using parallel computing not stop when I click the Stop optimization button?

When you use parallel computing, the software must wait until the current optimization iteration completes before it notifies the workers to stop the optimization. The optimization does not terminate immediately when you click **Stop**, and, instead, appears to continue running.

### See Also

`sdo.optimize` | `sdo.OptimizeOptions` | `sdo.getModelDependencies` | `parpool`

### Related Examples

- “Optimizing Time-Domain Response of Simulink® Models Using Parallel Computing” on page 3-199

### Concepts

- “Speedup Using Parallel Computing” on page 3-172

## Optimization Does Not Make Progress

### In this section...

“Should I worry about the scale of my responses and how constraints and design requirements are discretized?” on page 3-186

“Why don’t the responses and parameter values change at all?” on page 3-186

“Why does the optimization stall?” on page 3-186

### **Should I worry about the scale of my responses and how constraints and design requirements are discretized?**

No. Simulink Design Optimization software automatically normalizes constraints, design requirement and response data.

### **Why don’t the responses and parameter values change at all?**

The optimization problem you formulated might be nonsmooth. This means that small parameter changes have no effect on the amount by which response signals satisfy or violate the constraints and only large changes will make a difference. Try switching to a search-based method such as simplex search or pattern search. Alternatively, look for initial guesses outside of the dead zone where parameter changes have no effect. If you are optimizing the response of a Simulink model, you could also try removing nonlinear blocks such as Quantizer or Dead Zone.

### **Why does the optimization stall?**

When optimizing a Simulink model, certain parameter combinations can make the simulation stall for models with strong nonlinearities or frequent mode switching. In these cases, the ODE solvers take smaller and smaller step sizes. Stalling can also occur when the model’s ODEs become too stiff for some parameter combinations. A symptom of this behavior is when the Simulink model status is Running and clicking the **Stop** button fails to interrupt the optimization. When this happens, you can try one of the following solutions:

- Switch to a different ODE solver, especially one of the stiff solvers.
- Specify a minimum step size.
- Disable zero crossing detection if chattering is occurring.
- Tighten the lower and upper bounds on parameters that cause simulation difficulties. In particular, eliminate regions of the parameter space where some model assumptions are invalid and the model behavior can become erratic.

## Optimization Convergence

### In this section...

“What to do if the optimization does not get close to an acceptable solution?” on page 3-188

“Why does the optimization terminate before exceeding the maximum number of iterations, with a solution that does not satisfy all the constraints or design requirements?” on page 3-189

“What to do if the optimization takes a long time to converge even though it is close to a solution?” on page 3-189

“What to do if the response becomes unstable and does not recover?” on page 3-190

### What to do if the optimization does not get close to an acceptable solution?

- If you are using pattern search, check that you have specified appropriate maximum and minimum values for all your tuned parameters or compensator elements. The pattern search method looks inside these bounds for a solution. When they are set to their default values of Inf and -Inf, the method searches within  $\pm 100\%$  of the initial values of the parameters. In some cases this region is not large enough and changing the maximum and minimum values can expand the search region.
- Your optimization problem might have local minima. Consider running one of the search-based methods first to get closer to an acceptable solution.
- Reduce the number of tuned parameters and compensator elements by removing from the design variables or from the **Compensators** pane (when using a SISO Design Task) those parameters that you know only mildly influence the optimized responses. After you identify reasonable values for the key parameters, add the fixed parameters back to the tunable list and restart the optimization using these reasonable values as initial guesses.
- The software may have encountered errors during the optimization. Review the errors to determine if you can make changes to improve the optimization results. Changes may require modifications to the model, requirements, or optimization settings.



- In the Design Optimization tool, the software creates a structure named `EvalErrors` in the **Design Optimization Workspace** when the optimization completes with errors. Export this structure to the MATLAB workspace and examine its contents at the command line. `EvalErrors` has two fields, `Errors` and `DesignVars`, containing the errors encountered during optimization and the corresponding design variable values. To reproduce a specific error, use `sdo.setValueInModel` to run the model using the design variables that correspond to the error.
- At the command line, the second output of `sdo.optimize`, `opt_info`, is a structure that provides information regarding the optimization. `opt_info.exitflag` identifies the reason the optimization terminated. For more information regarding exit flags, see “Exit Flags and Exit Messages”.

### **Why does the optimization terminate before exceeding the maximum number of iterations, with a solution that does not satisfy all the constraints or design requirements?**

- It might not be possible to achieve your specifications. Try relaxing the constraints or design requirements that the response signals violate the most. After you find an acceptable solution to the relaxed problem, tighten some constraints again and restart the optimization.
- The optimization might have converged to a local minimum that is not a feasible solution. Restart the optimization from a different initial guess and/or use one of the search-based methods to identify another local minimum that satisfies the constraints.

### **What to do if the optimization takes a long time to converge even though it is close to a solution?**

- In a Design Optimization tool, click **Stop** to interrupt the optimization when you think the current optimized response signals are acceptable.

When you use a SISO Design Task, click **Stop Optimization** in the **Optimization** panel of the **Response Optimization** node in the Control and Estimation Tools Manager, when you think the current optimized response signals are acceptable.

- If you use the gradient descent method, try restarting the optimization. Restarting resets the Hessian estimate and might speed up convergence.
- Increase the convergence tolerances in the Optimization Options dialog to force earlier termination.
- Relax some of the constraints or design requirements to increase the size of the feasibility region.

### **What to do if the response becomes unstable and does not recover?**

While the optimization formulation has explicit safeguards against unstable or divergent response signals, the optimization can sometimes venture into an unstable region where simulation results become erratic and gradient methods fail to find a way back to the stable region. In these cases, you can try one of the following solutions:

- Add or tighten the lower and upper bounds on compensator element and parameter values. Instability often occurs when you allow some parameter values to become too large.
- Use a search-based method to find parameter values that stabilize the response signals and then start the gradient-based method using these initial values.
- When optimizing responses in a SISO Design Task, you can try adding additional design requirements that achieve the same or similar goal. For example, in addition to a settling time design requirement on a step response plot, you could add a settling time design requirement on a root-locus plot that restricts the location of the real parts of the poles. By adding overlapping design requirements in this way, you can force the optimization to meet the requirements.

## Optimization Speed and Parallel Computing

### In this section...

“How can I speed up the optimization?” on page 3-191

“Why are the optimization results with and without using parallel computing different?” on page 3-192

“Why do I not see the optimization speedup I expected using parallel computing?” on page 3-192

“Why does the optimization using parallel computing not make any progress?” on page 3-193

“Why does the optimization using parallel computing not stop when I click the **Stop optimization** button?” on page 3-193

### How can I speed up the optimization?

- The optimization time is dominated by the time it takes to simulate the model. When optimizing a Simulink model, you can enable the Accelerator mode using **Simulation > Mode > Accelerator** in the Simulink Editor, to dramatically reduce the optimization time.

---

**Note** The Rapid Accelerator mode in Simulink software is not supported for speeding up the optimization. For more information, see “Accelerating Model Simulations During Optimization” on page 3-170.

---

- The choice of ODE solver can also significantly affect the overall optimization time. Use a stiff solver when the simulation takes many small steps, and use a fixed-step solver when such solvers yield accurate enough simulations for your model. (These solvers must be accurate in the entire parameter search space.)
- Reduce the number of tuned compensator elements or parameters and constrain their range to narrow the search space.
- When specifying parameter uncertainty (not available when optimizing responses in a SISO Design Task), keep the number of sample values small

since the number of simulations grows exponentially with the number of samples. For example, a grid of 3 parameters with 10 sample values for each parameter requires  $10^3=1000$  simulations per iteration.

## **Why are the optimization results with and without using parallel computing different?**

- Different numerical precision on the client and worker machines can produce marginally different simulation results. Thus, the optimization method can take a completely different solution path and produce a different result.
- The client and worker machines must have models in identical states. For example, you must verify that the model running on the client uses exactly the same variable values as the workers. You must also verify that the client and workers are accessing model dependencies in identical states.
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- When you optimize a model that does not have a large number of parameters or does not take long to simulate, you might not see a speedup in the optimization time. In such cases, the overhead associated with creating and distributing the parallel tasks outweighs the benefits of running the optimization in parallel.

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To learn more about the expected speedup, see “Parallel Computing with the Pattern Search Method” on page 3-174.

## **Why does the optimization using parallel computing not make any progress?**

In some cases, the gradient computations on the remote worker machines may silently error out when you use parallel computing. In such cases, the Optimization Progress window shows that the `f(x)` and `max constraint` values do not change, and the optimization terminates after two iterations with the message `Unable to satisfy constraints`. To troubleshoot the problem:

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- 2** Check whether the remote workers have access to all model dependencies. Model dependencies include data variables and files required by the model to run.

To learn more, see “Model Dependencies” on page 3-177.

## **Why does the optimization using parallel computing not stop when I click the Stop optimization button?**

When you use parallel computing, the software must wait until the current optimization iteration completes before it notifies the workers to stop the optimization. The optimization does not terminate immediately when you click **Stop**, and, instead, appears to continue running.

## Undesirable Parameter Values

### In this section...

“What to do if the optimization drives the tuned compensator elements and parameters to undesirable values?” on page 3-194

“What to do if the optimization violates bounds on parameter values?” on page 3-194

### What to do if the optimization drives the tuned compensator elements and parameters to undesirable values?

- When a tuned compensator element or parameter is positive, or when its value is physically constrained to a given range, enter the lower and upper bounds (**Minimum** and **Maximum**) in one of the following:
  - Dialog box to select design variables (in Design optimization tool)
  - **Compensators** pane (in a SISO Design Task)

This information helps guide the optimization method towards a reasonable solution.

- Specify initial guesses that are within the range of desirable values.
- In the **Compensators** pane in a SISO Design Task, verify that no integrators/differentiators are selected for optimization. Optimizing the pole/zero location of integrators/differentiators can result in drastic changes in the system gain and lead to undesirable values.

### What to do if the optimization violates bounds on parameter values?

The Gradient descent optimization method `fmincon` violates the parameter bounds when it cannot simultaneously satisfy the signal constraints and the bounds. When this happens, try one of the following:

- Specify a different value for the parameter bound and restart the optimization. A guideline is to adjust the bound by 1% of the typical value.

For example, for a parameter with a typical value of 1 and lower bound of 0, change the lower bound to 0.01.

- Relax the signal constraints and restart the optimization. This approach results in a different solution path for the `Gradient descent` method.
- Restart the optimization immediately after it terminates by clicking **Optimize** in the Design Optimization tool. This approach uses the previous optimization results as the starting point for the next optimization cycle to refine the results.
- Use the following two-step approach to perform the optimization:
  - 1** Run an initial optimization to satisfy the signal constraints.

For example, run the optimization using the `Simplex search` method. This method satisfies the signal constraints but does not support the bounds on parameter values. The results obtained using this method provide the starting point for the optimization performed in the next step. To learn more about this method, see the `fminsearch` function reference page in the Optimization Toolbox documentation.

- 2** Reconfigure the optimization by selecting a different optimization method to satisfy both the signal constraints and the parameter bounds.

For example, change the optimization method to `Gradient descent` and run the optimization again.

---

**Tip** If Global Optimization Toolbox software is installed, you can select the `Pattern search` optimization method to optimize the model response.


---

## Reverting to Initial Parameter Values

### How do I quit an optimization and revert to my initial parameter values?

- Before running an optimization, do one of the following:
  - In the Design Optimization tool, click **Options**. Uncheck **Update model at end of optimization** in the **General Options** tab.
  - In the Design Optimization tool, click **Options**. Select **Save optimized variable values as new design variable set** in the **General Options** tab.
  - Make a copy of the design variable set in the **Design Optimization Workspace**.

If you want to revert to the initial parameter values after the optimization terminates or you stop the optimization by clicking **Stop**, select the design variable that contains the initial values in the **Design Variable Set**

drop-down list and click  adjacent to **Design variables Set**. Select the design variables in the dialog box and click **Update model variable values** to revert the model parameters to their original values.

- When using a SISO Design Task, the **Start Optimization** button becomes a **Stop Optimization** button after the optimization has begun. To quit the optimization, click the **Stop Optimization** button. To revert to the initial parameter values, select **Edit > Undo Optimize compensators** from the menu in the SISO Design Tool window.



## Manage Design Optimization Tool Session

### In this section...

“Save a Session” on page 3-197

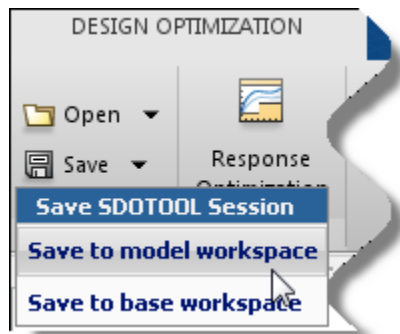
“Load a Session” on page 3-197

### Save a Session

Saving a session lets you reuse your settings and optimization results later. These settings include design requirements, design and uncertain variables, plots and optimization settings. Each Design Optimization tool session is associated with a Simulink model.

You can save the session as a MAT-file or workspace variable:

- To save the session as a MAT-file, click **Save** in the **Design Optimization** tab. A window opens where you specify the MAT-file name.
- To save the session as a model or MATLAB workspace variable, select **Save to model workspace** or **Save to base workspace** in the **Save** drop-down list.



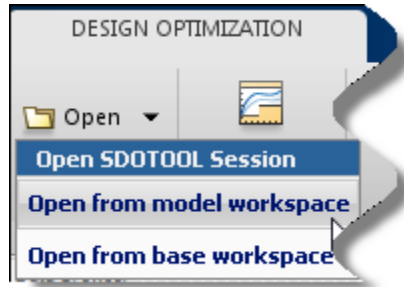
### Load a Session

You can load a saved MAT-file or workspace session:

- 1 Open a Design Optimization tool for the model.

- 2** To load a MAT-file, click **Open** in the **Design Optimization** tab. A window opens where you select the MAT-file to load.

To load a workspace variable, select **Open from model workspace** or **Open from base workspace** in the **Open** drop-down list.



## Optimizing Time-Domain Response of Simulink® Models Using Parallel Computing

This example shows how to use parallel computing to optimize the time-domain response of a Simulink® model. You use Simulink® Design Optimization™ and Parallel Computing Toolbox™ to tune the gains of a discrete PI controller of a boiler to meet the design requirements. The example also shows how the software automatically handles model path dependencies.

This example requires Parallel Computing Toolbox™.

### Opening the Model

The Simulink model consists of a boiler model and a discrete PI controller. When using parallel computing, Simulink Design Optimization performs an automatic path dependency check, which recognizes the boiler model library as an installed library.

In order to illustrate how model path dependencies are handled when using parallel computing, we copy the boiler model and library block to a temporary folder before opening the model.

```
pathToLib = boilerpressure_setup; %Copies boiler model and library to a t
addpath(pathToLib);
open_system('boilerpressure_demo')
```

```
Starting parpool using the 'local' profile ... connected to 4 workers.
```

### Design Requirements

The boiler pressure is regulated by a discrete PI controller. The design requirement for the controller is to limit the pressure variation of the boiler within  $\pm 5\%$  of the nominal pressure.

The initial controller has fairly good regulation characteristics but in the presence of additional heat disturbances, modeled by the Heat Disturbance block, we want to tune the controller performance to provide tighter pressure regulation.

Double-click the 'Response Optimization GUI with preloaded data' block in the Simulink model to open a pre-configured SDOTOOL. The SDOTOOL is configured with:

1. Upper and lower bounds representing a  $\pm 5\%$  allowable range on the drum pressure
2. A reference tracking objective to minimize the deviation of the drum pressure from nominal
3. The PI controller gains,  $K_p$  and  $K_i$ , are selected for tuning

Click **Plot Current Response** to display the drum pressure variations with the initial controller.

### **Configuring and Running the Optimization in the GUI Using Parallel Computing**

When computing the model response with the initial controller, this complex model took a long time to simulate. Using parallel computing can reduce the optimization time by simulating the model in parallel. For more information on parallel computing and optimization performance see the tutorial "Improving Optimization Performance Using Parallel Computing".

To configure the optimization problem to use parallel computing click **Options** in the SDOTOOL and select the **Parallel Options** tab. Select the "Use the parallel pool during optimization" option. This triggers an automated search for any model path dependencies. In this example, the folder that contains the Boiler Library block is found as a model path dependency, and is displayed in the Model path dependencies list box.

Note that the model path dependencies must be accessible by all the workers in the MATLAB pool. In this example, we opened a local MATLAB pool, and all the workers have access to the folder containing the Boiler Model library.

You can also manually edit the path dependency list, add paths using the folder browser, or rerun the automatic dependency checker.

Clicking OK configures the optimization to use parallel computing.

To run the optimization click the **Optimize** button. A progress window opens displaying optimization progress.

The final response shows that the optimized regulator tracks the reference pressure much more closely.

### **Configuring and Running the Optimization at the Command Line**

You can also use the command line functions to configure the optimization to use parallel computing and run the optimization.

Select the model variables for optimization and set lower limits

```
p = sdo.getParameterFromModel('boilerpressure_demo',{'Kp','Ki'});
p(1).Minimum = 0.001;
p(2).Minimum = 0.001;
```

Select the model signal to bound and create a simulator to simulate the model.

```
nPressure = Simulink.SimulationData.SignalLoggingInfo;
nPressure.BlockPath          = 'boilerpressure_demo/1//y0';
nPressure.OutputPortIndex   = 1;
nPressure.LoggingInfo.NameMode = 1;
nPressure.LoggingInfo.LoggingName = 'nPressure';

simulator = sdo.SimulationTest('boilerpressure_demo');
simulator.LoggingInfo.Signals = nPressure;
```

Get the optimization requirements defined by the check blocks in the model so that we can use them in the optimization problem.

```
bnds = getbounds('boilerpressure_demo/Drum pressure constraint');
PressureLimits = [bnds{:}];
```

```
bnds = getbounds('boilerpressure_demo/Drum pressure constraint(Reference Tr
PressureRegulation = [bnds{:}]);
requirements = struct(...
    'PressureLimits', PressureLimits, ...
    'PressureRegulation', PressureRegulation);
```

Define the function called during optimization. Notice that the function uses the simulator and requirements defined earlier to evaluate the design.

```
evalDesign = @(p) boilerpressure_design(p,simulator,requirements);
type boilerpressure_design
```

```
function design = boilerpressure_design(p,simulator,requirements)
%BOILERPRESSURE_DESIGN
%
% The boilerpressure_design function is used to evaluate a boiler
% controller design design.
%
% The |p| input argument is the vector of controller parameters.
%
% The |simulator| input argument is a sdo.SimulinkTest object used to
% simulate the |boilerpressure_demo| model and log simulation signals.
%
% The |requirements| input argument contains the design requirements used
% to evaluate the boiler controller design.
%
% The |design| return argument contains information about the design
% evaluation that can be used by the |sdo.optimize| function to optimize
% the design.
%
% see also sdo.optimize, sdoExampleCostFunction

% Copyright 2011 The MathWorks, Inc.

%% Simulate the model
%
% Use the simulator input argument to simulate the model and log model
% signals.
%
```

```
% First ensure that we simulate the model with the parameter values chosen
% by the optimizer.
%
simulator.Parameters = p;
%%
% Simulate the model and log signals.
%
simulator = sim(simulator);
%%
% Get the simulation signal log, the simulation log name is defined by the
% model |SignalLoggingName| property
%
logName = get_param('boilerpressure_demo','SignalLoggingName');
simLog = get(simulator.LoggedData,logName);

%% Evaluate the design requirements
%
% Use the requirements input argument to evaluate the design requirements
%
% Check the Pressure signal against the |PressureLimits| requirements.
%
nPressure = get(simLog,'nPressure');
c = [...
    evalRequirement(requirements.PressureLimits(1),nPressure.Values); ...
    evalRequirement(requirements.PressureLimits(2),nPressure.Values)];
%%
% Use the PressureLimits requirements as non-linear constraints for
% optimization.
design.Cleq = c(:);
%%
% Check the pressure signal against the |PressureRegulation| requirement.
%
f = evalRequirement(requirements.PressureRegulation,nPressure.Values);
%%
% Use the PressureRegulation requirement as an objective for optimization.
design.F = f;
end
```

Setup optimization options to use the parallel pool and specify the model and model dependencies used during optimization.

```

opt = sdo.OptimizeOptions;
opt.UseParallel           = 'always';
opt.OptimizedModel       = 'boilerpressure_demo';
opt.ParallelPathDependencies = sdo.getModelDependencies('boilerpressure_demo');

```

```

Warning: the following problems were found during MATLAB code analysis:
<a href="matlab:dependencies.openref('BlockCallback,OpenFcn','boilerpressure_demo')">
    First argument to "evalin" is not a literal string

```

Run the optimization

```
[pOpt,info] = sdo.optimize(evalDesign,p,opt);
```

```

Configuring parallel workers for optimization...
Parallel workers configured for optimization.

```

Optimization started 31-May-2013 11:13:52

Iter	F-count	f(x)	max constraint	Step-size	First-order optimality
0	1	17.5068	0		
1	2	11.6563	0	1.25	32.2
2	3	8.32632	0	1.27	17.4
3	4	0.694611	0	70.1	0.0391
4	5	0.562489	0	4.3	0.0355
5	7	0.543708	0	2.79	0.0316
6	12	0.543708	0	0.0515	0.0316

Local minimum possible. Constraints satisfied.

```

fmincon stopped because the size of the current step is less than
the selected value of the step size tolerance and constraints are
satisfied to within the selected value of the constraint tolerance.
Removing data from parallel workers...
Data removed from parallel workers.

```

#### Closing the Model

After the model is optimized, we remove the boiler model and library file from the temporary folder.



```
rmpath(pathToLib)
boilerpressure_cleanup(pathToLib)
bdclose('boilerpressure_demo')
```

```
Sending a stop signal to all the workers ... stopped.
```



# Sensitivity Analysis

---

- “What Is Sensitivity Analysis?” on page 4-2
- “Sampling Parameters for Sensitivity Analysis” on page 4-4
- “Sensitivity Analysis Methods” on page 4-11
- “Perform Sensitivity Analysis Using Parallel Computing” on page 4-14
- “Design Exploration using Parameter Sampling (Code)” on page 4-18
- “Identify Key Parameters for Estimation (Code)” on page 4-29

## What Is Sensitivity Analysis?

Generally, *sensitivity analysis* is defined as the study of how uncertainty in the output of a model can be attributed to different sources of uncertainty in the model input[1]. In the context of using Simulink Design Optimization software, sensitivity analysis refers to understanding how the parameters and states (optimization *design variables*) of a Simulink model influence the optimization cost function. Examples of using sensitivity analysis include:

- Before optimization — Determine the influence of the parameters of a Simulink model on the output. Use sensitivity analysis to rank parameters in order of influence so that you can determine the most influential parameters. Optimize the model by tuning the most influential parameters or perform experiments to better characterize those parameters.
- After optimization — Test how robust the cost function is to small changes in the values of optimized parameters.

One approach to sensitivity analysis is *local sensitivity analysis*, which is derivative based (numerical or analytical). Mathematically, the sensitivity of the cost function with respect to certain parameters is equal to the partial derivative of the cost function with respect to those parameters. The term *local* refers to the fact that all derivatives are taken at a single point. For simple cost functions, this approach is efficient. However, this approach can be infeasible for complex models, where formulating the cost function (or the partial derivatives) is nontrivial. For example, models with discontinuities do not always have derivatives.

Local sensitivity analysis is a *one-at-a-time* (OAT) technique. OAT techniques analyze the effect of one parameter on the cost function at a time, keeping the other parameters fixed. They explore only a small fraction of the design space, especially when there are many parameters. Also, they do not provide insight about how the interactions between parameters influence the cost function.

Another approach to sensitivity analysis is *global sensitivity analysis*, often implemented using Monte Carlo techniques. This approach uses a representative (global) set of samples to explore the design space. Use Simulink Design Optimization software to perform global sensitivity analysis. The workflow is as follows:

- 1 Sample the model parameters using experimental design principles. That is, for each parameter, generate multiple values that the parameter can assume. Define the parameter sample space by specifying probability distributions for each parameter. You can also specify parameter correlations.

For information about sampling parameters, see “Sampling Parameters for Sensitivity Analysis” on page 4-4.

- 2 Evaluate the optimization cost function at each sample point. You can plot the cost function output for the samples to visually analyze trends.
- 3 (Optional) Formally analyze the relation between the cost function and the samples. Analysis methods include correlation, partial correlation (requires a Statistics Toolbox™ license), and standardized regression. You can configure each analysis method to use either raw or ranked data.

For information about the analysis methods, see “Sensitivity Analysis Methods” on page 4-11.

## References

[1] Saltelli, A., Ratto, M., Andres, T., Campolongo, F., Cariboni, J., Gatelli, D., Saisana, M., and Tarantola, S. *Global Sensitivity Analysis. The Primer*, John Wiley and Sons, 2008.

## See Also

`sdo.sample` | `sdo.evaluate` | `sdo.analyze` | `sdo.scatterPlot`

## Related Examples

- “Design Exploration using Parameter Sampling (Code)” on page 4-18
- “Identify Key Parameters for Estimation (Code)” on page 4-29

## Concepts

- “Sensitivity Analysis Methods” on page 4-11
- “Sampling Parameters for Sensitivity Analysis” on page 4-4

## Sampling Parameters for Sensitivity Analysis

You can perform global sensitivity analysis using Simulink Design Optimization software. You vary the value of the Simulink model parameters and states of interest in a specific range. These parameters and states are the optimization *design variables*, collectively referred to as *parameters*. Each combination of values for the different parameters is referred to as a *sample* or *sample point*. A collection of samples is referred to as a *design space*, *parameter sample space*, or, simply, *sample space*. You evaluate the optimization cost function for each point in the sample space. Then, you analyze the relation between the parameter value variations and the cost function value variations to understand how the parameters influence the cost function.

Each model evaluation has a computational expense and can be time intensive. Therefore, ideally, you want to use the smallest sample set that yields useful results. You can use techniques such as *design of experiments* (DOE) (also referred to as *experimental design*) to choose an efficient sample set for sensitivity analysis.

Use `sdo.ParameterSpace` to define the parameter space. This object specifies the probability distributions and correlations for the parameters. Use this object as an input to `sdo.sample` to generate samples from the specified parameter space.

Common considerations for parameter sampling include:

- “Probability Distribution” on page 4-4
- “Bounds” on page 4-5
- “Number of Samples” on page 4-5
- “Method of Sampling” on page 4-5
- “Custom Sample Sets” on page 4-8

### Probability Distribution

Specify the probability distribution function that is best suited for each parameter. Use your knowledge of the system (empirical or theoretical) to choose the probability distribution for the parameter.

The Simulink Design Optimization software allows you to specify uniform (default) and normal distributions. If you have a Statistics Toolbox license, you can also specify any univariate probability distribution that the toolbox provides.

Specify the probability distribution of a parameter using the `ParameterDistributions` property of an `sdo.ParameterSpace` object.

## Bounds

Specify the upper and lower bounds of the value of a parameter. These bounds define the sampling range for the parameter. Use your knowledge of the parameter's range of likely values to choose the bounds.

To specify the bounds of a parameter, use the `Minimum` and `Maximum` properties of a `param.Continuous` object. Use this updated `param.Continuous` object when you specify the parameter space using an `sdo.ParameterSpace` object.

## Number of Samples

Ideally, you want to use the smallest number of samples that yield useful results, because each sample requires a model evaluation.

As the number of parameters increases, the number of samples needed to explore the design space generally increases. For correlation or regression analysis, consider using  $10Np$  samples, where  $Np$  is the number of parameters.

Specify the number of samples as the second input argument of `sdo.sample`.

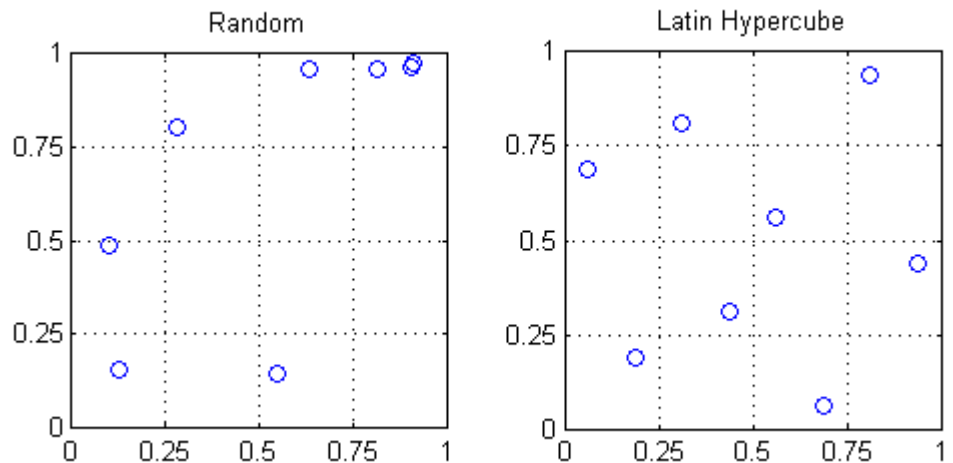
## Method of Sampling

After specifying the probability distributions and bounds for the parameters, you generate samples for the specified parameter space. You can specify the method used to generate these samples using the `Method` property of an `sdo.SampleOptions` object. Use this object as an input to `sdo.sample` to specify the sampling options. Specify the sampling method as one of the following:

- 'random' — Random samples drawn from the probability distributions specified for the parameters.

Suppose you specified a value for the RankCorrelation property of the `sdo.ParameterSpace` object that you use for sampling. The software uses the Iman-Conover method to impose the parameter correlations.

- 'lhs' — Latin hypercube samples drawn from the probability distributions specified for the parameters. Use this option for a more systematic space-filling approach than random sampling. The following figure shows the difference between random sampling and Latin hypercube design-based sampling.



The figure shows 8 samples for 2 parameters, drawn from a uniform distribution, in the interval from 0 to 1. Random sampling can result in the clustering of samples (see the top right-hand corner of the plot). Latin hypercube designs, with their stratified approach to sampling, are better able to avoid such clustering.

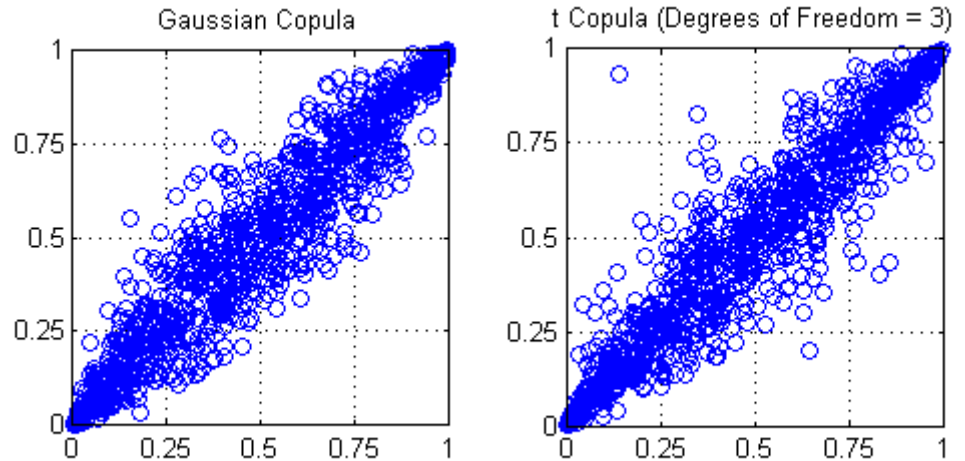
Suppose you specified a value for the RankCorrelation property of the `sdo.ParameterSpace` object that you use for sampling. The software uses the Iman-Conover method to impose the parameter correlations.

This method requires a Statistics Toolbox license.



- 'copula' — Random samples drawn from a copula. Use this option to impose correlations between the parameters.

You can use either a Gaussian copula (default) or a t copula. Specify the choice of copula using the `MethodOptions` property of the `sdo.SampleOptions` object. Use t copulas when the probability of extreme parameter values is not negligible. You must specify the degrees of freedom for a t copula. As you increase the degrees of freedom, the t copula converges to the Gaussian copula, and the probability of extreme parameter values becomes negligible. The following figure shows 1000 samples drawn for 2 parameters, in the interval from 0 to 1, using the Gaussian and t copulas.



In comparison to the Gaussian copula, the t copula has more samples that represent the extreme values of the parameters.

You can specify the correlation type as either Spearman's rank correlation or Kendall's rank correlation.

For the 'copula' method, you must also specify the value of the `RankCorrelation` property of the `sdo.ParameterSpace` object that you use for sampling.

This method requires a Statistics Toolbox license.

## Custom Sample Sets

You can specify a custom sample set. For example, suppose you want to generate a 1000 samples of the model parameter, R, which is a resistor.

```
R = param.Continuous('R',10);
```

Sample R in the 5% range of its nominal value. However, resistors of 1% tolerance are removed. So, you do not need to sample R in the 1% range. You can use the following approaches:

- “Specify Customized Probability Distribution” on page 4-8
- “Create Table of Custom Samples” on page 4-9

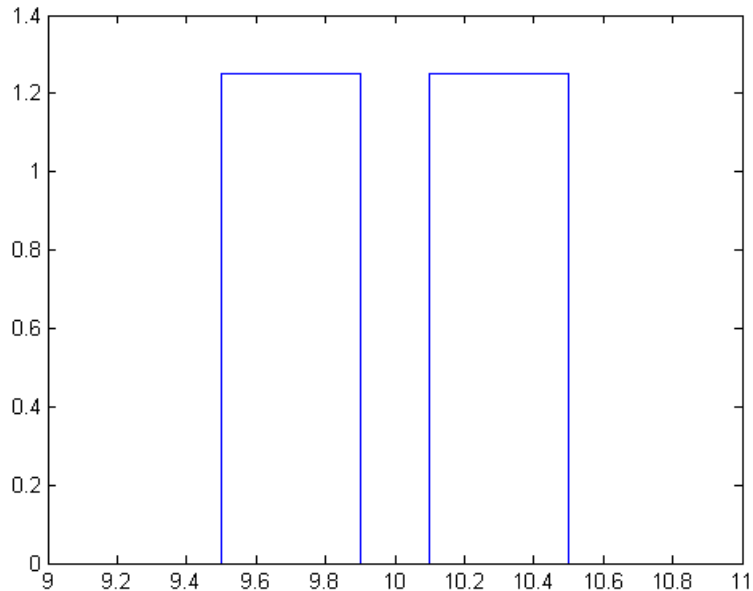
To visualize the samples and validate the sample space, use `sdo.scatterPlot`.

## Specify Customized Probability Distribution

Use a customized probability distribution to configure the parameter space and generate samples.

You can use tools provided by the Statistics Toolbox software to create customized probability distributions. For example,

```
x = [0.95 0.99 1.01 1.05]*R.Value;  
F = [0 0.5 0.5 1];  
  
pdR = makedist('PiecewiseLinear','x',x,'Fx',F);  
  
x = linspace(.9*R.Value, 1.1*R.Value, 1e3);  
plot(x, pdf(pdR, x));
```



The call to `makedist` specifies a piecewise linear distribution for the resistor value, with a “hole” in the 1% range.

Specify `pdR` as the probability distribution for the `R` parameter when you create the `sdo.ParameterSpace` object to define the parameter space.

```
ps = sdo.ParameterSpace(R,pdR);
```

Generate the samples using `sdo.sample`.

```
x = sdo.sample(ps,1000);
```

### Create Table of Custom Samples

Create a table of the custom samples. Specify one column for each parameter, and one row for each sample. The column name must be the same as the parameter name.

For example:

```
Rval = R.Value;  
Ns = 1000;  
x = table([linspace(.95*Rval,.99*Rval,Ns*.5) linspace(1.01*Rval,1.05*Rval,Ns*.5)]);
```

Consider another example, where you have two model parameters, A and B.

```
A = param.Continuous('A',1);  
B = param.Continuous('B',10);
```

Vary A for the following values: 2,3,4. Vary B for the following values: 20,30,40. Generate a table of samples for every combination of A and B.

```
Avals = [2 3 4];  
Bvals = [20 30 40];  
[Agrid,Bgrid] = meshgrid(Avals,Bvals);  
x = table(Agrid(:),Bgrid(:),'VariableNames',{'A','B'});
```

### See Also

[sdo.sample](#) | [sdo.SampleOptions](#)

### Related Examples

- “Design Exploration using Parameter Sampling (Code)” on page 4-18

### Concepts

- “What Is Sensitivity Analysis?” on page 4-2

## Sensitivity Analysis Methods

To analyze how the parameters and states (collectively referred to as *parameters*) of a Simulink model influence the cost function, first generate samples of the parameters. Then, evaluate the cost function for each sample. Finally, analyze the relationship between the parameter variations and the cost function values. Perform this analysis in the following ways:

- “Visual Analysis” on page 4-11
- “Quantitative Analysis” on page 4-11

### Visual Analysis

Plot the cost function evaluations against the parameter samples to identify trends. This method is informal and provides visual intuition about how the various parameters affect the cost function.

You can use tools such as:

- `sdo.scatterPlot` — Scatter plot of the parameter samples against the cost function evaluation
- `surf`, `mesh` — 3-D plot of samples of two parameters against the cost function evaluation

### Quantitative Analysis

Obtain summary statistics using `sdo.analyze`. This function performs linear correlation analysis by default. You can specify other analysis method(s) using an `sdo.AnalyzeOptions` options object.

Available analysis methods include:

Method Name	Description
Correlation	Use to analyze how a model parameter and the cost function are correlated
Partial correlation (requires a Statistics Toolbox license)	Use to analyze how a model parameter and the cost function are correlated, removing the effects of the remaining parameters
Standardized regression	Use when you expect that the model parameters linearly influence the cost function

For information about the formulations of these methods, see `sdo.AnalyzeOptions`.

### Linear vs. Ranked Analysis

Each of these methods supports the following analysis types:

- Linear analysis, also referred to as *Pearson* analysis — Uses raw data for analysis. Best suited when you expect a linear relation between the parameters and cost function.
- Ranked analysis, also referred to as *Spearman* analysis and *ranked transformation* — Uses ranks of data for analysis. Best suited when you expect a nonlinear monotonic relation between the parameters and the cost function.

For an example of ranked analysis, suppose you had the following data set:

$x_1$	$x_2$	$y$
9	20	340
5	60	106
2.3	50.4	870.5

Here  $x_1$  and  $x_2$  are model parameters, and  $y$  is the cost function. Each row represents a sample and the associated cost function evaluation.

The data is ranked on a per column basis. For example, when you rank the data in column 1 ( $x_1$ ), which contains the entries 9, 5, and 2.3, the ranked data is equal to 3, 2, and 1. The ranked data set for the samples of  $x_1$ ,  $x_2$  and  $y$  are as follows:

$x_1$	$x_2$	$y$
3	1	2
2	3	1
1	2	3

The ranked data set can be used for correlation, partial correlation, or standardized regression analysis.

Linear analysis retains information about intervals between data values, whereas ranked analysis does not.

## See Also

`sdo.AnalyzeOptions` | `sdo.analyze` | `sdo.sample` | `sdo.evaluate`

## Related Examples

- “Identify Key Parameters for Estimation (Code)” on page 4-29

## Concepts

- “What Is Sensitivity Analysis?” on page 4-2

## Perform Sensitivity Analysis Using Parallel Computing

### In this section...

“Configure Your System for Parallel Computing” on page 4-14

“Model Dependencies” on page 4-14

“Perform Sensitivity Analysis Using Parallel Computing” on page 4-16

### Configure Your System for Parallel Computing

To perform global sensitivity analysis, you sample the model parameters and states (collectively referred to as *parameters*), and evaluate the cost function for each sample. You use `sdo.evaluate` to perform the cost function evaluation (also referred to as *model evaluation*). Evaluating the model for a large number of samples can be time consuming. You can speed up the performance of `sdo.evaluate` using parallel computing on multicore processors or multiprocessor networks. When you call `sdo.evaluate` with the parallel computing option enabled, the software uses the available parallel pool. If no parallel pool is available and **Automatically create a parallel pool** is selected in your Parallel Computing Toolbox preferences, then the software starts a parallel pool using the settings in those preferences.

To ensure that the parallel workers are able to access the file and path dependencies, create a cluster profile that specifies the same. The parallel pool used to evaluate the model must be associated with this cluster profile. For information regarding creating a cluster profile, see “Create and Modify Cluster Profiles” in the Parallel Computing Toolbox documentation.

To manually open a parallel pool that uses a specific cluster profile, use:

```
parpool(MyProfile);
```

`MyProfile` is the name of a cluster profile.

### Model Dependencies

*Model dependencies* are any referenced models, data (model variables etc.), S-functions, or additional files necessary to run the model. Before starting the



parallel model evaluation, you must verify that all the remote workers can access the model dependencies. Otherwise, you may get unexpected results.

### **Making File Dependencies Accessible to Remote Workers**

When you use parallel computing, the Simulink Design Optimization software helps you identify model path dependencies. To do so, the software uses the Simulink Manifest Tools. However, the manifest tools may not find all the files required by your model. For example, folders containing code for your model or block callbacks may not be detected. To learn more, see “Scope of Dependency Analysis” in the Simulink documentation.

- If your model has undetected file dependencies, then specify them in the Files and Folders section of the cluster profile.
- If your model has path dependencies that are undetected or inaccessible by the remote workers, then add them to the list of model path dependencies. For more information, see “Perform Sensitivity Analysis Using Parallel Computing” on page 4-16.

### **Making Data Dependencies Accessible to Remote Workers**

You can check whether a model has access to all its data dependencies, such as variables required for model initialization. On your local machine, complete the following steps:

- 1** Close the model, and clear the MATLAB workspace.
- 2** Load the model. Verify that only the specified dependencies are accessible to the model.
- 3** Simulate the model. If the model errors, a dependency is missing. For example, if a simulation error occurs because a variable is not defined, you can correct the problem in one of the following ways:
  - Add the variable to the model workspace.
  - Create a MATLAB script that creates the variable, and add the file to the list of dependencies. Modify the `PreLoadFcn` callback of the model to add a call to the MATLAB script.

### Perform Sensitivity Analysis Using Parallel Computing

To evaluate a model using parallel computing:

- 1 Ensure that the software can access parallel pool workers that use the appropriate cluster profile.

For more information, see “Configure Your System for Parallel Computing” on page 4-14.

- 2 Open the model.
- 3 Specify the cost function and generate parameter samples for sensitivity analysis.
- 4 Enable parallel computing using an evaluation option set, `opt`.

```
opt = sdo.EvaluateOptions;  
opt.UseParallel = 'always';
```

- 5 Find the model path dependencies.

```
dirs = sdo.getModelDependencies(modelname)
```

---

**Note** `sdo.getModelDependencies` may not detect all the path dependencies in your model.

For more information, see “Model Dependencies” on page 4-14.

---

- 6 (Optional) Modify `dirs` to include the path dependencies that `sdo.getModelDependencies` does not detect.

```
dirs = vertcat(dirs, '\\hostname\C$\matlab\work')
```

- 7 (Optional) Modify `dirs` to make paths on local drives accessible to remote workers.

```
dirs = regexprep(dirs, 'C:', '\\\\hostname\C$\\')
```

- 8 Add the path dependencies for evaluation.

```
opt.ParallelPathDependencies = dirs;
```

- 9 Specify the name of the model to be evaluated in parallel.

```
opt.ModelName = modelname;
```

- 10 Evaluate the model.

```
[pOpt,opt_info] = sdo.evaluate(fcn,samples,opt);
```

**See Also**

[sdo.evaluate](#) | [sdo.EvaluateOptions](#) | [sdo.getModelDependencies](#) | [parpool](#)

## Design Exploration using Parameter Sampling (Code)

This example shows how to sample and explore a design space. You explore the design of a Continuously Stirred Tank Reactor to minimize product concentration variation and production cost. The design includes feed stock uncertainty.

You explore the CSTR design by characterizing design parameters using probability distributions. You use the distributions to generate random samples in the design space and perform Monte-Carlo evaluation of the design at these sample points. You then create plots to visualize the design space and select the best design. You can then use the best design as an initial guess for optimization of the design.

You can also use the sampled design space and Monte-Carlo evaluation output to analyze the influence of design parameters on the design, see "Sensitivity Analysis for Parameter Estimation (Code)"

### Continuously Stirred Tank Reactor (CSTR) Model

Continuously Stirred Tank Reactors (CSTRs) are common in the process industry. The Simulink model, `sdnCSTR`, models a jacketed diabatic (i.e., non-adiabatic) tank reactor described in [1]. The CSTR is assumed to be perfectly mixed, with a single first-order exothermic and irreversible reaction,  $A \rightarrow B$ , the reactant, is converted to  $B$ , the product.

In this example, you use the following two-state CSTR model, which uses basic accounting and energy conservation principles:

- $C_A$  and  $C_{A0}$  - Concentrations of A in the CSTR and in the feed [ $\text{kgmol}/\text{m}^3$ ]
- $T$ ,  $T_0$ , and  $T_c$  - CSTR, feed, and coolant temperatures [K]

- and - Volumetric flow rate [ $\text{m}^3/\text{h}$ ] and the density of the material in the CSTR [ $1/\text{m}^3$ ]
- and - Height [m] and heated cross-sectional area [ $\text{m}^2$ ] of the CSTR.
- - Pre-exponential non-thermal factor for reaction [ $1/\text{h}$ ]
- and - Activation energy and heat of reaction for [ $\text{kcal}/\text{kgmol}$ ]
- - Boltzmann's gas constant [ $\text{kcal}/(\text{kgmol} * \text{K})$ ]
- and - Heat capacity [ $\text{kcal}/\text{K}$ ] and heat transfer coefficients [ $\text{kcal}/(\text{m}^2 * \text{K} * \text{h})$ ]

Open the Simulink model.

```
open_system('sdoCSTR');
```

### **CSTR Design Problem**

Assume that the CSTR is cylindrical, with the coolant applied to the base of the cylinder. Tune the CSTR cross-sectional area, , and CSTR height, , to meet the following design goals:

- Minimize the variation in residual concentration, . Variations in the residual concentration negatively affect the quality of the CSTR product. Minimizing the variations also improves CSTR profit.
- Minimize the mean coolant temperature . Heating or cooling the jacket coolant temperature is expensive. Minimizing the mean coolant temperature improves CSTR profit.

The design must allow for variations in the quality of supply feed concentration, , and feed temperature, . The CSTR is fed with feed from different suppliers. The quality of the feed differs from supplier to supplier and also varies within each supply batch.

### **Specify Design Variables**

Select the following model parameters as design variables:

- Cylinder cross-sectional area
- Cylinder height

```
p = sdo.getParameterFromModel('sdoCSTR',{ 'A', 'h' });
```

Limit the cross-sectional area to a range of [0.2 2] m<sup>2</sup>.

```
p(1).Minimum = 0.2;  
p(1).Maximum = 2;
```

Limit the height to a range of [0.5 3] m.

```
p(2).Minimum = 0.5;  
p(2).Maximum = 3;
```

### **Sample the Design Space**

Create a parameter space for the design variables. The parameter space characterizes the allowable parameter values and combinations of parameter values.

```
pSpace = sdo.ParameterSpace(p);
```

The parameter space uses default uniform distributions for the design variables. The distribution lower and upper bounds are set to the design variable minimum and maximum value respectively.

Use the `sdo.sample` function to generate samples from the parameter space. You use the samples to evaluate the model and explore the design space.

```
rng('default') %For reproducibility  
pSmp1 = sdo.sample(pSpace,30);
```

Use the `sdo.scatterPlot` command to visualize the sampled parameter space. The scatter plot shows the parameter distributions on the diagonal subplots and pairwise parameter combinations on the off diagonal subplots.

```
figure, sdo.scatterPlot(pSmp1)
```

### Specify Uncertain Variables

Select the feed concentration and feed temperature as uncertain variables. You evaluate the design using different values of feed temperature and concentration.

```
pUnc = sdo.getParameterFromModel('sdoCSTR',{ 'FeedCon0','FeedTemp0' });
```

Create a parameter space for the uncertain variables. Use normal distributions for both variables. Specify the mean as the current parameter value. Specify a variance of 5% of the mean for the feed concentration and 1% of the mean for the temperature.

```
uSpace = sdo.ParameterSpace(pUnc);
uSpace = setDistribution(uSpace,'FeedCon0',makedist('normal',pUnc(1).Value,
uSpace = setDistribution(uSpace,'FeedTemp0',makedist('normal',pUnc(2).Value
```

The feed concentration is inversely correlated with the feed temperature. Add this information to the parameter space.

```
uSpace.RankCorrelation = [1 -0.6; -0.6 1];
```

The rank correlation matrix has a row and column for each parameter with the (i,j) entry specifying the correlation between the i and j parameters.

Sample the parameter space. The scatter plot shows the correlation between concentration and temperature.

```
uSmpl = sdo.sample(uSpace,60);
sdo.scatterPlot(uSmpl)
```

Ideally you want to evaluate the design for every combination of points in the design and uncertain spaces, which implies  $30 \times 60 = 1800$  simulations. Each simulation takes around 0.5 sec. You can use parallel computing to speed up the evaluation. For this example you instead only use the samples that

have maximum & minimum concentration and temperature values, reducing the evaluation time to around 1 min.

```
[~,iminC] = min(uSmpl.FeedCon0);  
[~,imaxC] = max(uSmpl.FeedCon0);  
[~,iminT] = min(uSmpl.FeedTemp0);  
[~,imaxT] = max(uSmpl.FeedTemp0);  
uSmpl = uSmpl(unique([iminC,imaxC,iminT,imaxT]) ,:)
```

uSmpl =

FeedCon0	FeedTemp0
9.4555	303.58
11.175	288.13
11.293	290.73
8.9308	294.16

### Create Evaluation Function

Create a function that evaluates the design for a given sample point in the design space. The design is evaluated on how well it minimizes the variation in residual concentration and mean coolant temperature.

### Specify Design Requirements

Evaluating a point in the design space requires logging model signals. Logged signals are used to evaluate the design requirements.

Log the following signals:

- CSTR concentration, available at the second output port of the sdoCSTR/CSTR block

```
Conc = Simulink.SimulationData.SignalLoggingInfo;  
Conc.BlockPath = 'sdoCSTR/CSTR';  
Conc.OutputPortIndex = 2;
```



```
Conc.LoggingInfo.NameMode      = 1;
Conc.LoggingInfo.LoggingName = 'Concentration';
```

- Coolant temperature, available at the first output of the sdoCSTR/Controller block

```
Coolant = Simulink.SimulationData.SignalLoggingInfo;
Coolant.BlockPath      = 'sdoCSTR/Controller';
Coolant.OutputPortIndex = 1;
Coolant.LoggingInfo.NameMode      = 1;
Coolant.LoggingInfo.LoggingName = 'Coolant';
```

Create and configure a simulation test object to log the required signals.

```
simulator = sdo.SimulationTest('sdoCSTR');
simulator.LoggingInfo.Signals = [Conc,Coolant];
```

### Evaluation Function

Use an anonymous function with one argument that calls the sdoCSTR\_design function.

```
evalDesign = @(p) sdoCSTR_design(p,simulator,pUnc,uSmpl);
```

The evalDesign function:

- Has one input argument that specifies the CSTR dimensions
- Returns the optimization objective value

The sdoCSTR\_design function uses a for loop that iterates through the sample values specified for the feed concentration and temperature. Within the loop, the function:

- Simulates the model using the current design point, feed concentration, and feed temperature values
- Calculates the residual concentration variation and coolant temperature costs

To view the objective function, type `edit sdoCSTR_design`.

```
type sdoCSTR_design
```

```
function design = sdoCSTR_design(p,simulator,pUnc,smplUnc)
%SDOCSTR_DESIGN
%
% The sdoCSTR_design function is used to evaluate a CSTR design.
%
% The |p| input argument is the vector of CSTR dimensions.
%
% The |simulator| input argument is a sdo.SimulinkTest object used to
% simulate the |sdoCSTR| model and log simulation signals.
%
% The |pUnc| input argument is a vector of parameters to specify the CSTR
% input feed concentration and feed temperature. The |smplUnc| argument is
% a table of different feed concentration and temperature values.
%
% The |design| return argument contains information about the design
% evaluation that can be used by the |sdo.optimize| function to optimize
% the design.
%
% see also sdo.optimize, sdoExampleCostFunction
%

% Copyright 2012-2013 The MathWorks, Inc.

%% Model Simulations and Evaluations
%
% For each value in |smplUnc|, configure and simulate the model. Use
% the logged concentration and coolant signals to compute the design cost.
%
costConc      = 0;
costCoolant   = 0;
for ct=1:size(smplUnc,1)
    %Set the feed concentration and temperature values
    pUnc(1).Value = smplUnc{ct,1};
    pUnc(2).Value = smplUnc{ct,2};
```

```

%Simulate model
simulator.Parameters = [p; pUnc];
simulator = sim(simulator);
logName = get_param('sdoCSTR','SignalLoggingName');
simLog = get(simulator.LoggedData,logName);

%Compute Concentration cost based on the standard deviation of the
%concentration from a nominal value.
Sig = find(simLog,'Concentration');
costConc = costConc+10*std(Sig.Values-2);

%Compute coolant cost based on the mean deviation from room
%temperature.
Sig = find(simLog,'Coolant');
costCoolant = costCoolant+abs(mean(Sig.Values - 294))/30;
end

%% Return Total Cost
%
% Compute the total cost as a sum of the concentration and coolant costs.
%
design.F = costConc + costCoolant;

%%
% Add the individual cost terms to the return argument. These are not used
% by the optimizer, but included for convenience.
design.costConc = costConc;
design.costCoolant = costCoolant;
end

```

### **Evaluate**

Use the `sdo.evaluate` command to evaluate the model at the sample design points.

```
y = sdo.evaluate(evalDesign,p,pSmpl);
```

Model evaluated at 30 samples.

View the results of the evaluation using a scatter plot. The scatter plot shows pairwise plots for each design variable (A,h) and design cost. The plot include the total cost, F, as well as coolant and concentration costs, `costCoolant` and `costConc` respectively.

```
sdo.scatterPlot(pSmpl,y);
```

The plot shows that larger cross-sectional areas result in lower total costs. However it is difficult to tell how the height influences the total cost.

Create a mesh plot showing the total cost as a function of A and h.

```
Ftotal = scatteredInterpolant(pSmpl.A,pSmpl.h,y.F);
xR = linspace(min(pSmpl.A),max(pSmpl.A),60);
yR = linspace(min(pSmpl.h),max(pSmpl.h),60);
[xx,yy] = meshgrid(xR,yR);
zz = Ftotal(xx,yy);
mesh(xx,yy,zz)
view(56,30)
title('Total cost as function of A and h')
zlabel('Ftotal')
xlabel(p(1).Name), ylabel(p(2).Name);
```

The plot shows that high values of A and h result in lower costs. The best design in the sampled space corresponds to the design with the lowest cost value.

```
[~,idx] = min(y.F);
pBest = [y(idx,:), pSmpl(idx,:)]
```

```
pBest =
```

F	costConc	costCoolant	A	h
---	----------	-------------	---	---

```
2.1052    1.5757    0.52953    1.8483    2.1158
```

### Refine the Design Space

The total cost surface plot shows that low cost designs are designs with A in the range [1.5 2] and h in the range [2 3]. Modify the parameter space distributions for A and h and resample the design space to focus on this region.

```
pSpace = setDistribution(pSpace, 'A', makedist('uniform', 1.5, 2));
pSpace = setDistribution(pSpace, 'h', makedist('uniform', 2, 3));
pSmp1 = sdo.sample(pSpace, 30);
```

Add the pBest found earlier to the new samples so that it is part of the refined design space.

```
pSmp1 = [pSmp1; pBest(:, 4:5)];
sdo.scatterPlot(pSmp1)
```

### Evaluate using Refined Design Space

```
y = sdo.evaluate(evalDesign, p, pSmp1);
```

Model evaluated at 31 samples.

Create a mesh plot for this section of the design space. The surface indicates that better designs are near the A = 1.9, h = 2.1 point.

```
Ftotal = scatteredInterpolant(pSmp1.A, pSmp1.h, y.F);
xR = linspace(min(pSmp1.A), max(pSmp1.A), 60);
yR = linspace(min(pSmp1.h), max(pSmp1.h), 60);
[xx, yy] = meshgrid(xR, yR);
zz = Ftotal(xx, yy);
mesh(xx, yy, zz)
view(56, 30)
title('Total cost as function of A and h')
zlabel('Ftotal')
xlabel(p(1).Name), ylabel(p(2).Name);
```

Find the best design from the new design space and compare with the best design point found earlier.

```
[~,idx] = min(y.F);  
pBest = [pBest; [y(idx,:), pSmpl(idx,:)]]
```

```
pBest =
```

F	costConc	costCoolant	A	h
2.1052	1.5757	0.52953	1.8483	2.1158
1.979	1.4838	0.49528	1.9695	2.1174

The best design in the refined design space is better than the design found earlier. This indicates that there may be better designs in the same region and warrants refining the design space further. Alternatively you can use the best design point as an initial guess for optimization.

### Related Examples

To learn how to optimize the CSTR design using the `sdo.optimize` command, see "Design Optimization with Uncertain Variables (Code)".

To learn how to analyze the influence of design parameters on the design using the `sdo.analyze` command, see "Sensitivity Analysis for Parameter Estimation (Code)".

### References

[1] Bequette, B.W. *Process Dynamics: Modeling, Analysis and Simulation*. 1st ed. Upper Saddle River, NJ: Prentice Hall, 1998.

Close the model

```
bdclose('sdoCSTR')
```

## Identify Key Parameters for Estimation (Code)

This example shows how to use sensitivity analysis to narrow down the number of parameters that you need to estimate to fit a model. This example uses a model of the vestibulo-ocular reflex, which generates compensatory eye movements.

### Model Description

The vestibulo-ocular reflex (VOR) enables the eyes to move at the same speed and in the opposite direction as the head, so that vision is not blurred when the head moves during normal activity. For example, if the head turns in one direction, the eyes turn in the opposite direction, with the same speed. This happens even in the dark. In fact, the VOR is most easily characterized by measurements in the dark, to ensure that eye movements are predominantly driven by the VOR.

The file `sdoVOR_Data.mat` contains uniformly sampled data of stimulation and eye movements. If the VOR were perfectly compensatory, then a plot of eye movement data, when flipped vertically, would overlay exactly on top of a plot of head motion data. Such a system would be described by a gain of 1 and a phase of 180 degrees. However, when we plot the data in the file `sdoVOR_Data.mat`, the eye movements are close, but not perfectly compensatory.

```
load('sdoVOR_Data.mat'); % Column vectors: Time HeadData EyeData
figure
plot(Time, HeadData, ':b', Time, EyeData, '-g')
xlabel('Time (sec)')
ylabel('Angular Velocity (deg/sec)')
ylim([-110 110])
legend('Head Data', 'Eye Data')
```

The eye movement data does not perfectly overlay the head motion data, and this can be modeled by several factors. Head rotation is sensed by organs in the inner ears, known as semicircular canals. These detect head motion and transmit signals about head motion to the brain, which sends motor commands to the eye muscles, so that eye movements compensate

for head motion. We would like to use this eye movement data to estimate the parameters in the models for these various stages. The model we will use is shown below. There are four parameters in the model: Delay, Gain, Tc, and Tp.

```
model_name = 'sdoVOR';  
open_system(model_name)
```

The Delay parameter models the fact that there is some delay in communicating the signals from the inner ear to the brain and the eyes. This delay is due to the time needed for chemical neurotransmitters to traverse the synaptic clefts between nerve cells. Based on the number of synapses involved in the vestibulo-ocular reflex, this delay is expected to be around 5 ms. For estimation purposes, we will assume it is between 2 and 9 ms.

```
Delay = sdo.getParameterFromModel(model_name, 'Delay');  
Delay.Value = 0.005; % seconds  
Delay.Minimum = 0.002;  
Delay.Maximum = 0.009;
```

The Gain parameter models the fact that the the eyes do not move quite as much as the head does. We will use 0.8 as our initial guess, and assume it is between 0.6 and 1.

```
Gain = sdo.getParameterFromModel(model_name, 'Gain');  
Gain.Value = 0.8;  
Gain.Minimum = 0.6;  
Gain.Maximum = 1;
```

The Tc parameter models the dynamics associated with the semicircular canals, as well as some additional neural processing. The canals are high-pass filters, because after a subject has been put into rotational motion, the neurally active membranes in the canals slowly relax back to resting position, so the canals stop sensing motion. Thus in the plot above, after the stimulation undergoes transition edges, the eye movements tend to depart from the stimulation over time. Based on mechanical characteristics of the canals, combined with additional neural processing which prolongs this



time constant to improve the accuracy of the VOR, we will estimate the Tc parameter to be 15 seconds, and assume it is between 10 and 30 seconds.

```
Tc = sdo.getParameterFromModel(model_name, 'Tc');
Tc.Value = 15;
Tc.Minimum = 10;
Tc.Maximum = 30;
```

Finally, the Tp parameter models the dynamics of the oculomotor plant, i.e. the eye and the muscles and tissues attached to it. The plant can be modeled by two poles, however it is believed that the pole with the larger time constant is cancelled by precompensation in the brain, to enable the eye to make quick movements. Thus in the plot, when the stimulation undergoes transition edges, the eye movements follow with only a little delay. For the Tp parameter, we will use 0.01 seconds as our initial guess, and assume it is between 0.005 and 0.05 seconds.

```
Tp = sdo.getParameterFromModel(model_name, 'Tp');
Tp.Value = 0.01;
Tp.Minimum = 0.005;
Tp.Maximum = 0.05;
```

Collect these parameters into a vector.

```
v = [Delay Gain Tc Tp];
```

### **Compare Measured Data to Initial Simulated Output**

Create an Experiment object. Specify HeadData as input.

```
Exp = sdo.Experiment(model_name);
Exp.InputData = timeseries(HeadData, Time);
```

Associate eye movement data with model output.

```
EyeMotion = Simulink.SimulationData.Signal;
EyeMotion.Name = 'EyeMotion';
EyeMotion.BlockPath = [model_name '/Oculomotor Plant'];
EyeMotion.PortType = 'outport';
EyeMotion.PortIndex = 1;
EyeMotion.Values = timeseries(EyeData, Time);
```

Add EyeMotion to the experiment.

```
Exp.OutputData = EyeMotion;
```

Use the data's timing characteristics in the model.

```
stop_time = Time(end);  
set_param(gcs, 'StopTime', num2str(stop_time));  
dt = Time(2) - Time(1);  
set_param(gcs, 'FixedStep', num2str(dt))
```

Create a simulation scenario using the experiment, and obtain the simulated output.

```
Exp = setEstimatedValues(Exp, v); % use vector of parameters/states  
Simulator = createSimulator(Exp);  
Simulator = sim(Simulator);
```

Search for the model\_residual signal in the logged simulation data.

```
SimLog = find(Simulator.LoggedData, ...  
    get_param(model_name, 'SignalLoggingName') );  
EyeSignal = find(SimLog, 'EyeMotion');
```

The model output does not match the data very well, as shown by the residual, which we can compute by calling the objective function.

```
estFcn = @(v) sdoVOR_Objective(v, Exp, 'Residuals');  
Model_Error = estFcn(v);  
plot(Time, EyeData, '-g', ...  
    EyeSignal.Values.Time, EyeSignal.Values.Data, '--c', ...  
    Time, Model_Error.F, '-r');  
xlabel('Time (sec)');  
ylabel('Angular Velocity (deg/sec)');  
legend('Eye Data', 'Model', 'Residual');
```

The objective function used above is defined in the file "sdoVOR\_Objective.m".

```
type sdoVOR_Objective.m
```

```
function vals = sdoVOR_Objective(v, Exp, Method)
% Compare model output with data
%
%   Inputs:
%       v - vector of parameters and/or states
%       Exp - Experiment object
%       Method - 'SSE' for scalar output, 'Residuals' for vector of residuals

% Requirement setup
req = sdo.requirements.SignalTracking;
req.Type = '==';
req.Method = Method;

% If Residuals requested, keep on same scale as signals, for plotting
switch Method
case 'Residuals'
    req.Normalize = 'off';
end

% Simulate the model
Exp = setEstimatedValues(Exp, v); % use vector of parameters/states
Simulator = createSimulator(Exp);
Simulator = sim(Simulator);

% Compare model output with data
SimLog = find(Simulator.LoggedData, ...
    get_param(Exp.ModelName, 'SignalLoggingName') );
OutputModel = find(SimLog, 'EyeMotion');
Model_Error = evalRequirement(req, OutputModel.Values, Exp.OutputData.Values);
vals.F = Model_Error;
```

### **Sensitivity Analysis**

Create an object to sample the parameter space.

```
ps = sdo.ParameterSpace([Delay ; Gain ; Tc ; Tp]);
```

Generate 100 samples from the parameter space.

```
rng('default'); % for reproducibility
x = sdo.sample(ps, 100);
sdo.scatterPlot(x);
```

The sampling above used default options, and these are reflected in the plots above. Parameter values were selected at random from distributions that were uniform over the range of each parameter. Consequently, the histogram plots along the diagonal appear approximately uniform. If Statistics Toolbox is available, a number of distributions may be used in addition to uniform and normal, and sampling can be done in a Latin hypercube pattern.

The off-diagonal plots above show scatter plots between pairs of different variables. Since we did not specify a RankCorrelation matrix in `ps`, the scatter plots do not indicate correlations. However, if parameters were believed to be correlated, this can be specified using the RankCorrelation property of `ps`.

For sensitivity analysis, it is simpler to use a scalar objective, so we will specify the sum of squared errors, "SSE":

```
estFcn = @(v) sdoVOR_Objective(v, Exp, 'SSE');
y = sdo.evaluate(estFcn, ps, x);
```

Model evaluated at 100 samples.

Evaluation could also be sped up using parallel computing.

Obtain the standardized regression coefficients.

```
opts = sdo.AnalyzeOptions;
opts.Method = 'StandardizedRegression';
sensitivities = sdo.analyze(x, y, opts);
```

Other types of analysis include correlation and, if Statistics Toolbox is available, partial correlation.

We can view the analysis results.

```
disp(sensitivities)
```

```

                F
-----
Delay          0.01303
Gain          -0.90873
Tc            -0.044395
Tp            0.19919

```

For standardized regression, parameters that highly influence the model output have sensitivity magnitudes close to 1. On the other hand, less influential parameters have smaller sensitivity magnitudes. We see that this objective function is sensitive to changes in the Gain and Tp parameters, but much less sensitive to changes in the Delay and Tc parameters.

You can validate sensitivity analysis results by resampling and reevaluating the objective function for the samples. You can also use engineering intuition for a quick analysis. For example, in this model, the time constant Tc ranges from 10 to 30 seconds. Even the minimum value of 10 seconds is large compared to the 2-second duration for which the head motion stimulation is held at constant velocity. Therefore, Tc is not expected to affect the output greatly. However, even when this kind of intuition is not readily available in other models, sensitivity analysis can help highlight which parameters are influential.

Based on the results of sensitivity analysis, designate the Delay and Tc parameters as fixed when optimizing. This reduction in the number of free parameters speeds up optimization.

```
Delay.Free = false;
Tc.Free = false;
```

### Optimization

We can use the minimum from sensitivity analysis as the initial guess for optimization.

```
[fval, idx_min] = min(y.F);
```

```

Delay.Value = x.Delay(idx_min);
Gain.Value = x.Gain(idx_min);
Tc.Value = x.Tc(idx_min);
Tp.Value = x.Tp(idx_min);
%
v = [Delay Gain Tc Tp];
opts = sdo.OptimizeOptions;
opts.Method = 'fmincon';

```

As was the case with model evaluations in sensitivity analysis, parallel computing could be used to speed up the optimization.

```

vOpt = sdo.optimize(estFcn, v, opts);
disp(vOpt)

```

Optimization started 18-Jan-2014 17:22:30

Iter	F-count	f(x)	max constraint	Step-size	First-order optimality
0	5	13.4798	0		
1	18	12.2052	0	0.129	305
2	30	11.1441	0	0.0648	781
3	41	10.0493	0	0.0843	289
4	46	9.23607	0	0.0758	227
5	51	8.76122	0	0.0183	10.1
6	56	8.75862	0	0.00184	0.476
7	57	8.75862	0	8.41e-05	0.476

Local minimum possible. Constraints satisfied.

fmincon stopped because the size of the current step is less than the selected value of the step size tolerance and constraints are satisfied to within the selected value of the constraint tolerance.

(1,1) =

```

Name: 'Delay'
Value: 0.0038
Minimum: 0.0020
Maximum: 0.0090

```

```
Free: 0  
Scale: 0.0078  
Info: [1x1 struct]
```

(1,2) =

```
Name: 'Gain'  
Value: 0.9012  
Minimum: 0.6000  
Maximum: 1  
Free: 1  
Scale: 1  
Info: [1x1 struct]
```

(1,3) =

```
Name: 'Tc'  
Value: 16.6833  
Minimum: 10  
Maximum: 30  
Free: 0  
Scale: 16  
Info: [1x1 struct]
```

(1,4) =

```
Name: 'Tp'  
Value: 0.0157  
Minimum: 0.0050  
Maximum: 0.0500  
Free: 1  
Scale: 0.0156  
Info: [1x1 struct]
```

1x4 param.Continuous

### Visualizing Result of Optimization

Obtain the model response after estimation. Search for the `model_residual` signal in the logged simulation data.

```
Exp = setEstimatedValues(Exp, vOpt);
Simulator = createSimulator(Exp);
Simulator = sim(Simulator);
SimLog = find(Simulator.LoggedData, ...
    get_param(model_name, 'SignalLoggingName') );
EyeSignal = find(SimLog, 'EyeMotion');
```

Comparing the measured eye data with the optimized model response shows that the residuals are much smaller.

```
estFcn = @(v) sdoVOR_Objective(v, Exp, 'Residuals');
Model_Error = estFcn(vOpt);
plot(Time, EyeData, '-g', ...
    EyeSignal.Values.Time, EyeSignal.Values.Data, '--c', ...
    Time, Model_Error.F, '-r');
xlabel('Time (sec)');
ylabel('Angular Velocity (deg/sec)');
legend('Eye Data', 'Model', 'Residual');
```

Close the model

```
bdclose(model_name)
```



# Optimization-Based Control Design

---

- “Overview of Optimization-Based Compensator Design” on page 5-2
- “Time-Domain Design Requirements in Simulink” on page 5-4
- “Frequency-Domain Design Requirements in Simulink” on page 5-17
- “Time- and Frequency-Domain Requirements in SISO Design Tool” on page 5-39
- “Time-Domain Simulations in SISO Design Tool” on page 5-44
- “How to Design Optimization-Based Controllers for LTI Systems” on page 5-45
- “Optimize LTI System to Meet Frequency-Domain Requirements” on page 5-47
- “Designing Linear Controllers for Simulink Models” on page 5-68

## Overview of Optimization-Based Compensator Design

You can design optimization-based controllers for Simulink models to meet time and frequency-domain design requirements, as described in “Design Optimization to Meet Time- and Frequency-Domain Requirements (GUI)” on page 3-100.

If you have Control System Toolbox software installed, you can also design and optimize control systems by tuning controller elements or parameters within a SISO Design Task in the Control and Estimation Tools Manager. You can tune elements or parameters such as poles, zeros, and gains within any controller in the system and optimize the open and closed loop responses to meet time- and frequency-domain requirements.

Optimize the responses of systems in the SISO Design Task to meet both time- and frequency-domain performance requirements by graphically constraining signals:

- Add frequency-domain design requirements to plots such as root-locus, Nichols, and Bode in the SISO Design Task graphical tuning editor called SISO Design Tool.
- Add time-domain design requirements to plots such as step or impulse response (when displayed within the LTI Viewer as part of a SISO Design Task).

You can use optimization methods in a SISO Design Task in the Control and Estimation Tools Manager to tune both command-line LTI models as well as Simulink models:

- Create an LTI model using the Control System Toolbox command-line functions and use the `sisotool` function to create a SISO Design Task for the model. For an example, see “Optimize LTI System to Meet Frequency-Domain Requirements” on page 5-47.
- Use a Simulink Compensator Design task (from Simulink Control Design software) to automatically analyze the model and then create a SISO Design Task for a linearized version of the model. You can then use the optimization techniques in the SISO Design Task to tune the response of the linearized Simulink model. For an example, see “Design Optimization-Based PID Controller for Linearized Simulink Model (GUI)”.

---

**Note** When using response optimization within a SISO Design Task you cannot add uncertainty to system parameters.

---

When using a SISO Design Task, Simulink Design Optimization software automatically sets the model's simulation start and stop time and you cannot directly change them. By default, the simulation starts at 0 and continues until the SISO Design Task determines that the dynamics of the model have settled out. In addition, when the design requirements extend beyond this point, the simulation continues to the extent of the design requirements. Although you cannot directly adjust the start or stop time of the simulation, you can adjust the design requirements to extend further in time and thus force the simulation to continue to a certain point.

## Time-Domain Design Requirements in Simulink

### In this section...

“Specify Piecewise-Linear Lower and Upper Bounds” on page 5-4

“Specify Step Response Characteristics” on page 5-32


“Track Reference Signals” on page 5-9

“Specify Custom Requirements” on page 5-35

“Edit Design Requirements” on page 5-14

### Specify Piecewise-Linear Lower and Upper Bounds

To specify upper and lower bounds on a signal:


- 1 In the Design Optimization tool, select **Signal Bound** in the **New** drop-down list. A window opens where you specify upper or lower bounds on a signal.
- 2 Specify a requirement name in the **Name** box.
- 3 Select the requirement type using the **Type** list.
- 4 Specify the edge start and end times and corresponding amplitude in the **Time (s)** and **Amplitude** columns.
- 5 Click  to specify additional bound edges.

Select a row and click  to delete a bound edge.

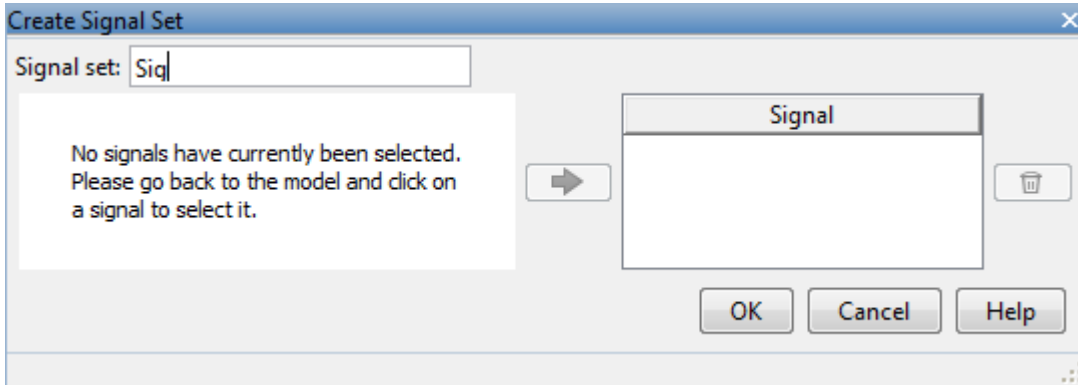
- 6 In the **Select Signals to Bound** area, select a logged signal to apply the requirement to.

If you have already selected signals, as described in “Specify Signals to Log” on page 3-13, they appear in the list. Select the corresponding check-box.


If you haven’t selected a signal to log:

- a Click . A window opens where you specify the logged signal.

- b** In the Simulink model window, click the signal to which you want to add a requirement.



The window updates and displays the name of the block and the port number where the selected signal is located.

- c** Select the signal and click  to add it to the signal set.
- d** In the **Signal set** box, enter a name for the selected signal set.

Click **OK**. A new variable, with the specified name, appears in the **Design Optimization Workspace** of the Design Optimization tool window.

**7** Click **OK**.

A variable with the specified requirement name appears in the **Design Optimization Workspace**. A graphical display of the requirement also appears in the Design Optimization tool window.

- 8** (Optional) In the graphical display, you can:
- “Move Constraints Graphically” on page 3-22
  - “Position Constraints Exactly” on page 3-23

Alternatively, you can add a Check Custom Bounds block to your model to specify piecewise-linear bounds.

## Specify Step Response Characteristics

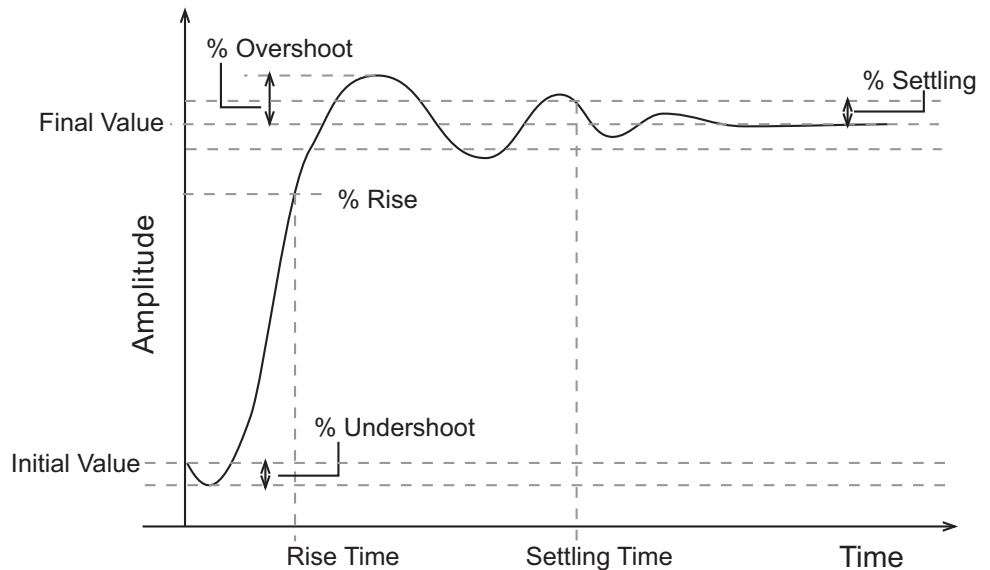
To specify step response characteristics:

- 1 You can apply this requirement to either a signal or a linearization of your model.

In the Design Optimization Tool, click **New**. To apply this requirement to a signal, select the **Step Response Envelope** entry in the **New Time Domain Requirement** section of the **New** list. To apply this requirement to a linearization of your model, select the **Step Response Envelope** entry in the **New Frequency Domain Requirement** section of the **New** list. The latter option requires Simulink Control Design software.

A window opens where you specify the step response requirements on a signal, or system.

- 2 Specify a requirement name in the **Name** box.
- 3 Specify the step response characteristics:



- **Initial value:** Input level before the step occurs
- **Step time:** Time at which the step takes place
- **Final value:** Input level after the step occurs
- **Rise time:** The time taken for the response signal to reach a specified percentage of the step's range. The step's range is the difference between the final and initial values.
- **% Rise:** The percentage used in the rise time.
- **Settling time:** The time taken until the response signal settles within a specified region around the final value. This settling region is defined as the final step value plus or minus the specified percentage of the final value.
- **% Settling:** The percentage used in the settling time.
- **% Overshoot:** The amount by which the response signal can exceed the final value. This amount is specified as a percentage of the step's range. The step's range is the difference between the final and initial values.
- **% Undershoot:** The amount by which the response signal can undershoot the initial value. This amount is specified as a percentage of the step's range. The step's range is the difference between the final and initial values.

#### 4 Specify the signals or systems to be bound.


You can apply this requirement to a model signal or to a linearization of your Simulink model (requires Simulink Control Design software).

- Apply this requirement to a model signal:

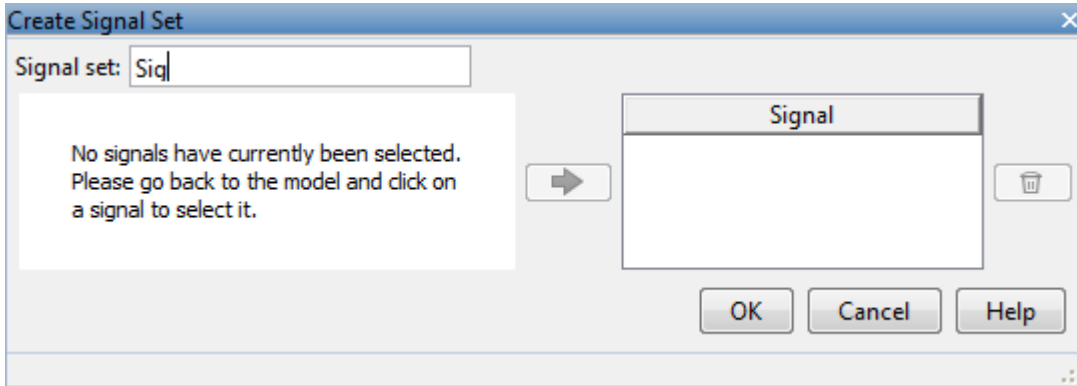
In the **Select Signals to Bound** area, select a logged signal to which you will apply the requirement.

If you have already selected a signal to log, as described in “Specify Signals to Log” on page 3-13, it appears in the list. Select the corresponding check-box.


If you haven't selected a signal to log:

- Click . A window opens where you specify the logged signal.

- b In the Simulink model window, click the signal to which you want to add a requirement.



The window updates and displays the name of the block and the port number where the selected signal is located.

- c Select the signal and click  to add it to the signal set.
- d In the **Signal set** box, enter a name for the selected signal set.

Click **OK**. A new variable, with the specified name, appears in the **Design Optimization Workspace** of the Design Optimization tool window.


- Apply this requirement to a linear system.

Linear systems are defined by snapshot times at which the model is linearized and sets of linearization I/O points defining the system inputs and outputs.

- a Specify the simulation time at which the model is linearized using the **Snapshot Times** box. For multiple simulation snapshot times, specify a vector.
- b Select the linearization input/output set from the **Linearization I/O** area.

If you have already created a linearization input/output set, it will appear in the list. Select the corresponding check box.



If you have not created a linearization input/output set, click  to open the Create linearization I/O set dialog box.

For more information on using this dialog box, see “Create Linearization I/O Sets” on page 3-82.

For more information on linearization, see “What Is Linearization?”.

#### 5 Click **OK**.

A variable with the specified requirement name appears in the **Design Optimization Workspace**. A graphical display of the requirement also appears in the Design Optimization tool window.

Alternatively, you can use the Check Step Response Characteristics block to specify step response bounds for a signal.

#### **See Also**

“Design Optimization to Meet Step Response Requirements (GUI)”

## **Track Reference Signals**

Use reference tracking to force a model signal to match a desired signal.

To track a reference signal:

- 1 In the Design Optimization tool, select **Signal Tracking** in the **New** drop-down list. A window opens where you specify the reference signal to track.
- 2 Specify a requirement name in the **Name** box.
- 3 Define the reference signal by entering vectors, or variables from the workspace, in the **Time vector** and **Amplitude** fields.

Click **Update reference signal data** to use the new amplitude and time vector as the reference signal.


- 4 Specify how the optimization solver minimizes the error between the reference and model signals using the **Tracking Method** list:

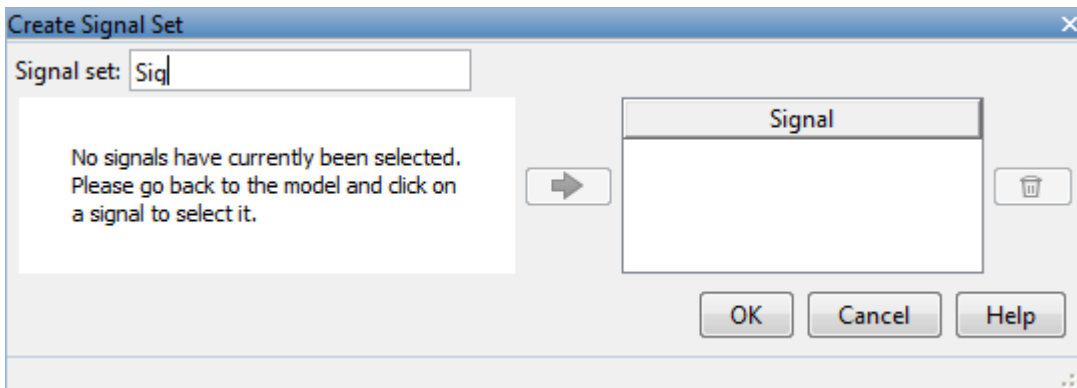
- SSE — Reduces the sum of squared errors
- SAE — Reduces the sum of absolute errors

5 In the **Specify Signal to Track Reference Signal** area, select a logged signal to apply the requirement to.


If you already selected a signal to log, as described in “Specify Signals to Log” on page 3-13, they appear in the list. Select the corresponding check-box.

If you haven’t selected a signal to log:

- Click . A window opens where you specify the logged signal.
- In the Simulink model window, click the signal to which you want to add a requirement.



The window updates and displays the name of the block and the port number where the selected signal is located.

- Select the signal and click  to add it to the signal set.
- In the **Signal set** box, enter a name for the selected signal set.

Click **OK**. A new variable, with the specified name, appears in the **Design Optimization Workspace** of the Design Optimization tool window.

- e Select the check-box corresponding to the signal and click **OK**.

A variable with the specified requirement name appears in the **Design Optimization Workspace**. A graphical display of the signal bound also appears in the Design Optimization tool window.

---

**Note** When tracking a reference signal, the software ignores the maximally feasible solution option. For more information on this option, see “Selecting Optimization Termination Options” on page 3-79.

---


Alternatively, you can use the Check Against Reference block to specify a reference signal to track.


### See Also

“Design Optimization to Track Reference Signal (GUI)”

## Specify Custom Requirements

To specify custom requirements, such as minimizing system energy:

- 1 In the Design Optimization tool, select **Custom Requirement** in the **New** list. A window opens where you specify the custom requirement.
- 2 Specify a requirement name in the **Name** box.
- 3 Specify the requirement type using the **Type** list.
- 4 Specify the name of the function that contains the custom requirement in the **Function** box. The field must be specified as a function handle using `@`. The function must be on the MATLAB path. Click  to review or edit the function.

If the function does not exist, clicking  opens a template MATLAB file. Use this file to implement the custom requirement. The default function name is `myCustomRequirement`.

- 5** (Optional) If you want to prevent the solver from considering specific parameter combinations, select the **Error if constraint is violated** check box. Use this option for parameter-only constraints.

During an optimization iteration, the solver evaluates requirements with this option selected first.

- If the constraint is violated, the solver skips evaluating any remaining requirements and proceeds to the next iterate.
- If the constraint is *not* violated, the solver evaluates the remaining requirements for the current iterate. If any of the remaining requirements bound signals or systems, then the solver simulates the model .

For more information, see “Skip Model Simulation Based on Parameter Constraint Violation (GUI)” on page 3-152.

---

**Note** If you select this check box, then do not specify signals or systems to bound. If you *do* specify signals or systems, then this check box is ignored.

---

- 6** (Optional) Specify the signal or system, or both, to be bound.

You can apply this requirement to model signals, or a linearization of your Simulink model (requires Simulink Control Design software), or both.


Click **Select Signals and Systems to Bound (Optional)** to view the signal and linearization I/O selection area.

- Apply this requirement to a model signal:

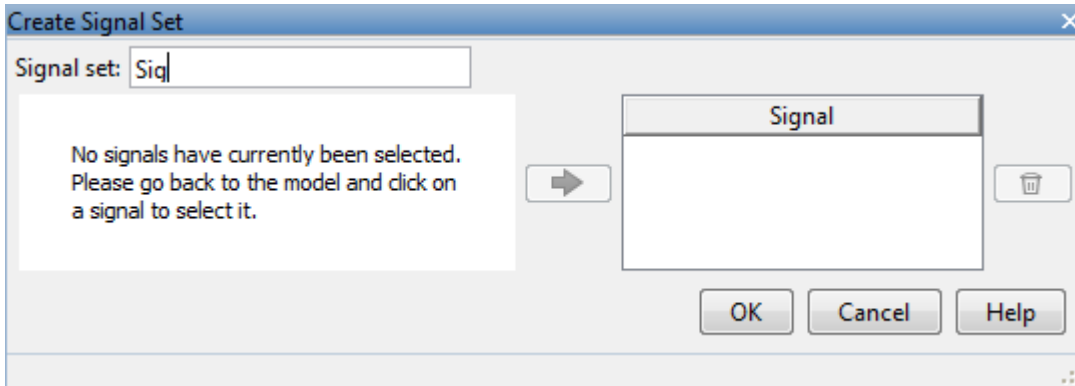
In the **Signal** area, select a logged signal to which you will apply the requirement.

If you have already selected a signal to log, as described in “Specify Signals to Log” on page 3-13, it appears in the list. Select the corresponding check box.


If you have not selected a signal to log:

- Click . A window opens where you specify the logged signal.

- b In the Simulink model window, click the signal to which you want to add a requirement.



The window updates and displays the name of the block and the port number where the selected signal is located.

- c Select the signal and click  to add it to the signal set.
- d In the **Signal set** box, enter a name for the selected signal set.


Click **OK**. A new variable, with the specified name, appears in the **Design Optimization Workspace** of the Design Optimization tool window.

- Apply this requirement to a linear system.

Linear systems are defined by snapshot times at which the model is linearized and sets of linearization I/O points defining the system inputs and outputs.

- a Specify the simulation time at which the model is linearized using the **Snapshot Times** box. For multiple simulation snapshot times, specify a vector.
- b Select the linearization input/output set from the **Linearization I/O** area.

If you have already created a linearization input/output set, it will appear in the list. Select the corresponding check box.

If you have not created a linearization input/output set, click  to open the Create linearization I/O set dialog box. For more information on using this dialog box, see “Create Linearization I/O Sets” on page 3-82.

For more information on linearization, see “What Is Linearization?”.

### 7 Click OK.

A new variable, with the specified name, appears in the **Design Optimization Workspace** of the Design Optimization tool. A graphical display of the requirement also appears in the Design Optimization tool window.

### See Also

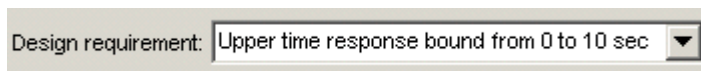
- “Design Optimization to Meet a Custom Objective (GUI)” on page 3-105
- “Design Optimization to Meet Custom Signal Requirements (GUI)” on page 3-122

## Edit Design Requirements

The Edit Design Requirement dialog box allows you to exactly position constraint segments and to edit other properties of these constraints. The dialog box has two main components:

- An upper panel to specify the constraint you are editing
- A lower panel to edit the constraint parameters

The upper panel of the Edit Design Requirement dialog box resembles the image in the following figure.



In the context of the SISO Tool in Control System Toolbox software, **Design requirement** refers to both the particular editor within the SISO Tool that contains the requirement and the particular requirement within that

editor. To edit other constraints within the SISO Tool, select another design requirement from the drop-down menu.

### Edit Design Requirement Dialog Box Parameters

The particular parameters shown within the lower panel of the Edit Design Requirement dialog box depend on the type of constraint/requirement. In some cases, the lower panel contains a grid with one row for each segment and one column for each constraint parameter. The following table summarizes the various constraint parameters.

#### Edit Design Requirement Dialog Box Parameters

Parameter	Found in	Description
<b>Time</b>	Upper and lower time response bounds on step and impulse response plots	Defines the time range of a segment within a constraint/requirement.
<b>Amplitude</b>	Upper and lower time response bounds on step and impulse response plots	Defines the beginning and ending amplitude of a constraint segment.
<b>Slope (1/s)</b>	Upper and lower time response bounds	Defines the slope, in 1/s, of a constraint segment. It is an alternative method of specifying the magnitude values. Entering a new <b>Slope</b> value changes any previously defined magnitude values.
<b>Final value</b>	Step response bounds	Defines the input level after the step occurs.
<b>Rise time</b>	Step response bounds	Defines a constraint segment for a particular rise time.
<b>% Rise</b>	Step response bounds	The percentage of the step's range used to describe the rise time.
<b>Settling time</b>	Step response bounds	Defines a constraint segment for a particular settling time.

**Edit Design Requirement Dialog Box Parameters (Continued)**

<b>Parameter</b>	<b>Found in</b>	<b>Description</b>
<b>% Settling</b>	Step response bounds	The percentage of the final value that defines the settling region used to describe the settling time.
<b>% Overshoot</b>	Step response bounds	
<b>% Undershoot</b>	Step response bounds	Defines the constraint segments for a particular percent undershoot.



## Frequency-Domain Design Requirements in Simulink

### In this section...

“Specify Lower Bounds on Gain and Phase Margin” on page 5-17

“Specify Piecewise-Linear Lower and Upper Bounds on Frequency Response” on page 5-19

“Specify Bound on Closed-Loop Peak Gain” on page 5-21

“Specify Lower Bound on Damping Ratio” on page 5-23

“Specify Upper and Lower Bounds on Natural Frequency” on page 5-25

“Specify Upper Bound on Approximate Settling Time” on page 5-27

“Specify Piecewise-Linear Upper and Lower Bounds on Singular Values” on page 5-29

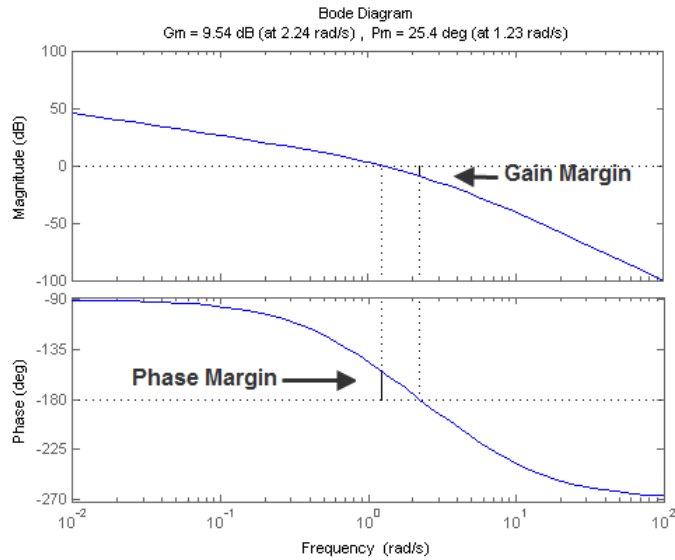
“Specify Step Response Characteristics” on page 5-32

“Specify Custom Requirements” on page 5-35

### Specify Lower Bounds on Gain and Phase Margin

To specify lower bounds on the gain and phase margin of a linear system:

- 1** In the Design Optimization tool, select **Gain and Phase Margin** in the **New** list. A window opens where you specify lower bounds on the gain and phase margin of your linear system.
- 2** Specify a requirement name in **Name**.
- 3** Specify bounds on the gain margin or phase margin, or both.



- **Gain margin** — Amount of gain increase or decrease required to make the loop gain unity at the frequency where the phase angle is  $-180^\circ$ .
- **Phase margin** — Amount of phase increase or decrease required to make the phase angle  $-180^\circ$  when the loop gain is 1.0


To specify a lower bound on the gain margin or phase margin, or both, select the corresponding check box and enter the lower bound value.

- 4** In the **Select Systems to Bound** section, select the linear systems to which this requirement applies.

Linear systems are defined by snapshot times at which the model is linearized and sets of linearization I/O points defining the system inputs and outputs.

- Specify the simulation time at which the model is linearized using the **Snapshot Times** box. For multiple simulation snapshot times, specify a vector.
- Select the linearization input/output set from the **Linearization I/O** area.

If you have already created a linearization input/output set, it will appear in the list. Select the corresponding check box.

If you have not created a linearization input/output set, click  to open the Create linearization I/O set dialog box.

For more information on using this dialog box, see “Create Linearization I/O Sets” on page 3-82.

For more information on linearization, see “What Is Linearization?”.

**5** Click **OK**.

A variable with the specified requirement name appears in the **Design Optimization Workspace**. A graphical display of the requirement also appears in the Design Optimization tool window.

**6** (Optional) In the graphical display, you can:

- “Move Constraints Graphically” on page 3-22
- “Position Constraints Exactly” on page 3-23


Alternatively, you can use the Check Gain and Phase Margins block to specify bounds on the gain and phase margin. (Requires Simulink Control Design.)

## Specify Piecewise-Linear Lower and Upper Bounds on Frequency Response

To specify upper or lower bounds on the magnitude of a system response:

- 1** In the Design Optimization tool, select **Bode Magnitude** in the **New** list. A window opens where you specify the lower or upper bounds on the magnitude of the system response.
- 2** Specify a requirement name in the **Name** box.
- 3** Specify the requirement type using the **Type** list.
- 4** Specify the edge start and end frequencies and corresponding magnitude in the **Frequency** and **Magnitude** columns.

**5** Insert or delete bound edges.

Click  to specify additional bound edges.


Select a row and click  to delete a bound edge.

**6** In the **Select Systems to Bound** section, select the linear systems to which this requirement applies.

Linear systems are defined by snapshot times at which the model is linearized and sets of linearization I/O points defining the system inputs and outputs.

- a** Specify the simulation time at which the model is linearized using the **Snapshot Times** box. For multiple simulation snapshot times, specify a vector.
- b** Select the linearization input/output set from the **Linearization I/O** area.

If you have already created a linearization input/output set, it will appear in the list. Select the corresponding check box.

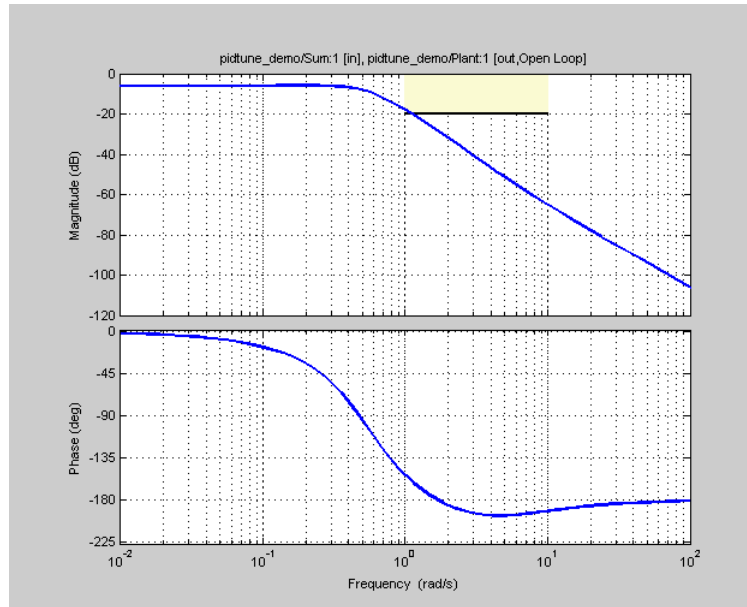
If you have not created a linearization input/output set, click  to open the Create linearization I/O set dialog box.

For more information on using this dialog box, see “Create Linearization I/O Sets” on page 3-82.

For more information on linearization, see “What Is Linearization?”.

**7** Click **OK**.

A new variable with the specified name appears in the **Design Optimization Workspace** of the Design Optimization tool window. A graphical display of the requirement also appears in the Design Optimization tool window.



**8** (Optional) In the graphical display, you can:

- “Move Constraints Graphically” on page 3-22
- “Position Constraints Exactly” on page 3-23

Alternatively, you can use the Check Bode Characteristics block to specify bounds on the magnitude of the system response. (Requires Simulink Control Design.)

## Specify Bound on Closed-Loop Peak Gain

To specify an upper bound on the closed-loop peak response of a system:


- 1** In the Design Optimization tool, select **Closed-Loop Peak Gain** in the **New** list. A window opens where you specify an upper bound on the closed-loop peak gain of the system.
- 2** Specify a requirement name in the **Name** box.

- 3** Specify the upper bound on the closed-loop peak gain in the **Closed-Loop peak gain** box.
- 4** In the **Select Systems to Bound** section, select the linear systems to which this requirement applies.

Linear systems are defined by snapshot times at which the model is linearized and sets of linearization I/O points defining the system inputs and outputs.

- a** Specify the simulation time at which the model is linearized using the **Snapshot Times** box. For multiple simulation snapshot times, specify a vector.
- b** Select the linearization input/output set from the **Linearization I/O** area.

If you have already created a linearization input/output set, it will appear in the list. Select the corresponding check box.

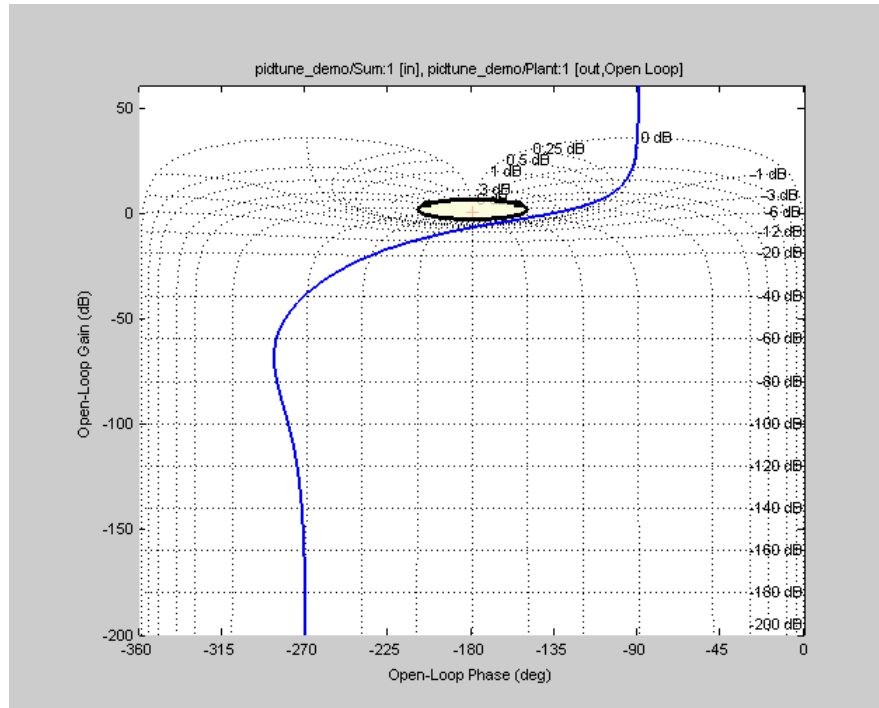
If you have not created a linearization input/output set, click  to open the Create linearization I/O set dialog box.

For more information on using this dialog box, see “Create Linearization I/O Sets” on page 3-82.

For more information on linearization, see “What Is Linearization?”.

- 5** Click **OK**.

A new variable with the specified name appears in the **Design Optimization Workspace** of the Design Optimization tool window. A graphical display of the requirement also appears in the Design Optimization tool window.



6 (Optional) In the graphical display, you can:

- “Move Constraints Graphically” on page 3-22
- “Position Constraints Exactly” on page 3-23

Alternatively, you can use the Check Nichols Characteristics block to specify bounds on the magnitude of the system response. (Requires Simulink Control Design.)

## Specify Lower Bound on Damping Ratio

To specify a lower bound on the damping ratio of the system:


- 1 In the Design Optimization tool, select **Damping Ratio** in the **New** list. A window opens where you specify an upper bound on the damping ratio of the system.

- 2 Specify a requirement name in the **Name** box.
- 3 Specify the lower bound on the damping ratio in the **Damping ratio** box.
- 4 In the **Select Systems to Bound** section, select the linear systems to which this requirement applies.

Linear systems are defined by snapshot times at which the model is linearized and sets of linearization I/O points defining the system inputs and outputs.

- a Specify the simulation time at which the model is linearized using the **Snapshot Times** box. For multiple simulation snapshot times, specify a vector.
- b Select the linearization input/output set from the **Linearization I/O** area.

If you have already created a linearization input/output set, it will appear in the list. Select the corresponding check box.

If you have not created a linearization input/output set, click  to open the Create linearization I/O set dialog box.

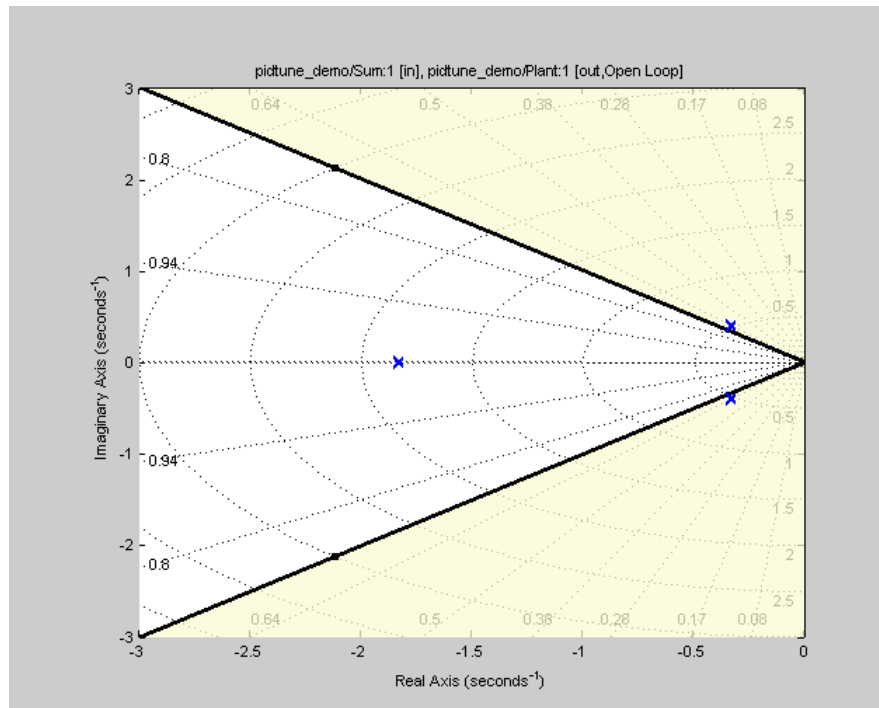
For more information on using this dialog box, see “Create Linearization I/O Sets” on page 3-82.

For more information on linearization, see “What Is Linearization?”.

- 5 Click **OK**.

A new variable with the specified name appears in the **Design Optimization Workspace** of the Design Optimization tool. A graphical display of the requirement also appears in the Design Optimization tool window.





6 (Optional) In the graphical display, you can:

- “Move Constraints Graphically” on page 3-22
- “Position Constraints Exactly” on page 3-23

Alternatively, you can use the Check Pole-Zero Characteristics block to specify a bound on the damping ratio. (Requires Simulink Control Design.)

## Specify Upper and Lower Bounds on Natural Frequency

To specify a bound on the natural frequency of the system:


- 1 In the Design Optimization tool, select **Natural Frequency** in the **New** list. A window opens where you specify a bound on the natural frequency of the system.

- 2 Specify a requirement name in the **Name** box.
- 3 Specify a lower or upper bound on the natural frequency in the **Natural frequency** box.
- 4 In the **Select Systems to Bound** section, select the linear systems to which this requirement applies.

Linear systems are defined by snapshot times at which the model is linearized and sets of linearization I/O points defining the system inputs and outputs.

- a Specify the simulation time at which the model is linearized using the **Snapshot Times** box. For multiple simulation snapshot times, specify a vector.
- b Select the linearization input/output set from the **Linearization I/O** area.

If you have already created a linearization input/output set, it will appear in the list. Select the corresponding check box.

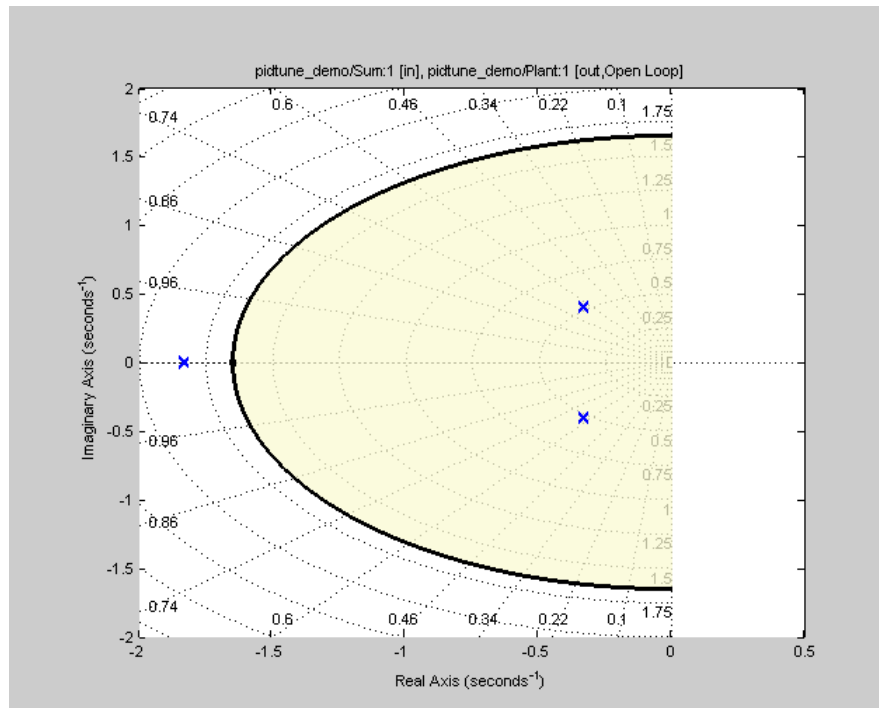
If you have not created a linearization input/output set, click  to open the Create linearization I/O set dialog box.

For more information on using this dialog box, see “Create Linearization I/O Sets” on page 3-82.

For more information on linearization, see “What Is Linearization?”.

- 5 Click **OK**.

A new variable with the specified name appears in the **Design Optimization Workspace** of the Design Optimization tool. A graphical display of the requirement also appears in the Design Optimization tool window.



**6** (Optional) In the graphical display, you can:

- “Move Constraints Graphically” on page 3-22
- “Position Constraints Exactly” on page 3-23

Alternatively, you can use the Check Pole-Zero Characteristics block to specify a bound on the natural frequency. (Requires Simulink Control Design.)

## Specify Upper Bound on Approximate Settling Time

To specify an upper bound on the approximate settling time of the system:

- 1** In the Design Optimization tool, select **Settling Time** in the **New** list. A window opens where you specify an upper bound on the approximate settling time of the system.
- 2** Specify a requirement name in the **Name** box.


**3** Specify the upper bound on the approximate settling time in the **Settling time** box.

**4** In the **Select Systems to Bound** section, select the linear systems to which this requirement applies.

Linear systems are defined by snapshot times at which the model is linearized and sets of linearization I/O points defining the system inputs and outputs.

- a** Specify the simulation time at which the model is linearized using the **Snapshot Times** box. For multiple simulation snapshot times, specify a vector.
- b** Select the linearization input/output set from the **Linearization I/O** area.

If you have already created a linearization input/output set, it will appear in the list. Select the corresponding check box.

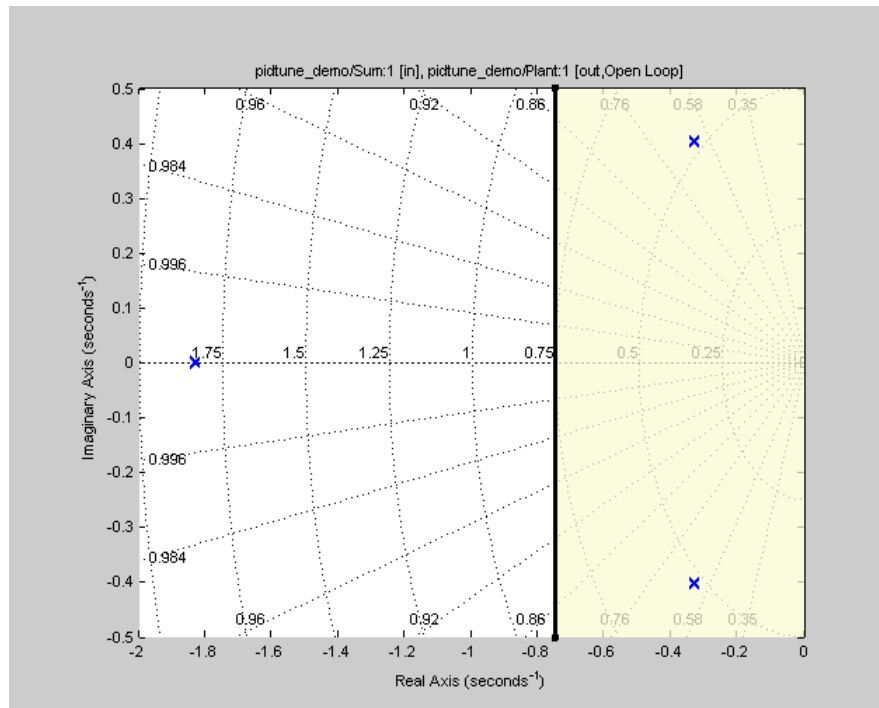
If you have not created a linearization input/output set, click  to open the Create linearization I/O set dialog box.

For more information on using this dialog box, see “Create Linearization I/O Sets” on page 3-82.

For more information on linearization, see “What Is Linearization?”.

**5** Click **OK**.

A new variable with the specified name appears in the **Design Optimization Workspace** of the Design Optimization tool. A graphical display of the requirement also appears in the Design Optimization tool window.



6 (Optional) In the graphical display, you can:


- “Move Constraints Graphically” on page 3-22
- “Position Constraints Exactly” on page 3-23

Alternatively, you can use the Check Pole-Zero Characteristics block to specify the approximate settling time. (Requires Simulink Control Design.)

## Specify Piecewise-Linear Upper and Lower Bounds on Singular Values

To specify piecewise-linear upper and lower bounds on the singular values of a system:

- 1 In the Design Optimization tool, select **Singular Values** in the **New** list. A window opens where you specify the lower or upper bounds on the singular values of the system.
- 2 Specify a requirement name in the **Name** box.
- 3 Specify the requirement type using the **Type** list.
- 4 Specify the edge start and end frequencies and corresponding magnitude in the **Frequency** and **Magnitude** columns, respectively.
- 5 Insert or delete bound edges.

Click  to specify additional bound edges.


Select a row and click  to delete a bound edge.

- 6 In the **Select Systems to Bound** section, select the linear systems to which this requirement applies.

Linear systems are defined by snapshot times at which the model is linearized and sets of linearization I/O points defining the system inputs and outputs.

- a Specify the simulation time at which the model is linearized using the **Snapshot Times** box. For multiple simulation snapshot times, specify a vector.
- b Select the linearization input/output set from the **Linearization I/O** area.

If you have already created a linearization input/output set, it will appear in the list. Select the corresponding check box.

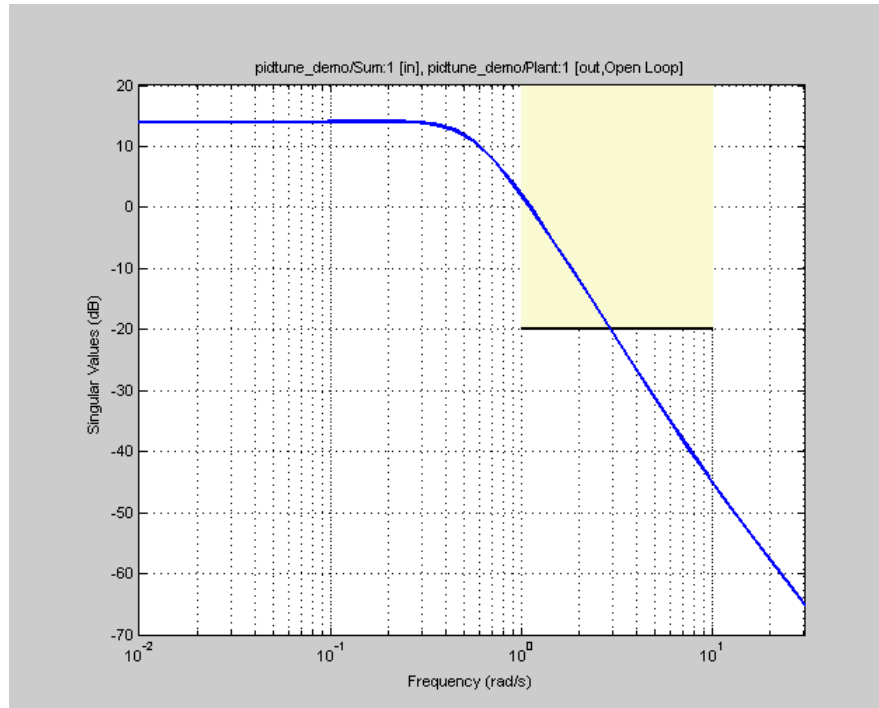
If you have not created a linearization input/output set, click  to open the Create linearization I/O set dialog box.

For more information on using this dialog box, see “Create Linearization I/O Sets” on page 3-82.

For more information on linearization, see “What Is Linearization?”.

**7** Click **OK**.

A new variable with the specified name appears in the **Design Optimization Workspace** of the Design Optimization tool. A graphical display of the requirement also appears in the Design Optimization tool window.

**8** (Optional) In the graphical display, you can:

- “Move Constraints Graphically” on page 3-22
- “Position Constraints Exactly” on page 3-23

Alternatively, you can use the Check Singular Value Characteristics block to specify bounds on the singular value. (Requires Simulink Control Design.)

## Specify Step Response Characteristics

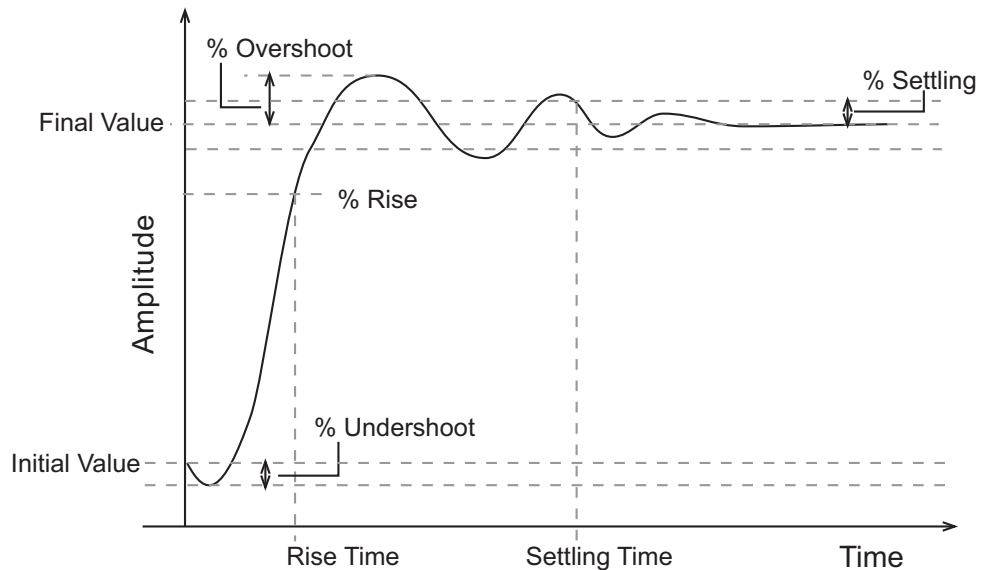
To specify step response characteristics:

- 1 You can apply this requirement to either a signal or a linearization of your model.

In the Design Optimization Tool, click **New**. To apply this requirement to a signal, select the **Step Response Envelope** entry in the **New Time Domain Requirement** section of the **New** list. To apply this requirement to a linearization of your model, select the **Step Response Envelope** entry in the **New Frequency Domain Requirement** section of the **New** list. The latter option requires Simulink Control Design software.

A window opens where you specify the step response requirements on a signal, or system.

- 2 Specify a requirement name in the **Name** box.
- 3 Specify the step response characteristics:





- **Initial value:** Input level before the step occurs
- **Step time:** Time at which the step takes place
- **Final value:** Input level after the step occurs
- **Rise time:** The time taken for the response signal to reach a specified percentage of the step's range. The step's range is the difference between the final and initial values.
- **% Rise:** The percentage used in the rise time.
- **Settling time:** The time taken until the response signal settles within a specified region around the final value. This settling region is defined as the final step value plus or minus the specified percentage of the final value.
- **% Settling:** The percentage used in the settling time.
- **% Overshoot:** The amount by which the response signal can exceed the final value. This amount is specified as a percentage of the step's range. The step's range is the difference between the final and initial values.
- **% Undershoot:** The amount by which the response signal can undershoot the initial value. This amount is specified as a percentage of the step's range. The step's range is the difference between the final and initial values.

#### 4 Specify the signals or systems to be bound.


You can apply this requirement to a model signal or to a linearization of your Simulink model (requires Simulink Control Design software).

- Apply this requirement to a model signal:

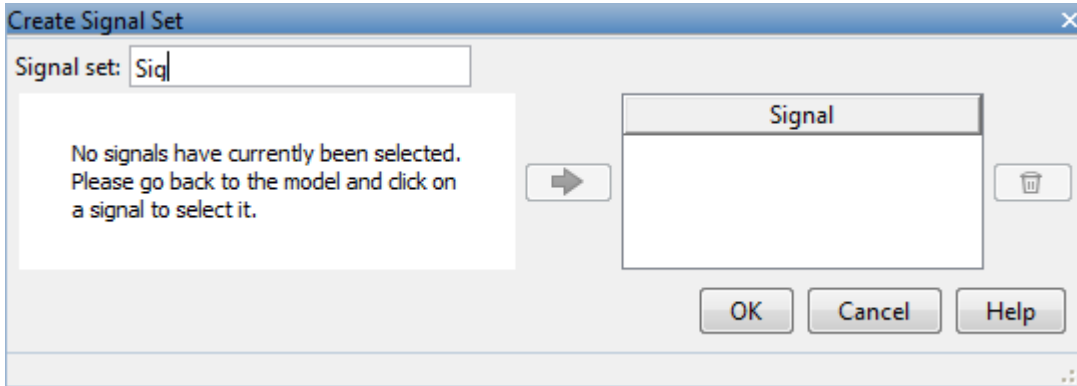
In the **Select Signals to Bound** area, select a logged signal to which you will apply the requirement.

If you have already selected a signal to log, as described in “Specify Signals to Log” on page 3-13, it appears in the list. Select the corresponding check-box.


If you haven't selected a signal to log:

- Click . A window opens where you specify the logged signal.

- b In the Simulink model window, click the signal to which you want to add a requirement.



The window updates and displays the name of the block and the port number where the selected signal is located.

- c Select the signal and click  to add it to the signal set.
- d In the **Signal set** box, enter a name for the selected signal set.


Click **OK**. A new variable, with the specified name, appears in the **Design Optimization Workspace** of the Design Optimization tool window.

- Apply this requirement to a linear system.

Linear systems are defined by snapshot times at which the model is linearized and sets of linearization I/O points defining the system inputs and outputs.

- a Specify the simulation time at which the model is linearized using the **Snapshot Times** box. For multiple simulation snapshot times, specify a vector.
- b Select the linearization input/output set from the **Linearization I/O** area.

If you have already created a linearization input/output set, it will appear in the list. Select the corresponding check box.

If you have not created a linearization input/output set, click  to open the Create linearization I/O set dialog box.

For more information on using this dialog box, see “Create Linearization I/O Sets” on page 3-82.

For more information on linearization, see “What Is Linearization?”.

### 5 Click **OK**.

A variable with the specified requirement name appears in the **Design Optimization Workspace**. A graphical display of the requirement also appears in the Design Optimization tool window.


Alternatively, you can use the Check Step Response Characteristics block to specify step response bounds for a signal.


### See Also

“Design Optimization to Meet Step Response Requirements (GUI)”

## Specify Custom Requirements

To specify custom requirements, such as minimizing system energy:

- 1 In the Design Optimization tool, select **Custom Requirement** in the **New** list. A window opens where you specify the custom requirement.
- 2 Specify a requirement name in the **Name** box.
- 3 Specify the requirement type using the **Type** list.
- 4 Specify the name of the function that contains the custom requirement in the **Function** box. The field must be specified as a function handle using @. The function must be on the MATLAB path. Click  to review or edit the function.

If the function does not exist, clicking  opens a template MATLAB file. Use this file to implement the custom requirement. The default function name is myCustomRequirement.

- 5** (Optional) If you want to prevent the solver from considering specific parameter combinations, select the **Error if constraint is violated** check box. Use this option for parameter-only constraints.

During an optimization iteration, the solver evaluates requirements with this option selected first.

- If the constraint is violated, the solver skips evaluating any remaining requirements and proceeds to the next iterate.
- If the constraint is *not* violated, the solver evaluates the remaining requirements for the current iterate. If any of the remaining requirements bound signals or systems, then the solver simulates the model .

For more information, see “Skip Model Simulation Based on Parameter Constraint Violation (GUI)” on page 3-152.

---

**Note** If you select this check box, then do not specify signals or systems to bound. If you *do* specify signals or systems, then this check box is ignored.

---

- 6** (Optional) Specify the signal or system, or both, to be bound.

You can apply this requirement to model signals, or a linearization of your Simulink model (requires Simulink Control Design software), or both.


Click **Select Signals and Systems to Bound (Optional)** to view the signal and linearization I/O selection area.

- Apply this requirement to a model signal:

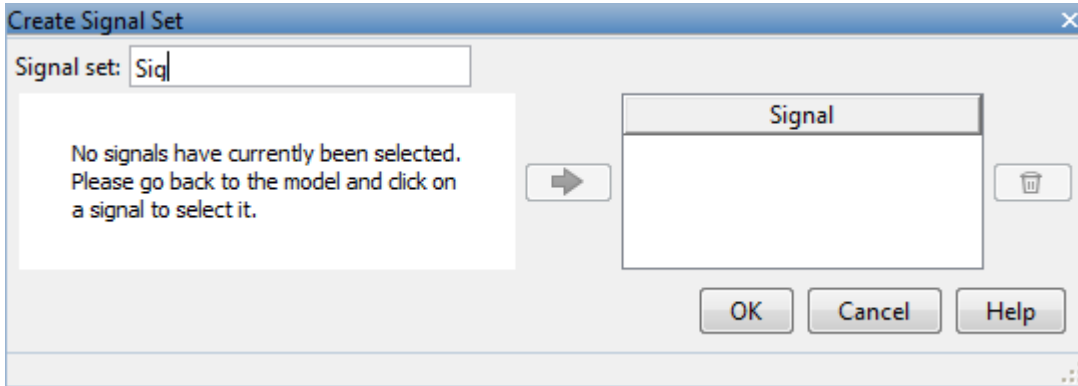
In the **Signal** area, select a logged signal to which you will apply the requirement.

If you have already selected a signal to log, as described in “Specify Signals to Log” on page 3-13, it appears in the list. Select the corresponding check box.


If you have not selected a signal to log:

- Click . A window opens where you specify the logged signal.

- b In the Simulink model window, click the signal to which you want to add a requirement.



The window updates and displays the name of the block and the port number where the selected signal is located.

- c Select the signal and click  to add it to the signal set.
- d In the **Signal set** box, enter a name for the selected signal set.


Click **OK**. A new variable, with the specified name, appears in the **Design Optimization Workspace** of the Design Optimization tool window.

- Apply this requirement to a linear system.

Linear systems are defined by snapshot times at which the model is linearized and sets of linearization I/O points defining the system inputs and outputs.

- a Specify the simulation time at which the model is linearized using the **Snapshot Times** box. For multiple simulation snapshot times, specify a vector.
- b Select the linearization input/output set from the **Linearization I/O** area.

If you have already created a linearization input/output set, it will appear in the list. Select the corresponding check box.

If you have not created a linearization input/output set, click  to open the Create linearization I/O set dialog box. For more information on using this dialog box, see “Create Linearization I/O Sets” on page 3-82.

For more information on linearization, see “What Is Linearization?”.

### 7 Click **OK**.

A new variable, with the specified name, appears in the **Design Optimization Workspace** of the Design Optimization tool. A graphical display of the requirement also appears in the Design Optimization tool window.

### **See Also**

- “Design Optimization to Meet a Custom Objective (GUI)” on page 3-105
- “Design Optimization to Meet Custom Signal Requirements (GUI)” on page 3-122

# Time- and Frequency-Domain Requirements in SISO Design Tool

## In this section...

“Root Locus Diagrams” on page 5-39

“Open-Loop and Prefilter Bode Diagrams” on page 5-41

“Open-Loop Nichols Plots” on page 5-41

“Step/Impulse Response Plots” on page 5-42

## Root Locus Diagrams

- “Settling Time” on page 5-39
- “Percent Overshoot” on page 5-39
- “Damping Ratio” on page 5-40
- “Natural Frequency” on page 5-40
- “Region Constraint” on page 5-41

## Settling Time

If you specify a settling time in the continuous-time root locus, a vertical line appears on the root locus plot at the pole locations associated with the value provided (using a first-order approximation). In the discrete-time case, the constraint is a curved line.

It is required that  $\text{Re}\{pole\} < -4.6/T_{\text{settling}}$  for continuous systems and

$\log(\text{abs}(pole))/T_{\text{discrete}} < -4.6/T_{\text{settling}}$  for discrete systems. This is an approximation of the settling time based on second-order dominant systems.

## Percent Overshoot

Specifying percent overshoot in the continuous-time root locus causes two rays, starting at the root locus origin, to appear. These rays are the locus of poles associated with the percent value (using a second-order approximation).

In the discrete-time case, the constraint appears as two curves originating at (1,0) and meeting on the real axis in the left-hand plane.

The percent overshoot  $p.o$  constraint can be expressed in terms of the damping ratio, as in this equation:

$$p.o. = 100e^{-\pi\zeta/\sqrt{1-\zeta^2}}$$

where  $\zeta$  is the damping ratio.

### Damping Ratio

Specifying a damping ratio in the continuous-time root locus causes two rays, starting at the root locus origin, to appear. These rays are the locus of poles associated with the damping ratio. In the discrete-time case, the constraint appears as curved lines originating at (1,0) and meeting on the real axis in the left-hand plane.

The damping ratio defines a requirement on  $-\text{Re}\{pole\}/\text{abs}\{pole\}$  for continuous systems and on

$$\begin{aligned}r &= \text{abs}(pSys) \\t &= \text{angle}(pSys) \\c &= -\log(r)/\sqrt{(\log(r))^2 + t^2}\end{aligned}$$

for discrete systems.

### Natural Frequency

If you specify a natural frequency, a semicircle centered around the root locus origin appears. The radius equals the natural frequency.

The natural frequency defines a requirement on  $\text{abs}\{pole\}$  for continuous systems and on



$$\begin{aligned}r &= \text{abs}(pSys) \\t &= \text{angle}(pSys) \\c &= \sqrt{(\log(r))^2 + t^2} / Ts_{model}\end{aligned}$$

for discrete systems.

### **Region Constraint**

Specifies an exclusion region in the complex plane, causing a line to appear between the two specified points with a shaded region below the line. The poles must not lie in the shaded region.

## **Open-Loop and Prefilter Bode Diagrams**

- “Gain and Phase Margins” on page 5-41
- “Upper Gain Limit” on page 5-41
- “Lower Gain Limit” on page 5-41

### **Gain and Phase Margins**

Specify a minimum phase and or a minimum gain margin.

### **Upper Gain Limit**

You can specify an upper gain limit, which appears as a straight line on the Bode magnitude curve. You must select frequency limits, the upper gain limit in decibels, and the slope in dB/decade.

### **Lower Gain Limit**

Specify the lower gain limit in the same fashion as the upper gain limit.

## **Open-Loop Nichols Plots**

- “Phase Margin” on page 5-42
- “Gain Margin” on page 5-42

- “Closed-Loop Peak Gain” on page 5-42
- “Gain-Phase Requirement” on page 5-42

### **Phase Margin**

Specify a minimum phase amount.

While displayed graphically at only one location around a multiple of -180 degrees, this requirement applies to phase margin regardless of actual phase (i.e., it is interpreted for all multiples of -180).

### **Gain Margin**

Specify a minimum gain margin.

While displayed graphically at only one location around a multiple of -180 degrees, this requirement applies to gain margin regardless of actual phase (i.e., it is interpreted for all multiples of -180).

### **Closed-Loop Peak Gain**

Specify a peak closed-loop gain at a given location. The specified value can be positive or negative in dB. The constraint follows the curves of the Nichols plot grid, so it is recommended that you have the grid on when using this feature.

While displayed graphically at only one location around a multiple of -180 degrees, this requirement applies to gain margin regardless of actual phase (i.e., it is interpreted for all multiples of -180).

### **Gain-Phase Requirement**

Specifies an exclusion region for the response on the Nichols plot. The response must not pass through the shaded region.

This only applies to the region (phase and gain) drawn.

### **Step/Impulse Response Plots**

- “Upper Time Response Bound” on page 5-43

- “Lower Time Response Bound” on page 5-43

### **Upper Time Response Bound**

You can specify an upper time response bound.

### **Lower Time Response Bound**

You can specify a lower time response bound.

## **Related Examples**

- “How to Design Optimization-Based Controllers for LTI Systems” on page 5-45
- “Optimize LTI System to Meet Frequency-Domain Requirements” on page 5-47
- “Design Optimization-Based PID Controller for Linearized Simulink Model (GUI)”

## **Time-Domain Simulations in SISO Design Tool**

When using a SISO Design Task, Simulink Design Optimization software automatically sets the model's simulation start and stop time and you cannot directly change them. By default, the simulation starts at 0 and continues until the SISO Design Task determines that the dynamics of the model have settled out. In addition, when the design requirements extend beyond this point, the simulation continues to the extent of the design requirements. Although you cannot directly adjust the start or stop time of the simulation, you can adjust the design requirements to extend further in time and thus force the simulation to continue to a certain point.

## How to Design Optimization-Based Controllers for LTI Systems

To design optimization-based linear controller for an LTI model:

- 1** Create and import a linear model into a SISO Design Task. You can create an LTI model at the MATLAB command line, as described in “Creating an LTI Plant Model” on page 5-48.
- 2** Create a SISO Design Task with design and analysis plots, as described in “Creating Design and Analysis Plots” on page 5-49.

To learn more about SISO Design Tool, see “Using the SISO Design Task in the Controls & Estimation Tools Manager” in the Control System Toolbox documentation.

- 3** Under **Automated Tuning** select **Optimization based tuning** as the **Design Method** and then click the **Optimize Compensators** button to create a **Response Optimization** task within the Control and Estimation Tools Manager. See “Creating a Response Optimization Task” on page 5-52 for more information.
- 4** Within the **Response Optimization** node, select the **Compensators** pane to select and configure the compensator elements you want to tune during the response optimization. See “Selecting Tunable Compensator Elements” on page 5-54 for more information.

---

**Note** Compensator elements or parameters cannot have uncertainty when used with frequency-domain based response optimization.

---

- 5** Under **Design requirements** in the **Response Optimization** node, select the design requirements you want the system to satisfy. See “Adding Design Requirements” on page 5-55 for more information.
- 6** Click the **Start Optimization** button within the **Response Optimization** node. The optimization progress results appear under **Optimization**. The **Compensators** pane contains the new, optimized compensator element

values. See “Optimizing the System’s Response” on page 5-63 for more information.

# Optimize LTI System to Meet Frequency-Domain Requirements

## In this section...

- “Introduction” on page 5-47
- “Design Requirements” on page 5-47
- “Creating an LTI Plant Model” on page 5-48
- “Creating Design and Analysis Plots” on page 5-49
- “Creating a Response Optimization Task” on page 5-52
- “Selecting Tunable Compensator Elements” on page 5-54
- “Adding Design Requirements” on page 5-55
- “Optimizing the System’s Response” on page 5-63
- “Creating and Displaying the Closed-Loop System” on page 5-66

## Introduction

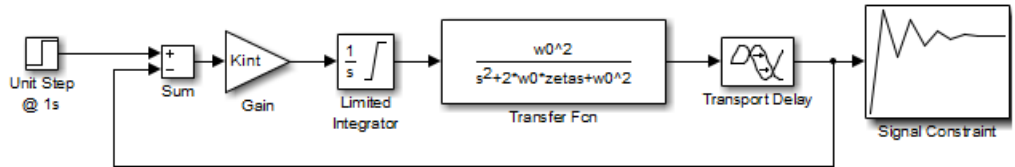
When you have Control System Toolbox software, you can place Simulink Design Optimization design requirements or constraints on plots in the SISO Design Tool graphical tuning editor and analysis plots that are part of a SISO Design Task. This allows you to include design requirements for response optimization in the frequency-domain in addition to the time-domain. This topic guides you through an example using frequency-domain design requirements to optimize the response of a system in the SISO Design Task.

You can specify frequency-domain design requirements to optimize response signals for any model that you can design within a SISO Design Task:

- Command-line LTI models created with the Control System Toolbox commands
- Simulink models that have been linearized using Simulink Control Design software

## Design Requirements

In this example, you use a linearized version of the following Simulink model.



You use optimization methods to design a compensator so that the closed loop system meets the following design specifications when you excite the system with a unit step input:

- A maximum 30-second settling time
- A maximum 10% overshoot
- A maximum 10-second rise time
- A limit of  $\pm 0.7$  on the actuator signal

### Creating an LTI Plant Model

In the `srotut1` model, the plant model is composed of a gain, a limited integrator, a transfer function, and a transport delay.

You want to design the compensator for the open loop transfer function of the linearized `srotut1` model. The linearized `srotut1` plant model is composed of the gain, an unlimited integrator, the transfer function, and a Padé approximation to the transport delay.

To create an open loop transfer function based on the linearized `srotut1` model, enter the following commands:

```
w0      = 1;
zeta    = 1;
Kint    = 0.5;
Tdelay  = 1;
[delayNum,delayDen] = pade(Tdelay,1);
integrator = tf(Kint,[1 0]);
transfer_fcn = tf(w0^2,[1 2*w0*zeta w0^2]);
delay_block = tf(delayNum,delayDen);
open_loopTF = integrator*transfer_fcn*delay_block;
```



If the plant model is an array of LTI models, the controller is designed for a nominal model only but you can analyze the control design for the remaining models in the array. For more information, see “Control Design Analysis of Multiple Models” in the Control System Toolbox documentation.

---

**Tip** You can directly linearize the Simulink model using Simulink Control Design software.

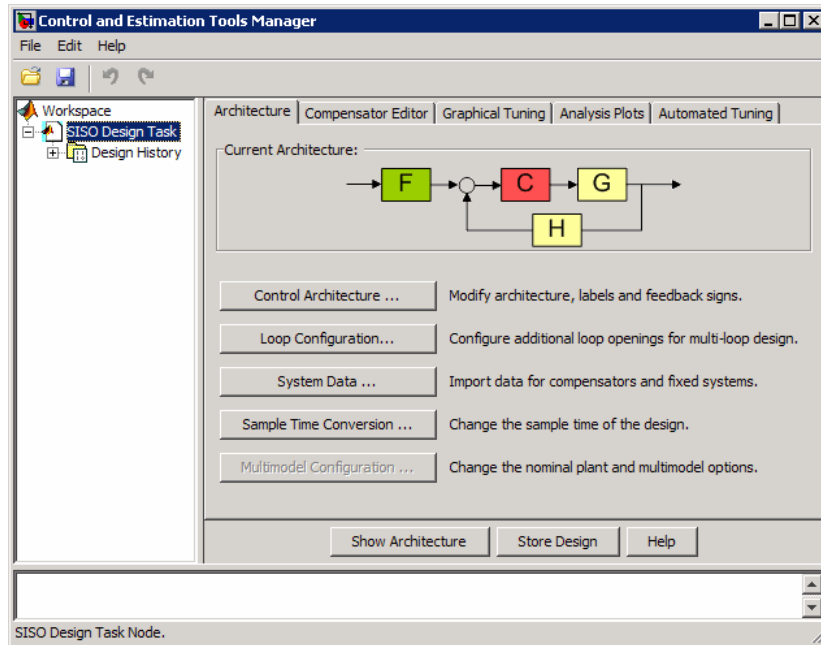
---

## Creating Design and Analysis Plots

This example uses a root locus diagram to design the response of the open loop transfer function, `open_loopTF`. To create a SISO Design Task, containing a root-locus plot for the open loop transfer function, use the following command:

```
sisotool('rlocus',open_loopTF)
```

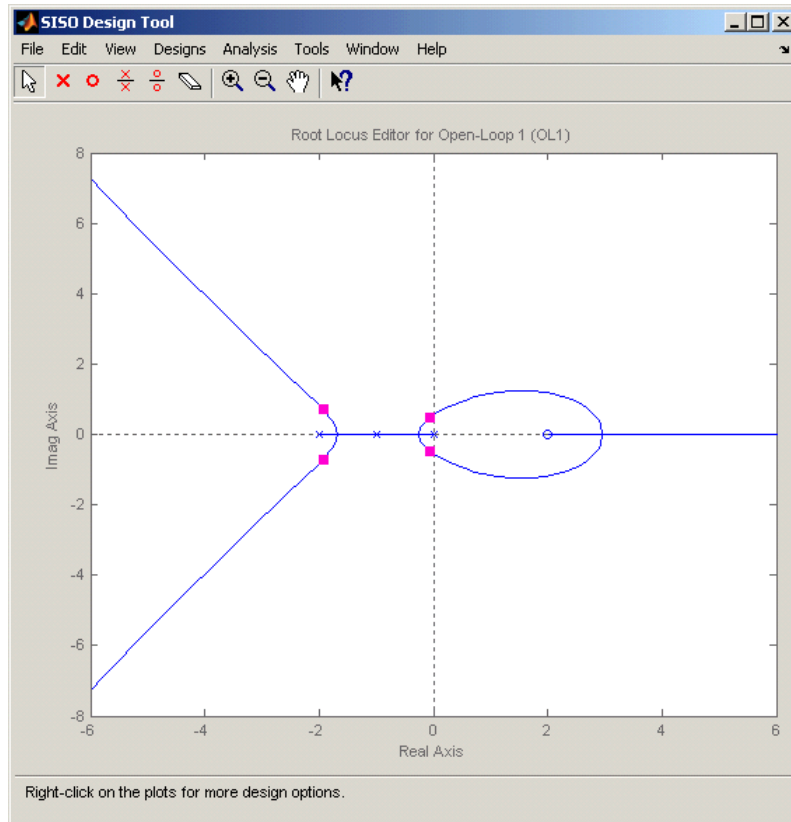
A **SISO Design Task** is created within the Control and Estimation Tools Manager, as shown in the following figure.



The Control and Estimation Tools Manager is a graphical environment for managing and performing tasks such as designing SISO systems. The SISO Design Task node contains five panels that perform actions related to designing SISO control systems. For more information, see “Using the SISO Design Task in the Controls & Estimation Tools Manager” in Control System Toolbox documentation.

The **Architecture** pane, within the **SISO Design Task** node, lets you choose the architecture for the control system you are designing. This example uses the default architecture. In this system, the plant model,  $G$ , is the open loop transfer function `open_loopTF`, the prefilter,  $F$ , and the sensor,  $H$ , are set to 1, and the compensator,  $C$ , is the compensator that will be designed using response optimization methods.

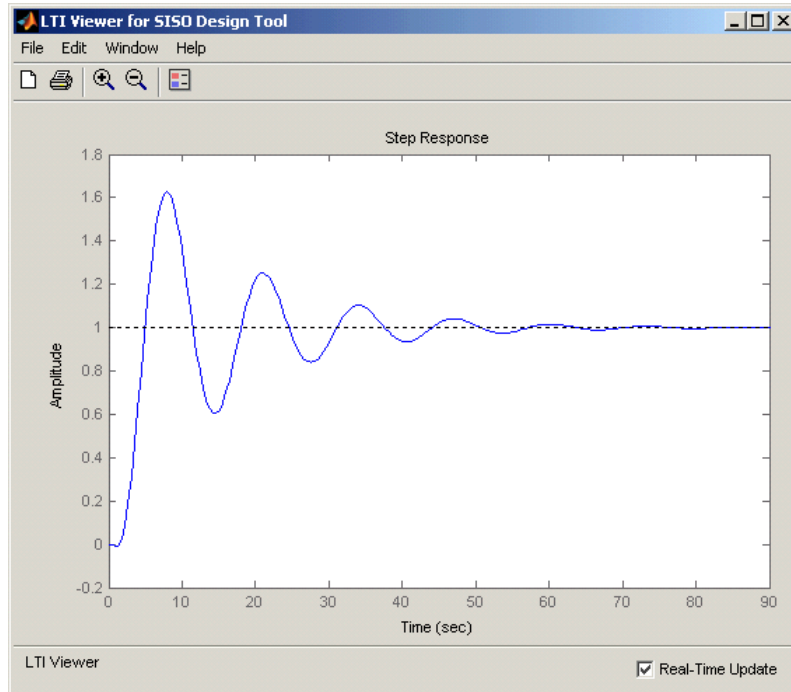
The SISO Design Task also contains a root locus diagram in the SISO Design Tool graphical tuning editor.



In addition to the root-locus diagram, it is helpful to visualize the response of the system with a step response plot. To add a step response:

- 1** Select the **Analysis Plots** pane with the **SISO Design Task** node of the Control and Estimation Tool Manager.
- 2** Select Step for the **Plot Type** of **Plot 1**.
- 3** Under **Contents of Plots**, select the check box in column **1** for the response **Closed Loop r to y**.

A step response plot appears in an LTI Viewer. The plot shows the response of the closed loop system from  $r$  (input to the prefilter,  $F$ ) to  $y$  (output of the plant model,  $G$ ):



### Creating a Response Optimization Task

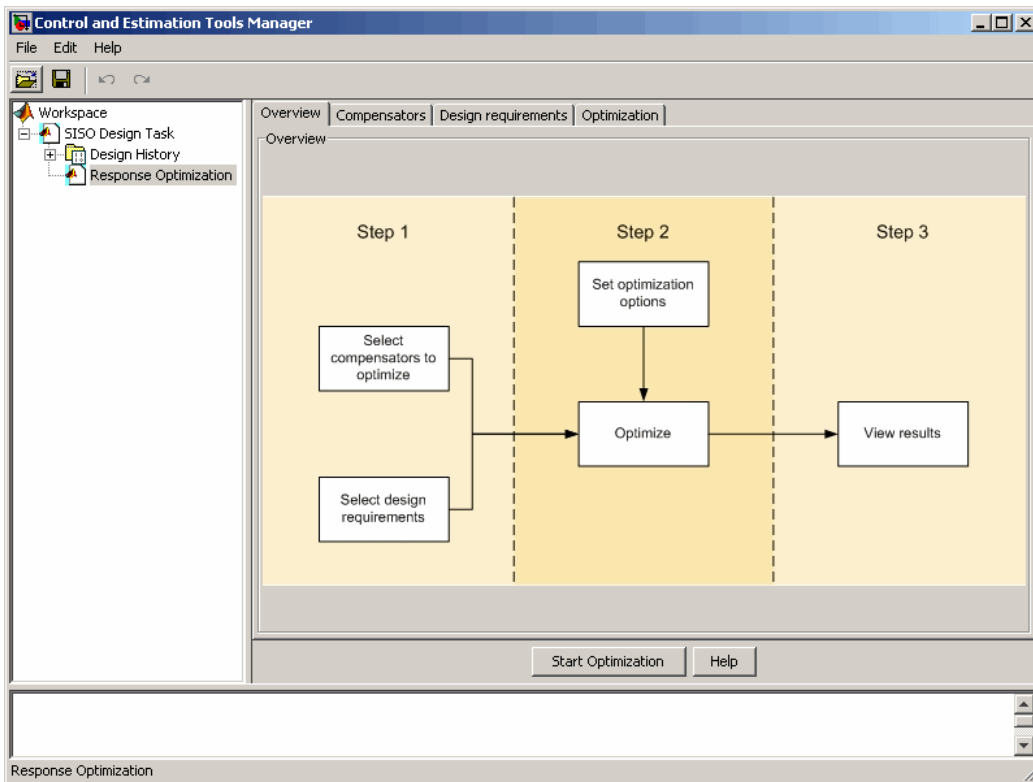
There are several possible methods for designing a SISO system; this example uses an automated approach involving response optimization methods. After creating the design and analysis plots as discussed in “Creating Design and Analysis Plots” on page 5-49, you are ready to start a response optimization task to design the compensator.

To create a response optimization task:

- 1 Select the **Automated Tuning** pane within the **SISO Design Task** node in the Control and Estimation Tools Manager.

- 2 In the **Automated Tuning** pane, select Optimization based tuning as the **Design Method**.
- 3 Click the **Optimize Compensators** button to create the **Response Optimization** node under the **SISO Design Task** node in the tree browser in the left pane of the Control and Estimation Tools Manager.

The **Response Optimization** node contains four panes as shown in the next figure.



With the exception of the first pane, each corresponds to a step in the response optimization process:

- **Overview:** A schematic diagram of the response optimization process.

- **Compensators:** Select and configure the compensator elements that you want to tune. See “Selecting Tunable Compensator Elements” on page 5-54.
- **Design requirements:** Select the design requirements that you want the system to meet after tuning the compensator elements. See “Adding Design Requirements” on page 5-55.
- **Optimization:** Configure optimization options and view the progress of the response optimization. See “Optimizing the System’s Response” on page 5-63.

---

**Note** When optimizing responses in a SISO Design Task, you cannot add uncertainty to parameters or compensator elements.

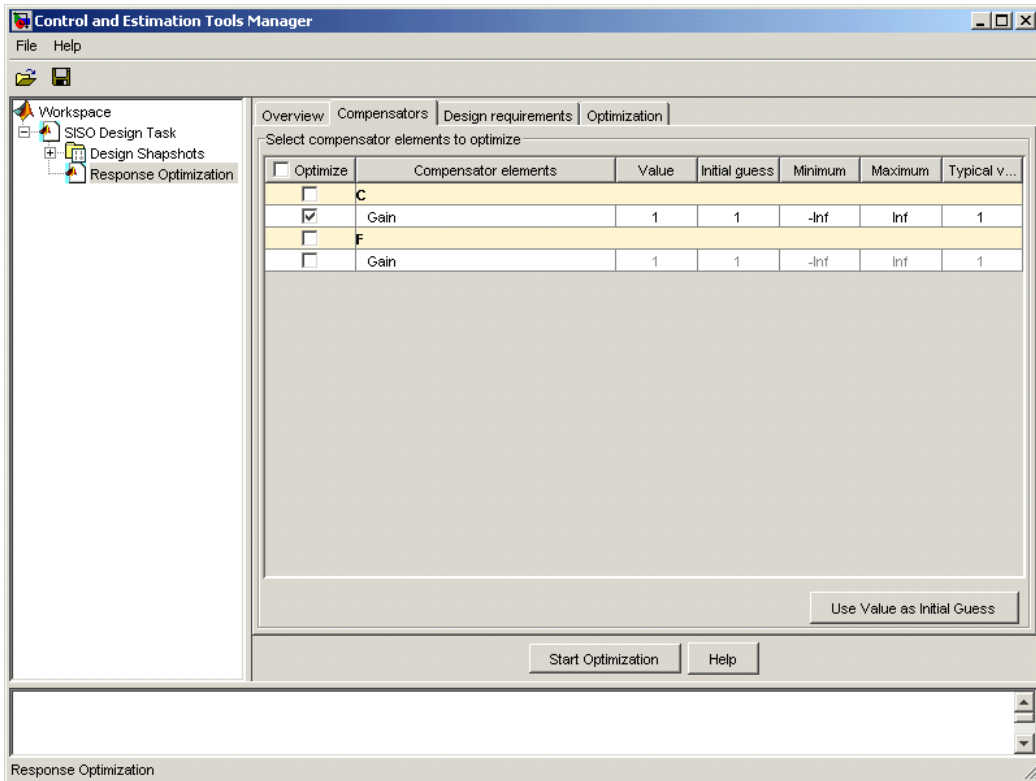
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### Selecting Tunable Compensator Elements

You can tune elements or parameters within compensators in your system so that the response of the system meets the design requirements you specify. To specify the compensator elements to tune:

- 1** Select the **Compensators** pane within the **Response Optimization** node.
- 2** Within the **Compensators** pane, select the check boxes in the **Optimize** column that correspond to the compensator elements you want to tune.

In this example, to tune the **Gain** in the compensator **C**, select the check box next to this element, as shown in the following figure.




---

**Note** Compensator elements or parameters cannot have uncertainty when used with frequency-domain based response optimization.

---

## Adding Design Requirements

You can use both frequency-domain and time-domain design requirements to tune parameters in a control system. The **Design requirements** pane within the **Response Optimization** node of the Control and Estimation Tools Manager provides an interface to create new design requirements and select those you want to use for a response optimization.

This example uses the design specifications described in “Design Requirements” on page 5-47. The following sections each create a new design requirement to meet these specifications:

- “Settling Time Design Requirement” on page 5-56
- “Overshoot Design Requirement” on page 5-57
- “Rise Time Design Requirement” on page 5-59
- “Actuator Limit Design Requirement” on page 5-60

After you add the design requirements, you can select a subset of requirements for controller design, as described in “Selecting the Design Requirements to Use During Response Optimization” on page 5-63.

### Settling Time Design Requirement

The first design specification for this example is to have a settling time of 30 seconds or less. This specification can be represented on a root-locus diagram as a constraint on the real parts of the poles of the open loop system.

To add this design requirement:

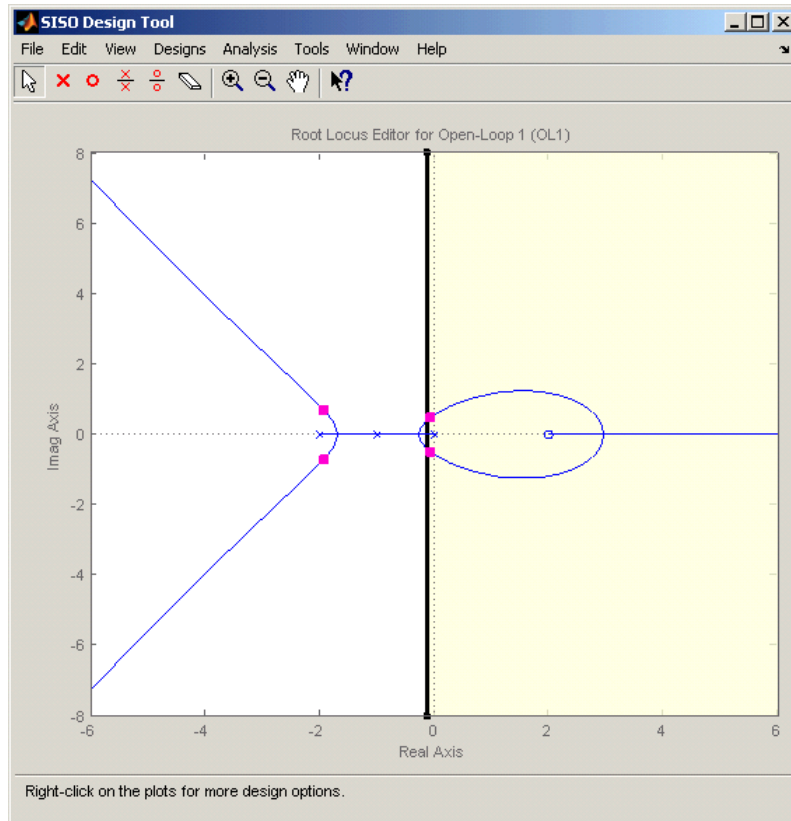
- 1** Select the **Design requirements** pane within the **Response Optimization** node of the Control and Estimation Tools Manager.
- 2** Click the **Add new design requirement** button. This opens the New Design Requirement dialog box.

Within this dialog box you can specify new design requirements and add them to a new or existing design or analysis plot.

- 3** Add a design requirement to the existing root-locus diagram:
  - a** Select Pole/zero settling time from the **Design requirement type** menu.
  - b** Select Open-Loop L from the **Requirement for response** menu.
  - c** Enter 30 seconds for the **Settling time**.
  - d** Click **OK**.



A vertical line should appear on the root-locus diagram, as shown in the following figure.

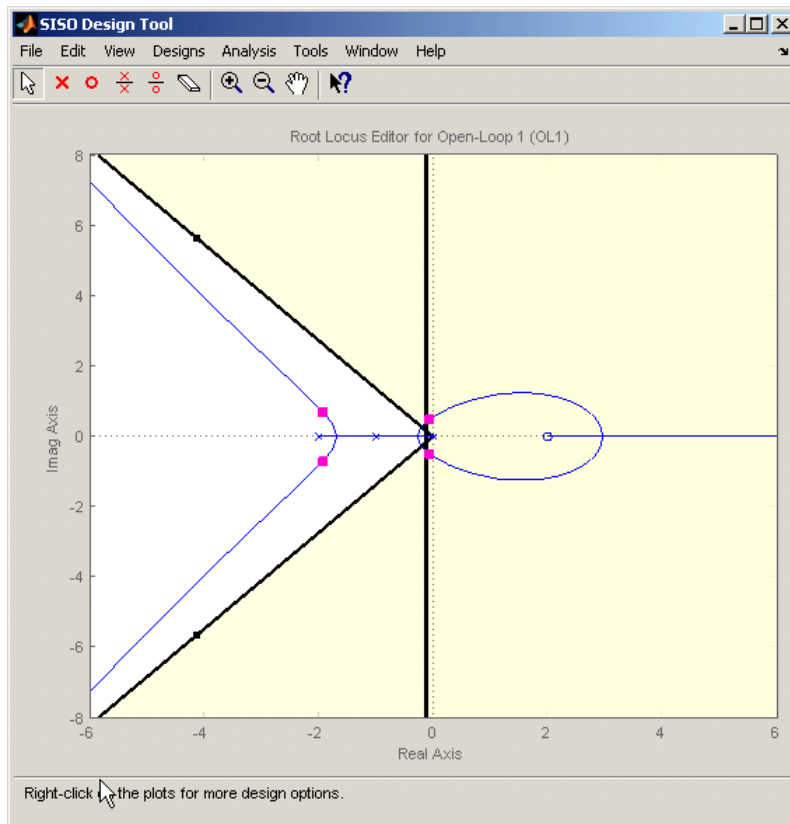


### Overshoot Design Requirement

The second design specification for this example is to have a percentage overshoot of 10% or less. This specification is related to the damping ratio on a root-locus diagram. In addition to adding a design requirement with the **Add new design requirement** button, you can also right-click directly on the design or analysis plots to add the requirement, as shown next.

To add this design requirement:

- 1 Right-click anywhere within the white space of the root-locus diagram in the SISO Design Tool window. Select **Design Requirements** > **New** to open the New Design Requirement dialog box.
- 2 Select **Percent overshoot** as the **Design requirement type** and enter 10 as the **Percent overshoot**.
- 3 Click **OK** to add the design requirement to the root-locus diagram. The design requirement appears as two lines radiating at an angle from the origin, as shown in the following figure.



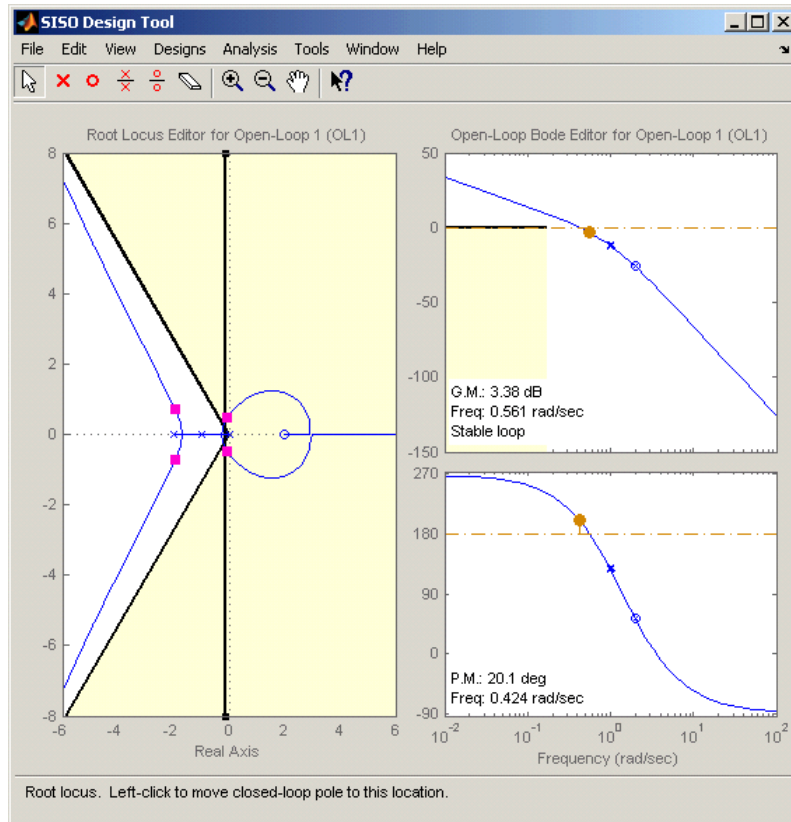
## Rise Time Design Requirement

The third design specification for this example is to have a rise time of 10 seconds or less. This specification is related to a lower limit on a Bode Magnitude diagram.

To add this design requirement:

- 1** Select the **Graphical Tuning** pane in the **SISO Design Task** node of the Control and Estimation Tools Manager.
- 2** For Plot 2, set **Plot Type** to Open-Loop Bode.
- 3** Right-click anywhere within the white space of the open-loop bode diagram in the SISO Design Tool window. Select **Design Requirements > New** to open the New Design Requirement dialog box.
- 4** Create a design requirement to represent the rise time and add it to the new Bode plot:
  - a** Select **Lower gain limit** from the **Design requirement type** menu.
  - b** Enter  $1e-2$  to  $0.17$  for the **Frequency** range.
  - c** Enter  $0$  to  $0$  for the **Magnitude** range.
  - d** Click **OK**.

A Bode diagram appears within the SISO Design Tool window. The magnitude plot of the Bode diagram includes a horizontal line representing the design requirement, as shown in the following figure.

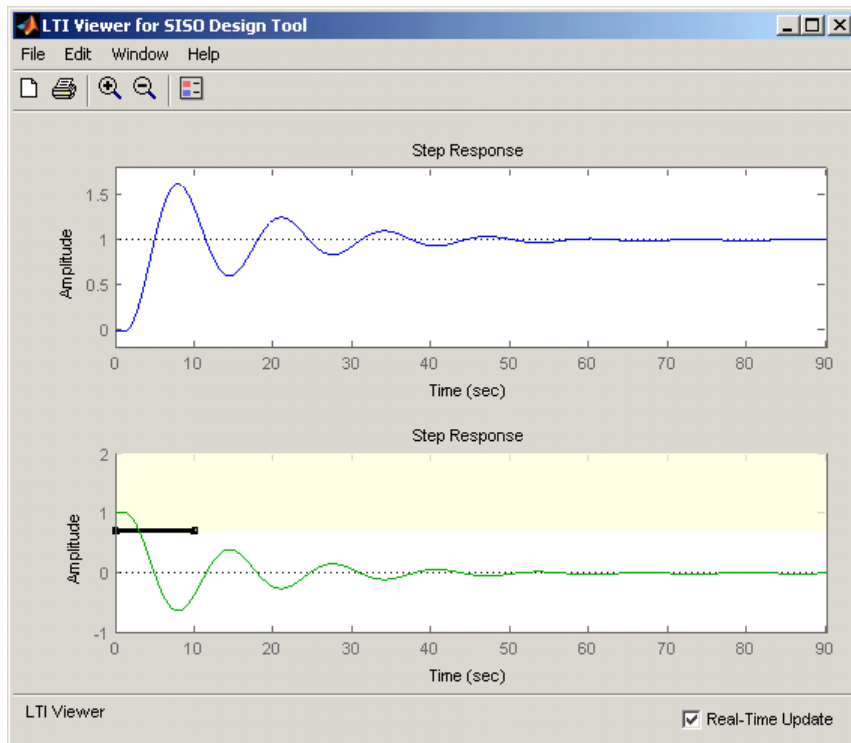


## Actuator Limit Design Requirement

The fourth design specification for this example is to limit the actuator signal to within  $\pm 0.7$ . To add this design requirement:

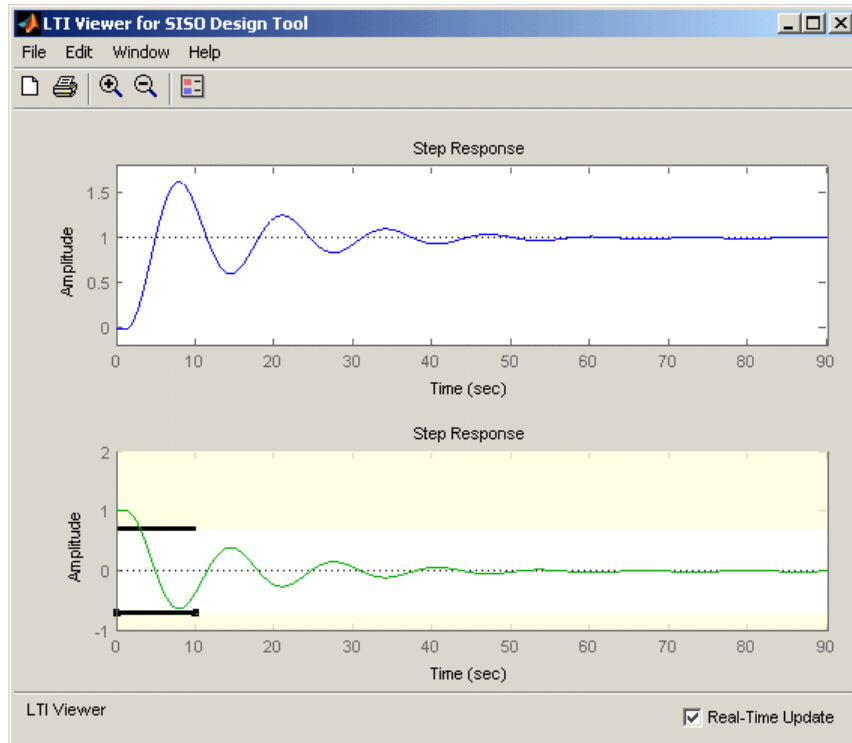
- 1** Select the **Design requirements** pane in the **Response Optimization** node of the Control and Estimation Tools Manager.
- 2** Click the **Add new design requirement** button to open the New Design Requirement dialog box.
- 3** Create a time-domain design requirement to represent the upper limit on the actuator signal, and add it to a new step response plot in the LTI Viewer:

- a Select Step response upper amplitude limit from the **Design requirement type** menu.
- b Select Closed Loop  $r$  to  $u$  from the **Requirement for response** menu.
- c Enter 0 to 10 for the **Time** range.
- d Enter 0.7 to 0.7 for the **Amplitude** range.
- e Click **OK**. A second step response plot for the closed loop response from  $r$  to  $u$  appears in the LTI Viewer. The plot contains a horizontal line representing the upper limit on the actuator signal.
- f To extend this limit for all times (to  $t=\infty$ ), right click on the black edge of the design requirement, somewhere toward the right edge, and select **Extend to inf**. The diagram should now appear as shown next.



To add the corresponding design requirement for the lower limit on the actuator signal:

- 1** Select the **Design requirements** pane in the **Response Optimization** node of the Control and Estimation Tools Manager.
- 2** Click the **Add new design requirement** button to open the New Design Requirement dialog box.
- 3** Create a time-domain design requirement to represent the lower limit on the actuator signal, and add it to the step response plot in the LTI Viewer:
  - a** Select **Step response lower amplitude limit** from the **Design requirement type** menu.
  - b** Select **Closed Loop r to u** from the **Requirement for response** menu.
  - c** Enter 0 to 10 for the **Time** range.
  - d** Enter -0.7 to -0.7 for the **Amplitude** range.
  - e** Click **OK**. The step response plot now contains a second horizontal line representing the lower limit on the actuator signal.
  - f** To extend this limit for all times (to  $t=\infty$ ), right-click in the yellow shaded area and select **Extend to inf**. The diagram should now appear as shown in the following figure.



## Selecting the Design Requirements to Use During Response Optimization

The design requirements give constraints on the dynamics of the system and the values of response signals. The table in the **Design requirements** tab lists all design requirements in the design and analysis plots. Select the check boxes next to the design requirements you want to use in the response optimization. This example uses all the current design requirements.

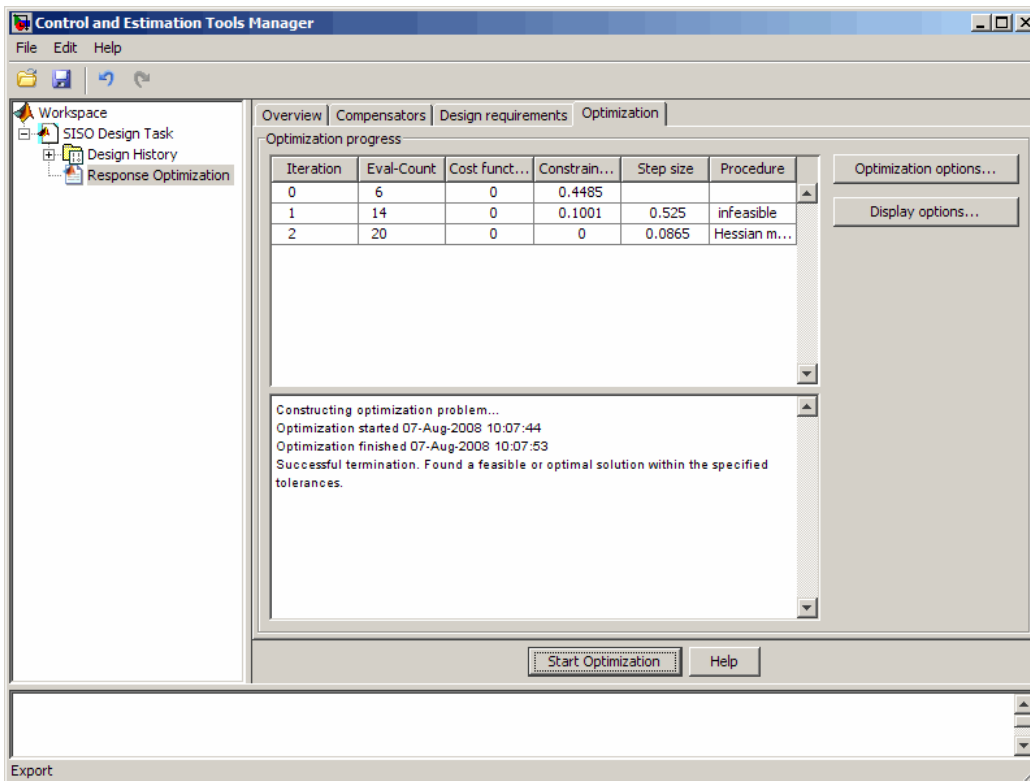
## Optimizing the System's Response

After selecting the compensator elements to tune and adding design requirements for the response signals to satisfy, you are ready to being the response optimization.

The **Optimization** pane within the **Response Optimization** node of the Control and Estimation Tools Manager displays the progress of the response optimization. The pane also contains options to configure the types of progress information displayed during the optimization and options to configure the optimization methods and algorithms.

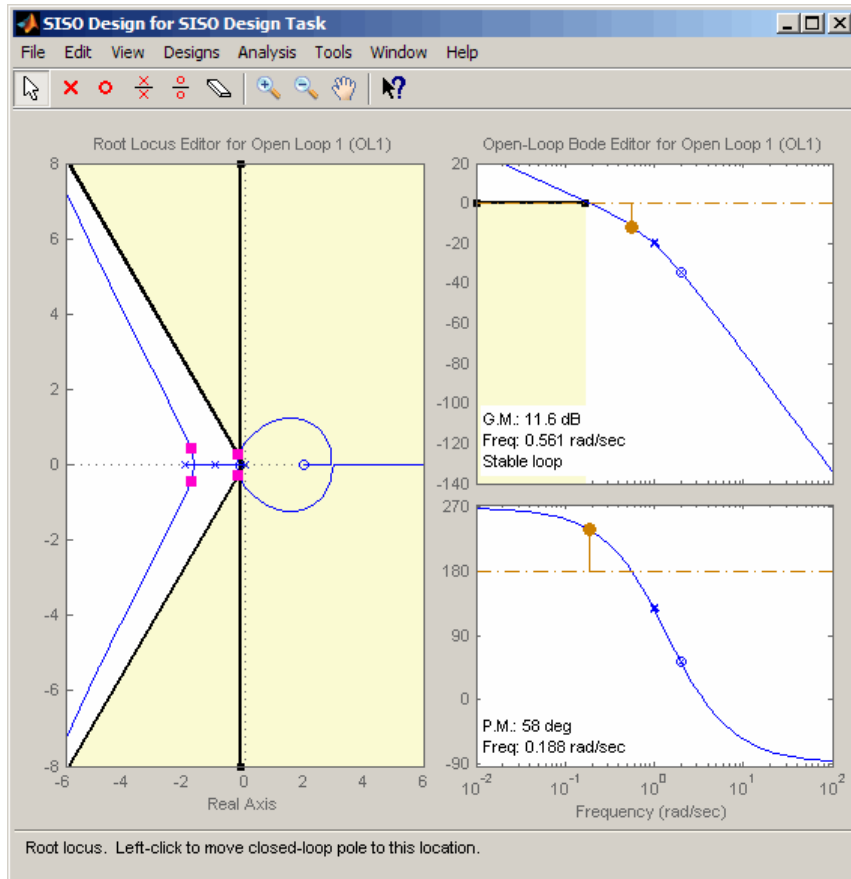
To optimize the response of the system in this example, click the **Start Optimization** button.

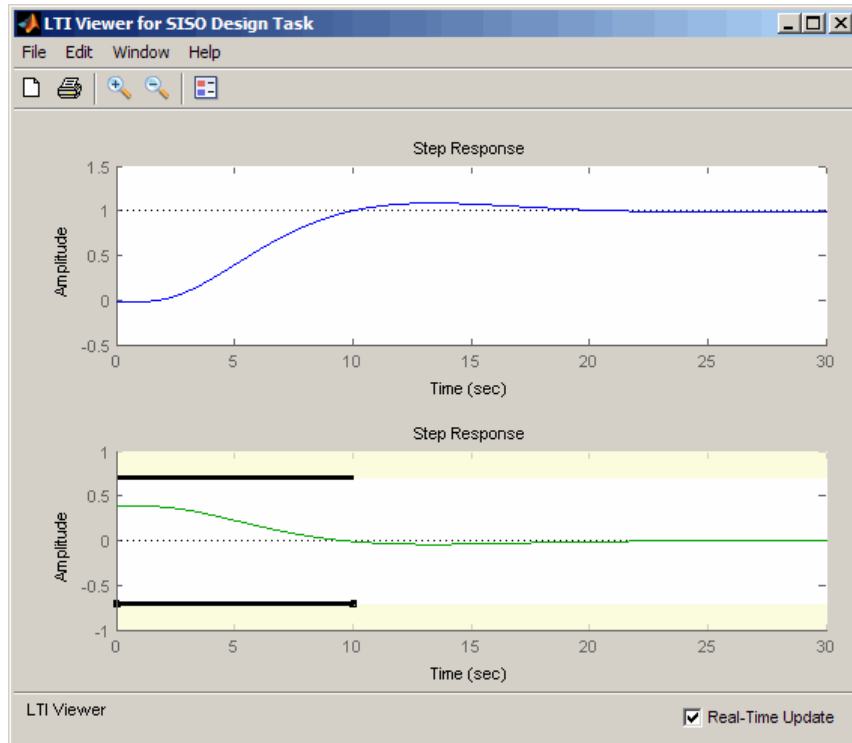
The **Optimization** pane displays the progress of the optimization, iteration by iteration, as shown next. Termination messages from the optimization method and suggestions for improving convergence also appear here.



The optimized signals in the design and analysis plots appear as follows:







### Creating and Displaying the Closed-Loop System

After designing a compensator by optimizing the response of the system, you can export the compensator to the MATLAB workspace, and create a model of the full closed-loop system.

- 1 Within the SISO Design Tool window, select **File > Export** to open the SISO Tool Export dialog box.
- 2 Select the compensator you designed, **Compensator C**, and then click the **Export to Workspace** button.

At the command line, enter the following command to create the closed-loop system, `CL`, from the open-loop transfer function, `open_loopTF`, and the compensator, `C`:

```
CL=feedback(C*open_loopTF,1)
```

This returns the following model:

Zero/pole/gain from input to output "Output":

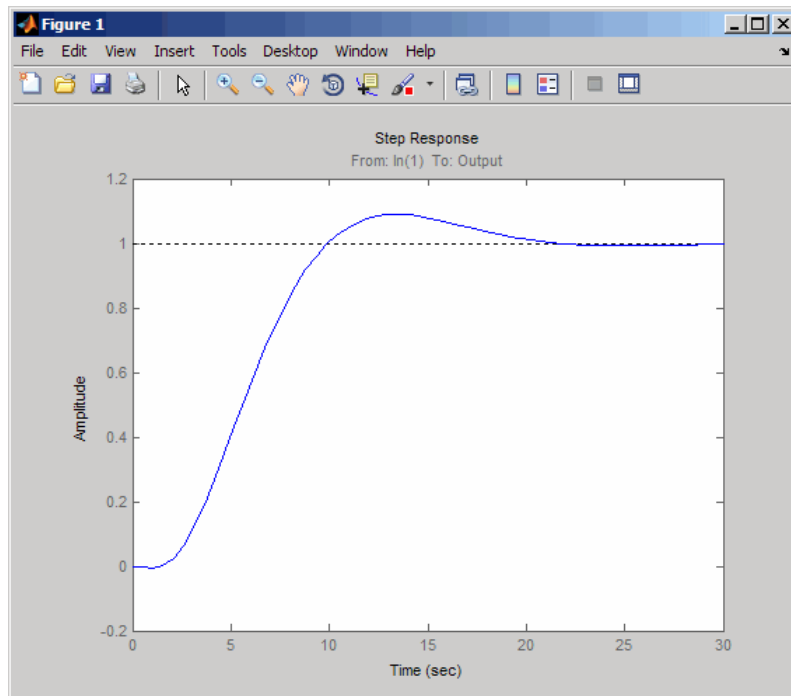
-0.19414 (s-2)

-----  
(s^2 + 0.409s + 0.1136) (s^2 + 3.591s + 3.418)

To create a step response plot of the closed loop system, enter the following command:

```
step(CL);
```

This produces the following figure:



## Designing Linear Controllers for Simulink Models

When you have Control System Toolbox and Simulink Control Design software, you can perform frequency-domain optimization of Simulink models.

You can use Simulink Control Design software to configure SISO Design Tool with compensators, inputs, outputs, and loops computed from a Simulink model. For more information, see “Creating a SISO Design Task” in Simulink Control Design documentation.

After you configure the SISO Design Tool, use Simulink Design Optimization software to optimize the controller parameters of the linearized Simulink model. For an example of optimization-based control design for a model linearized using Simulink Control Design software, see “Design Optimization-Based PID Controller for Linearized Simulink Model (GUI)”.

There is only one difference when tuning compensators derived from Simulink Control Design software: The tuning of compensators from a Simulink model is done through the masks of the Simulink blocks representing each compensator. When selecting parameters to optimize, users can tune the compensator in the pole, zero, or gain format, or in a format consistent with the Simulink block mask as shown in the following figure. Changing the compensator format is not possible when optimizing pure SISO Tool models (those not derived using Simulink Control Design software).

Function Block Parameters: az DTF

Discrete Transfer Fcn

Implement a z-transform transfer function. Specify the numerator and denominator coefficients in descending powers of z. The order of the denominator must be greater than or equal to the order of the numerator.

Main | Data Types | State Attributes

Data

	Source	Value
Numerator:	Dialog	[100.109745431442 -99.1097454314419]
Denominator:	Dialog	[1 -0.888934462738605]
Initial states:	Dialog	0

External reset: None

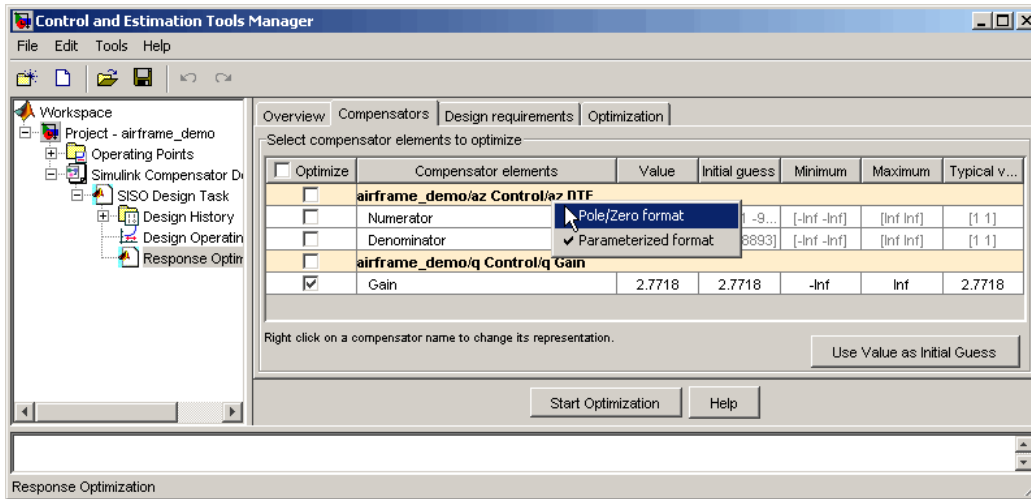
Input processing: Elements as channels (sample based)

Optimize by skipping divide by leading denominator coefficient (a0)

Sample time (-1 for inherited): 0.01

OK Cancel Help Apply

### Mask of a Simulink® compensator block



**Response optimization compensators pane**

# Lookup Tables

---

- “What are Adaptive Lookup Tables?” on page 6-2
- “How to Estimate Lookup Table Values” on page 6-5
- “Estimate Constrained Values of a Lookup Table” on page 6-6
- “Estimate Lookup Table Values from Data” on page 6-22
- “Building Models Using Adaptive Lookup Table Blocks” on page 6-36
- “Selecting an Adaptation Method” on page 6-40
- “Model Engine Using n-D Adaptive Lookup Table” on page 6-42
- “Using Adaptive Lookup Tables in Real-Time Environment” on page 6-56

## What are Adaptive Lookup Tables?

### Lookup Tables

*Lookup tables* store numeric data in a multidimensional array format. In the simpler two-dimensional case, lookup tables can be represented by matrices. Each element of a matrix is a numerical quantity, which can be precisely located in terms of two indexing variables. At higher dimensions, lookup tables can be represented by multidimensional matrices, whose elements are described in terms of a corresponding number of *indexing variables*.

Lookup tables provide a means to capture the dynamic behavior of a physical (mechanical, electronic, software) system. The behavior of a system with  $M$  inputs and  $N$  outputs can be approximately described by using  $N$  lookup tables, each consisting of an array with  $M$  dimensions.

You usually generate lookup tables by experimentally collecting or artificially creating the input and output data of a system. In general, you need as many indexing parameters as the number of input variables. Each indexing parameter may take a value within a predetermined set of data points, which are called the *breakpoints*. The set of all breakpoints corresponding to an indexing variable is called a *grid*. Thus, a system with  $M$  inputs is gridded by  $M$  sets of breakpoints. The software uses the breakpoints to locate the array elements, where the output data of the system are stored. For a system with  $N$  outputs, the software locates the  $N$  array elements and then stores the corresponding data at these locations.

After you create a lookup table using the input and output measurements as described previously, you can use the corresponding multidimensional array of values in applications without having to remeasure the system outputs. In fact, you need only the input data to locate the appropriate array elements in the lookup table because the software reads the approximate system output from the data stored at these locations. Therefore, a lookup table provides a suitable means of capturing the input-output mapping of a *static* system in the form of numeric data stored at predetermined array locations.

### Adaptive Lookup Tables

Statically defined lookup tables, as described in “Lookup Tables” on page 6-2, cannot accommodate the *time-varying* behavior (characteristics) of a



physical plant. Static lookup tables establish a permanent and static mapping of input-output behavior of a physical system. Conversely, the behavior of actual physical systems often varies with time due to wear, environmental conditions, and manufacturing tolerances. With such variations, the static mapping of input-output behavior of a plant described by the lookup table may no longer provide a valid representation of the plant characteristics.

*Adaptive lookup tables* incorporate the time-varying behavior of physical plants into the lookup table generation and maintenance process while providing all of the functionality of a regular lookup table.

The adaptive lookup table receives the input and output measurements of a plant's behavior, which are then used to dynamically create and update the content of the underlying lookup table. In addition to requiring the input data to create the lookup table, the adaptive lookup table also uses the output data of the plant to recalculate the table values. For example, you can collect the output data of the plant by placing sensors at appropriate locations in a physical system.

The software uses the input measurements to locate the array elements by comparing these input values with the breakpoints defined for each indexing variable. Next, it uses the output measurements to recalculate the numeric value stored at these array locations. However, unlike a regular table, which only stores the array data before the actual use of the lookup table, the adaptive table continuously improves the content of the lookup table. This continuous improvement of the table data is referred to as the *adaptation process* or *learning process*.

The adaptation process involves statistical and signal processing algorithms to recapture the input-output behavior of the plant. The adaptive lookup table always tries to provide a valid representation of the plant dynamics even though the plant behavior may be time varying. The underlying signal processing algorithms are also robust against reasonable measurement noise and they provide appropriate filtering of noisy output measurements.

**See Also**

Adaptive Lookup Table (1D Stair-Fit) | Adaptive Lookup Table (2D Stair-Fit)  
| Adaptive Lookup Table (nD Stair-Fit)

### **Related Examples**

- “Model Engine Using n-D Adaptive Lookup Table” on page 6-42

### **Concepts**

- “About Lookup Table Blocks”
- “Building Models Using Adaptive Lookup Table Blocks” on page 6-36

## How to Estimate Lookup Table Values

You can use lookup table Simulink blocks to approximate a system's behavior, as described in "About Lookup Table Blocks" in the Simulink documentation. After you build your system using lookup tables, you can use Simulink Design Optimization software to estimate the table values from measured I/O data.

Estimating lookup table values is an example of estimating parameters which are matrices or multi-dimensional arrays. The workflow for estimating parameters of a lookup table consist of the following tasks:

- 1** Creating a Simulink model using lookup table blocks.
- 2** Importing the measured input and output (I/O) data from which you want to estimate the table values.
- 3** Analyzing and preparing the I/O data for estimation.
- 4** Estimating the lookup table values.
- 5** Validating the estimated table values using a validation data set.

### Related Examples

- "Estimate Lookup Table Values from Data" on page 6-22
- "Estimate Constrained Values of a Lookup Table" on page 6-6

## Estimate Constrained Values of a Lookup Table

### In this section...

“Objectives” on page 6-6

“About the Data” on page 6-6

“Configuring a Project for Parameter Estimation” on page 6-7

“Estimating the Monotonically Increasing Table Values Using Default Settings” on page 6-9

“Validating the Estimation Results” on page 6-16

### Objectives

This example shows how to estimate constrained values of a lookup table. You apply monotonically increasing constraints to the lookup table values, and use the GUI to estimate the table values.

### About the Data

In this example, you use `lookup_increasing.mat`, which contains the measured I/O data for estimating the lookup table values. The MAT-file includes the following variables:

- `xdata1` — Consists of 602 uniformly-sampled input data points in the range  $[-5,5]$ .
- `ydata1` — Output data corresponding to the input data samples.

---

**Note** The output data is a monotonically increasing function of the input data.

---

- `time1` — Time vector.

You use the I/O data to estimate the values of the lookup table in the `lookup_increasing` Simulink model. The table contains eleven values, which are stored in the MATLAB variable `table`. To learn more about how to specify

the table's values, see “Enter Breakpoints and Table Data” in the Simulink documentation.

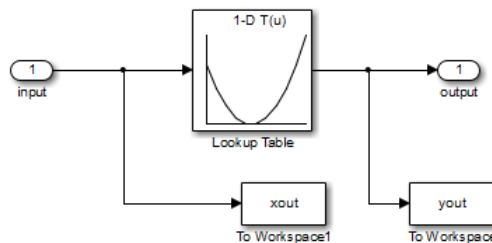
## Configuring a Project for Parameter Estimation

To estimate the monotonically increasing lookup table values, you must first configure a Control and Estimation Tools Manager project.

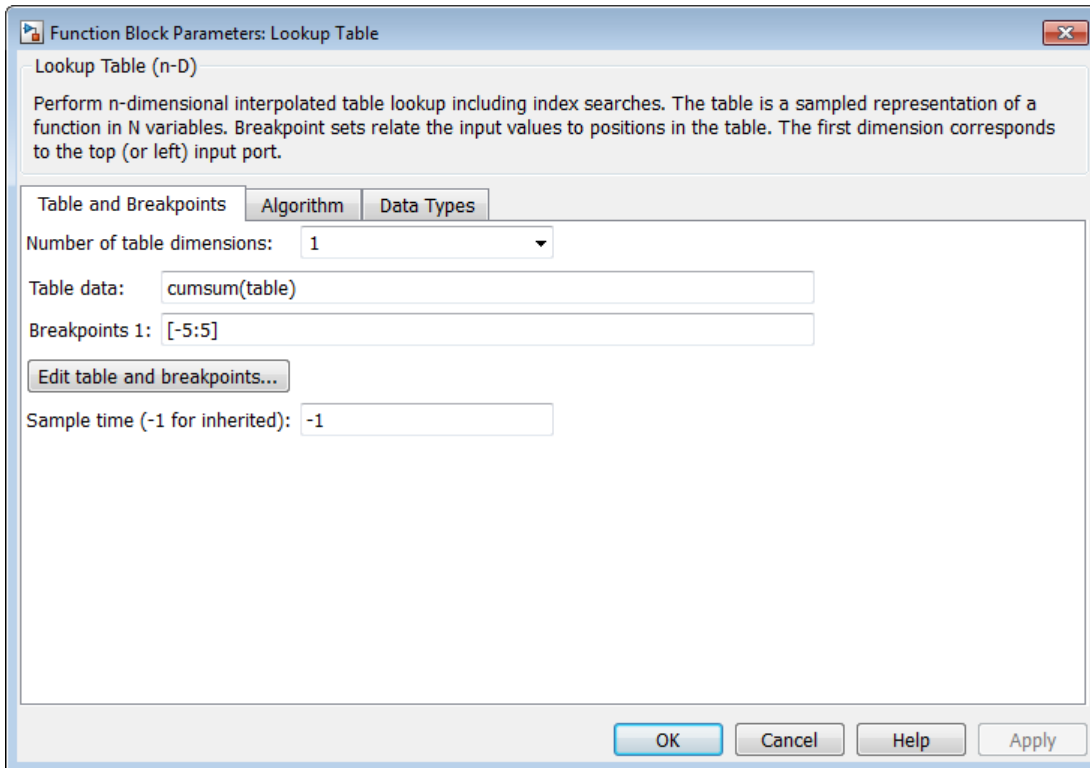
- 1 Open the lookup table model by typing the following command at the MATLAB prompt:

```
lookup_increasing
```

This command opens the Simulink model, and loads the estimation data in the MATLAB workspace.

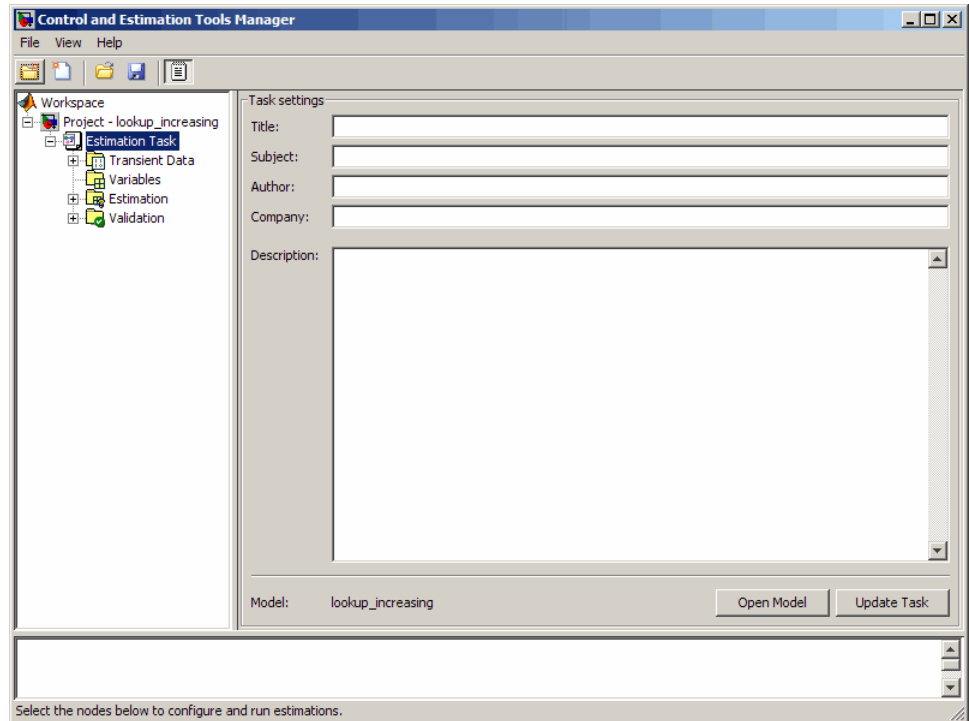


- 2 Double-click the Lookup Table block to view the monotonically increasing constraint applied to the table output values.



The **Table data** field of the Function Block Parameters dialog box shows the constraint. The cumulative sum function, `cumsum`, applies a monotonically increasing constraint on the table output values. This function computes the cumulative sum of the table values based on estimation of the individual table elements from the I/O data.

- 3 In the Simulink model, select **Analysis > Parameter Estimation** to open a new project named **lookup\_increasing** in the Control and Estimation Tools Manager GUI.



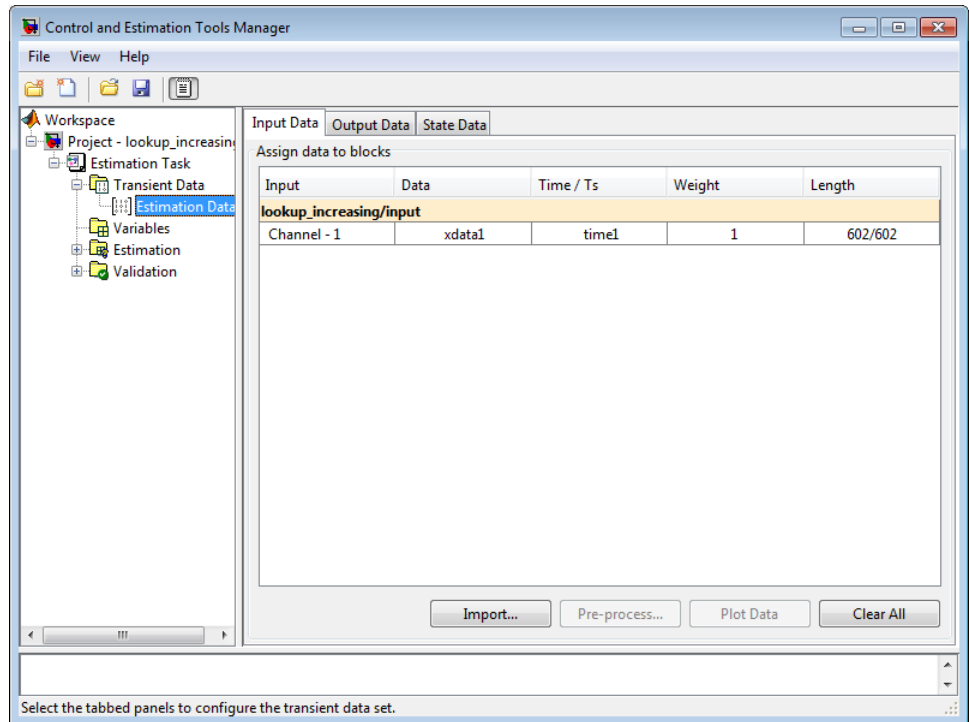
## Estimating the Monotonically Increasing Table Values Using Default Settings

After you configure a project for parameter estimation, as described in “Configuring a Project for Parameter Estimation” on page 6-7, use the following steps to estimate the constrained lookup table values:

- 1 Import the estimation I/O data, as described in the “Importing Data into the GUI” section of “Prepare Data for Parameter Estimation (GUI)”.

You can also load a preconfigured project that already contains the imported data. To do so, type the following commands at the MATLAB prompt:

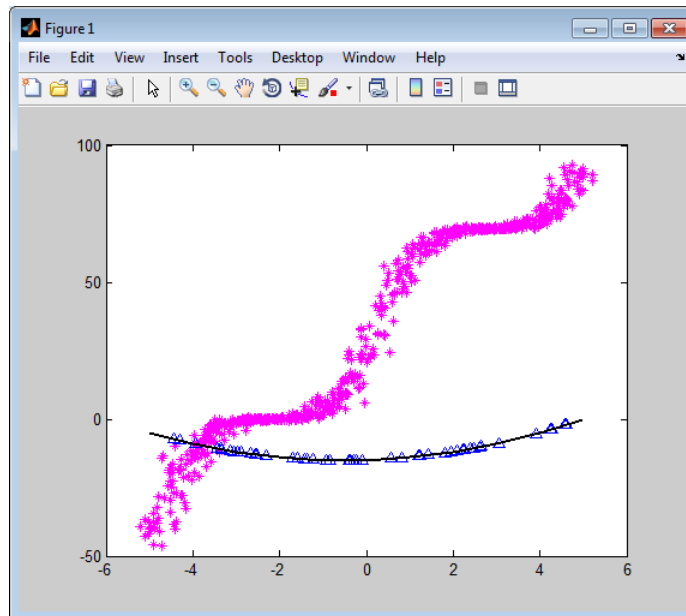
```
lookup_increasing;  
explorer.loadProject('lookup_increasing_import',...  
    'Project - lookup_increasing','Estimation Data')
```





- 2 Run an initial simulation to view the measured data, simulated table values and the initial table values by typing the following commands at the MATLAB prompt:

```
sim('lookup_increasing')
figure(1); plot(xdata1,ydata1, 'm*', xout, yout, 'b^')
hold on; plot(-5:5, cumsum(table), 'k', 'LineWidth', 2)
```



The x- and y-axes represent the input and output data, respectively. The figure shows the following plots:

- Measured data — Represented by the magenta stars (\*).

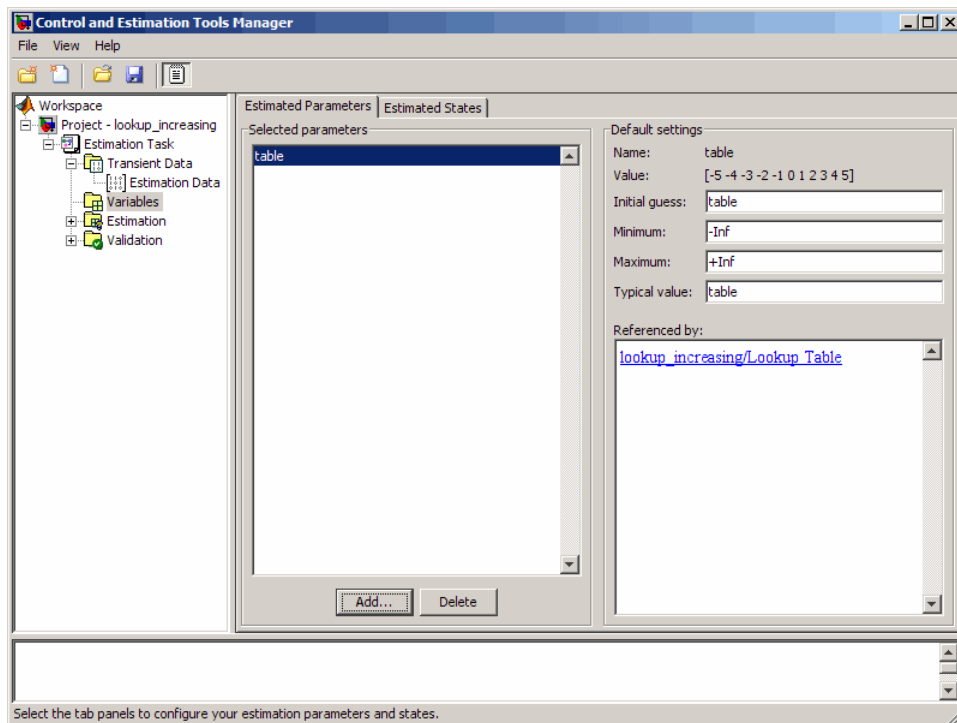
---

**Note** As described in “About the Data” on page 6-6, the output data is a monotonically increasing function of the input data.

---

- Initial table values — Represented by the black line.
- Initial simulation data — Represented by the blue deltas ( $\Delta$ ).

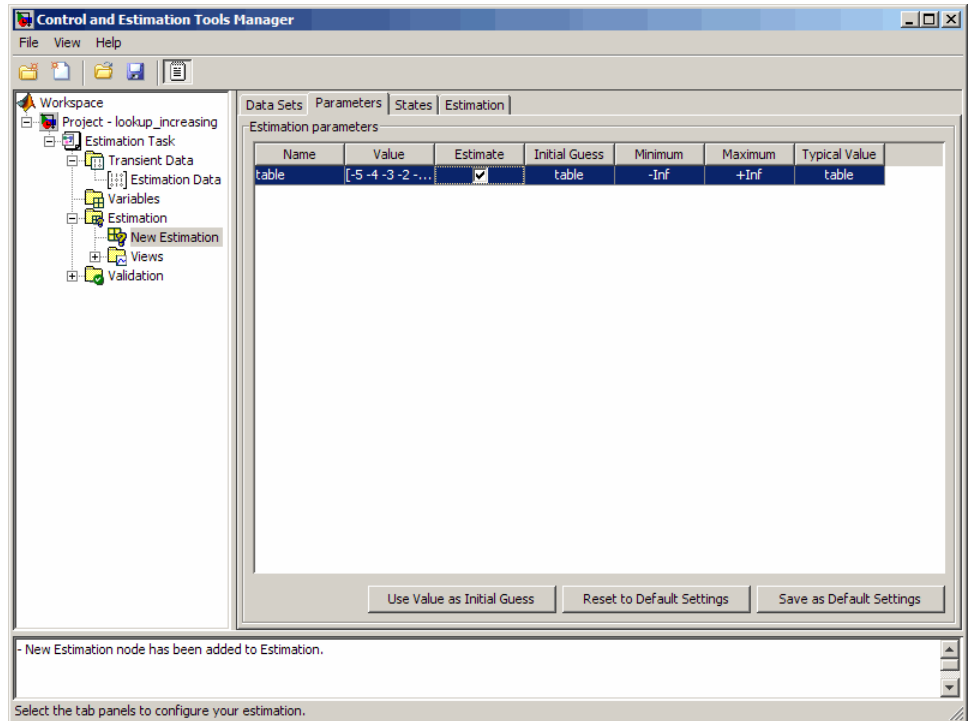
- 3 Select the table output values to estimate.
  - a In the Control and Estimation Tools Manager GUI, select the **Variables** node under the **Estimation Task** node.
  - b Click **Add** to open the Select Parameters dialog box, where you see the Simulink model parameters.
  - c Select **table**, and click **OK** to add the table values to the **Estimated Parameters** tab.



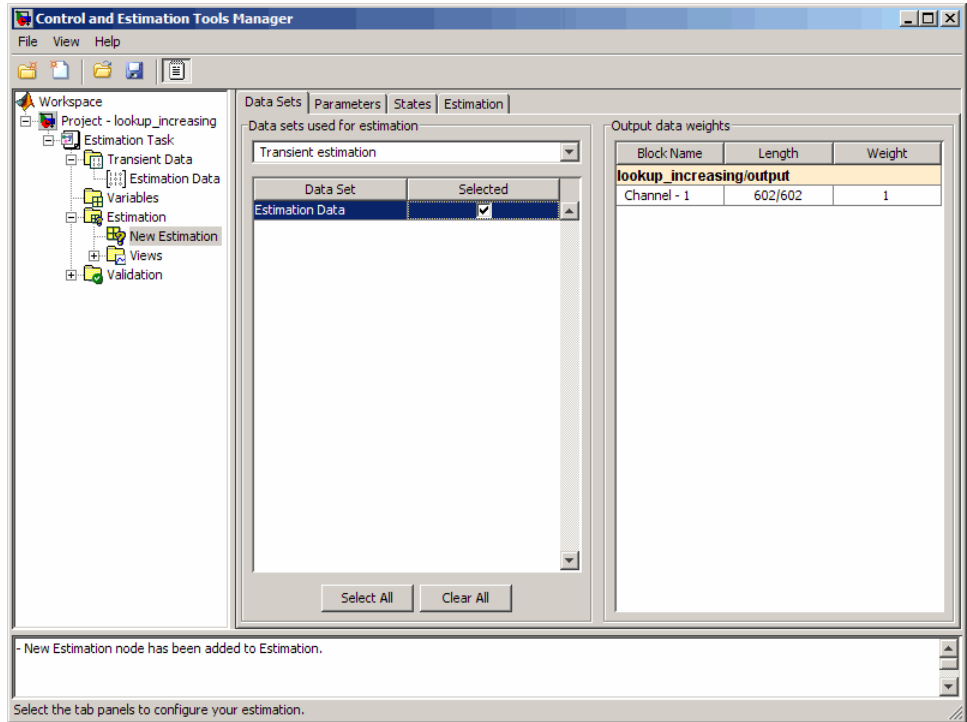
The **Default settings** area of the GUI displays the default settings for the table values. The **Value** field displays the initial table values.

- d Select the **Estimation** node, and click **New** to add a **New Estimation** node.

- e Select the **New Estimation** node. In the **Parameters** tab, select the **Estimate** check box to specify the lookup table values, table, for estimation.



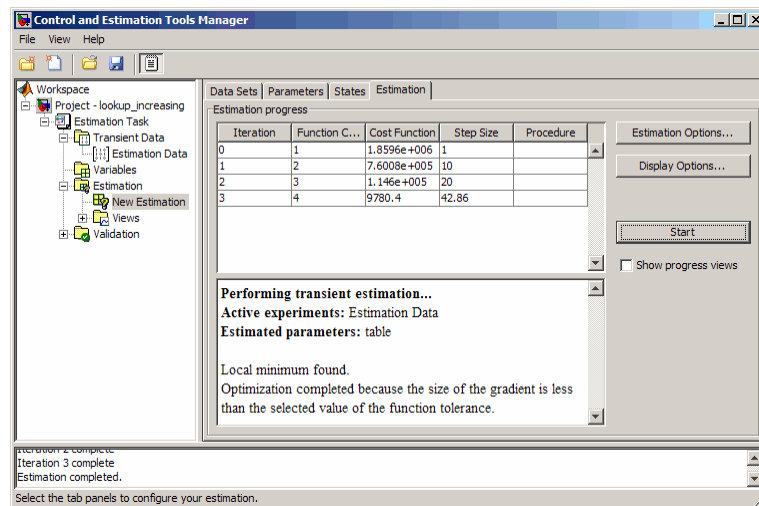
- 4 In the **Data Sets** tab of the **New Estimation** node, select the **Selected** check-box to specify the estimation data set.



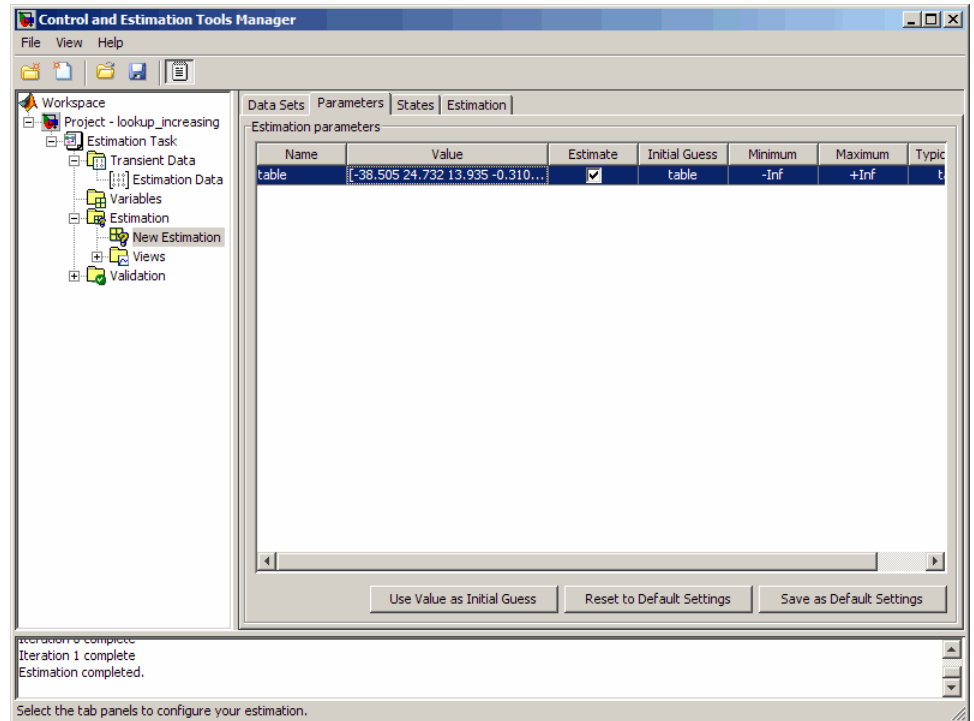
- 5 Estimate the parameters using the default settings.

- In the **Estimation** tab of the **New Estimation** node, click **Start** to start the estimation.

The Control and Tools Manager GUI updates at each iteration, and provides information about the estimation progress. After the estimation completes, the Control and Estimation Tools Manager GUI looks similar to the following figure.



- b Select the **Parameters** tab of the **New Estimation** node to view the estimated table values. The **Value** field displays the estimated table values.



## Validating the Estimation Results

After you estimate the table values, as described in “Estimating the Monotonically Increasing Table Values Using Default Settings” on page 6-9, you must use another data set to validate that you have not overfitted the model. You plot and examine the following plots to validate the estimation results:

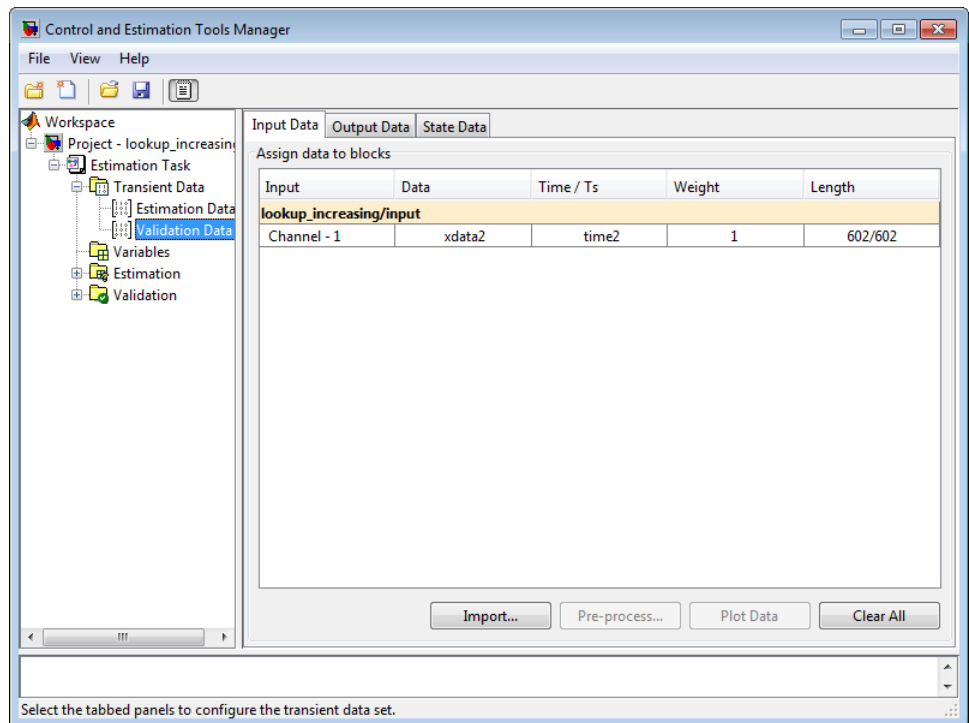
- Residuals plot
- Measured and simulated data plots

To validate the estimation results:

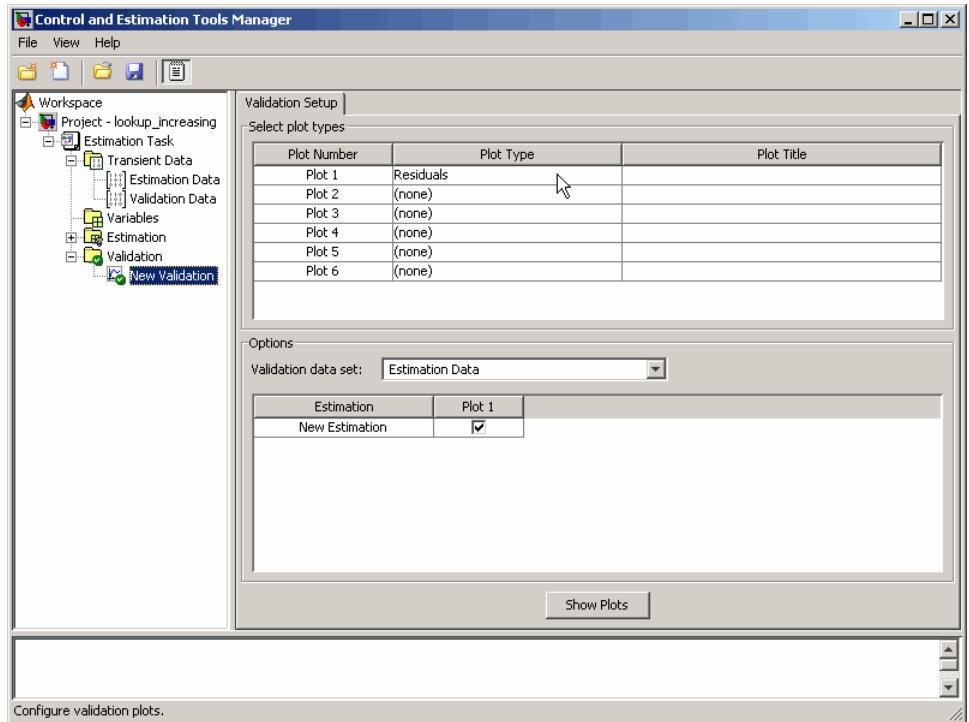
- 1 Import the validation I/O data, xdata2 and ydata2, and time vector, time2, in the Control and Estimation Tools Manager GUI.

You can load a project that already contains the estimated parameters, validation data set, and residuals plot. To do so, type the following commands at the MATLAB prompt:

```
lookup_increasing;
explorer.loadProject('lookup_increasing_val',...
    'Project - lookup_increasing', 'Validation Data')
```



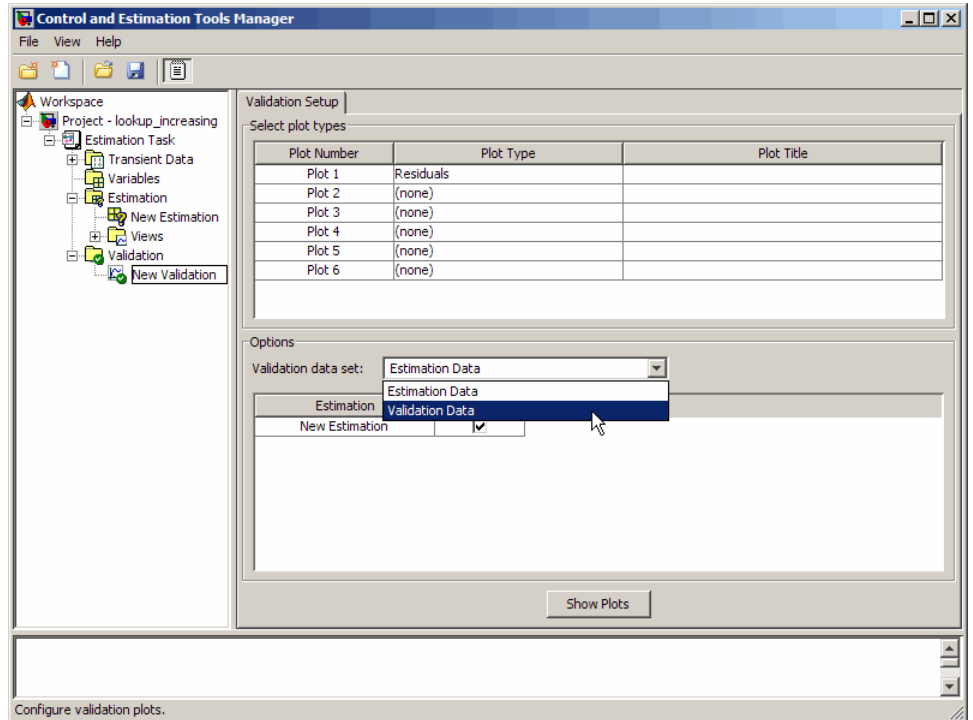
This project also contains the **Residuals** plot already configured in the **Select plot types** area of the GUI, as shown in the next figure. For more information on how to configure this plot, see “Compare Measured and Simulated Responses” on page 2-47.



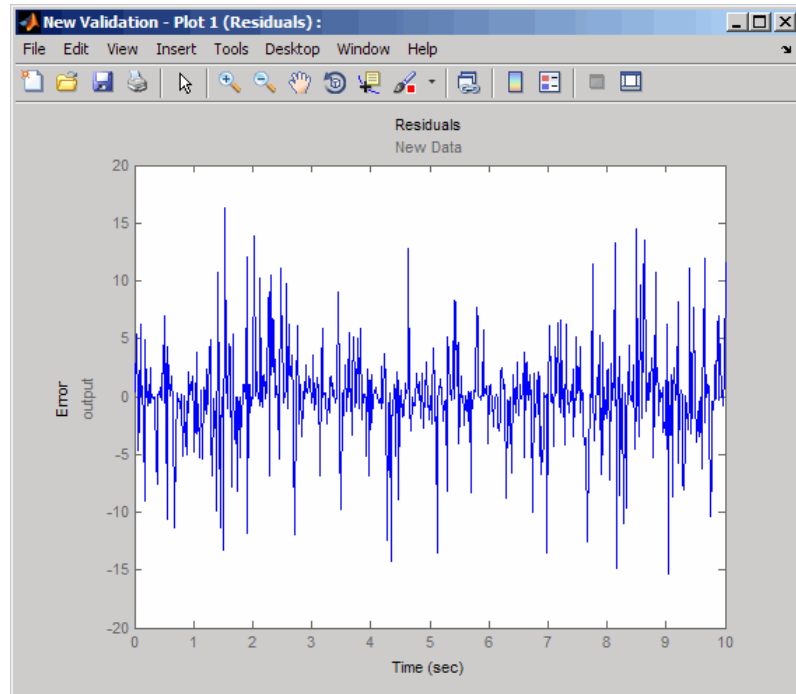
- 2 Plot and examine the residuals.
  - a Select the **New Validation** node under the **Validation** node.



- b** In the **Options** area, select **Validation Data** from the **Validation data set** drop-down list.



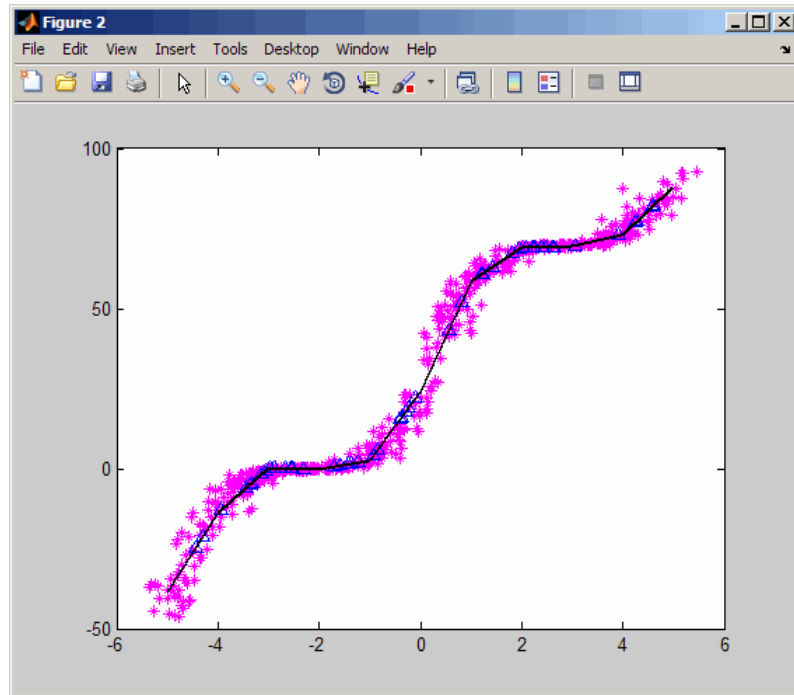
- c Click **Show Plots** to open the residuals plot.



The residuals, which show the difference between the simulated and measured data, lie the range  $[-15,15]$ — within 20% of the maximum output variation. This indicates a good match between the measured and the simulated table data values.

- 3 Plot and examine the validation data, simulated data and estimated table values.

```
sim('lookup_increasing')  
figure(2); plot(xdata2,ydata2, 'm*', xout, yout, 'b^')  
hold on; plot(-5:5, cumsum(table), 'k', 'LineWidth', 2)
```



The plot shows that the table values, shown as the black line, match both the measured data and the simulated table values. The table data values cover the entire range of input values, which indicates that all the lookup table values have been estimated.

## Estimate Lookup Table Values from Data

### In this section...

“Objectives” on page 6-22

“About the Data” on page 6-22

“Configuring a Project for Parameter Estimation” on page 6-22

“Estimating the Table Values Using Default Settings” on page 6-24

“Validating the Estimation Results” on page 6-30

### Objectives

This example shows how to estimate lookup table values from time-domain input-output (I/O) data.

### About the Data

In this example, you use the I/O data in `lookup_regular.mat` to estimate the values of a lookup table. The MAT-file includes the following variables:

- `xdata1` — Consists of 63 uniformly-sampled input data points in the range `[0,6.5]`.
- `ydata1` — Consists of output data corresponding to the input data samples.
- `time1` — Time vector.

You use the I/O data to estimate the lookup table values in the `lookup_regular` Simulink model. The lookup table in the model contains ten values, which are stored in the MATLAB variable `table`. The initial table values comprise a vector of 0s. To learn more about how to model a system using lookup tables, see “Guidelines for Choosing a Lookup Table” in the Simulink documentation.

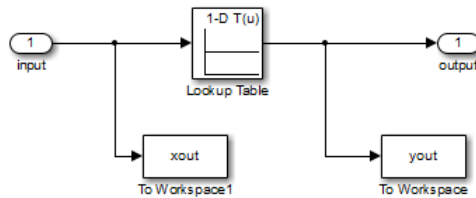
### Configuring a Project for Parameter Estimation

To estimate the lookup table values, you must first configure a Control and Estimation Tools Manager project.

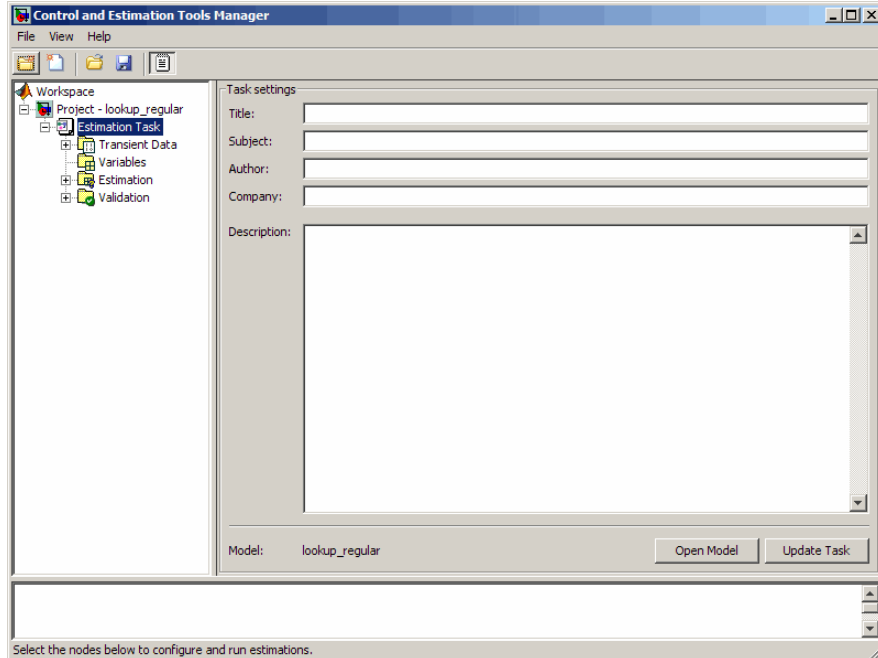
- 1 Open the lookup table model by typing the following command at the MATLAB prompt:

```
lookup_regular
```

This command opens the Simulink model, and loads the estimation data into the MATLAB workspace.



- 2 In the Simulink model, select **Analysis > Parameter Estimation** to open a new project named **lookup\_regular** in the Control and Estimation Tools Manager GUI.



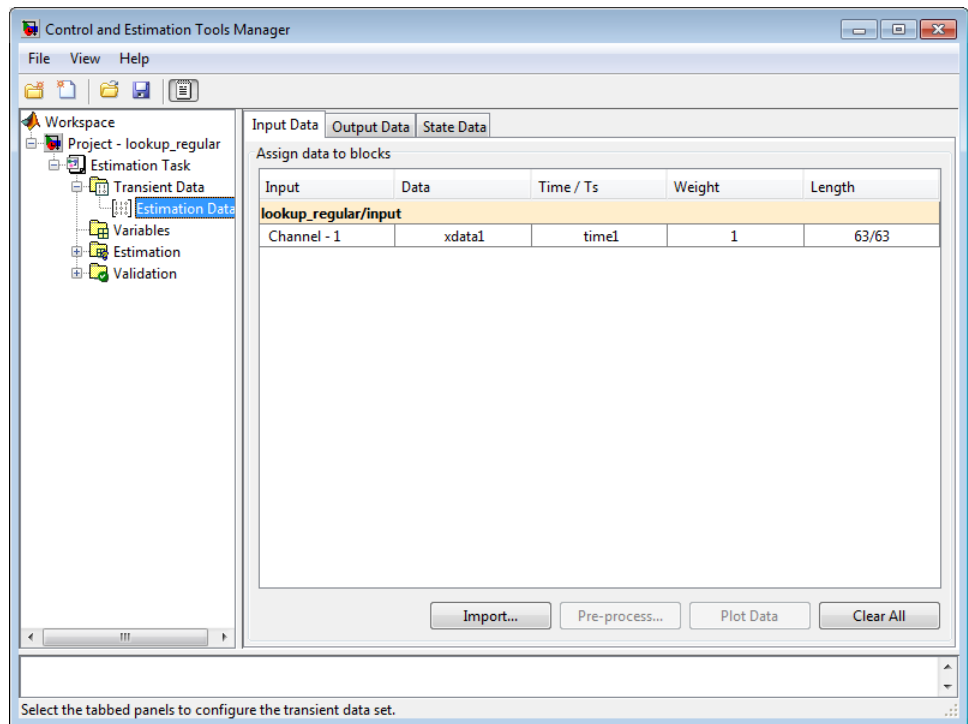
## Estimating the Table Values Using Default Settings

After you configure a project for parameter estimation, as described in “Configuring a Project for Parameter Estimation” on page 6-22, use the following steps to estimate the lookup table values.

- 1 Import the I/O data, `xdata1` and `ydata1`, and the time vector, `time1`, into the Control and Estimation Tools Manager GUI. For more information, see “Import Data (GUI)” on page 1-4.

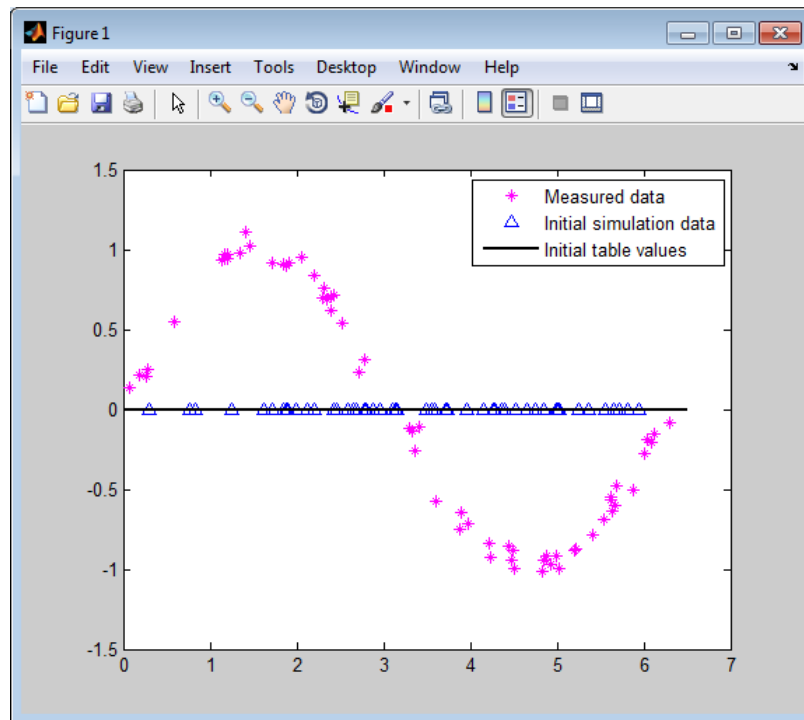
You can also load a preconfigured project that already contains the imported data. To do so, type the following command at the MATLAB prompt:

```
lookup_regular;
explorer.loadProject('lookup_regular_import',...
    'Project - lookup_regular', 'Estimation Data');
```



- 2** Run an initial simulation to view the I/O data, simulated output, and the initial table values. To do so, type the following commands at the MATLAB prompt:

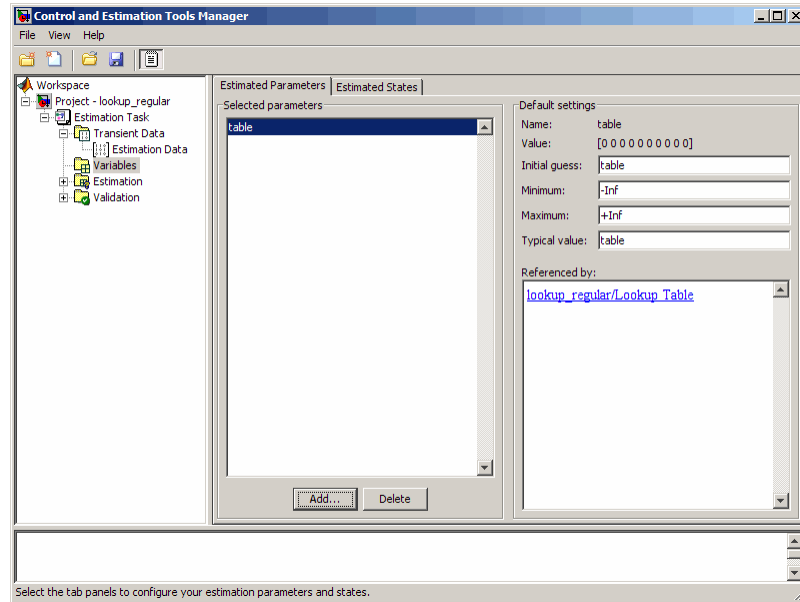
```
sim('lookup_regular')
figure(1); plot(xdata1,ydata1, 'm*', xout, yout,'b^')
hold on; plot(linspace(0,6.5,10), table, 'k', 'LineWidth', 2);
legend('Measured data','Initial simulation data','Initial table values');
```



The x- and y-axes of the figure represent the input and output data, respectively.

- 3** Select the table values to estimate.
- a** In the Control and Estimation Tools Manager GUI, select the **Variables** node under the **Estimation Task** node.
  - b** Click **Add** to open the Select Parameters dialog box, which shows the Simulink model parameters.

- c Select table, and click **OK** to add the table values to the **Estimated Parameters** tab.

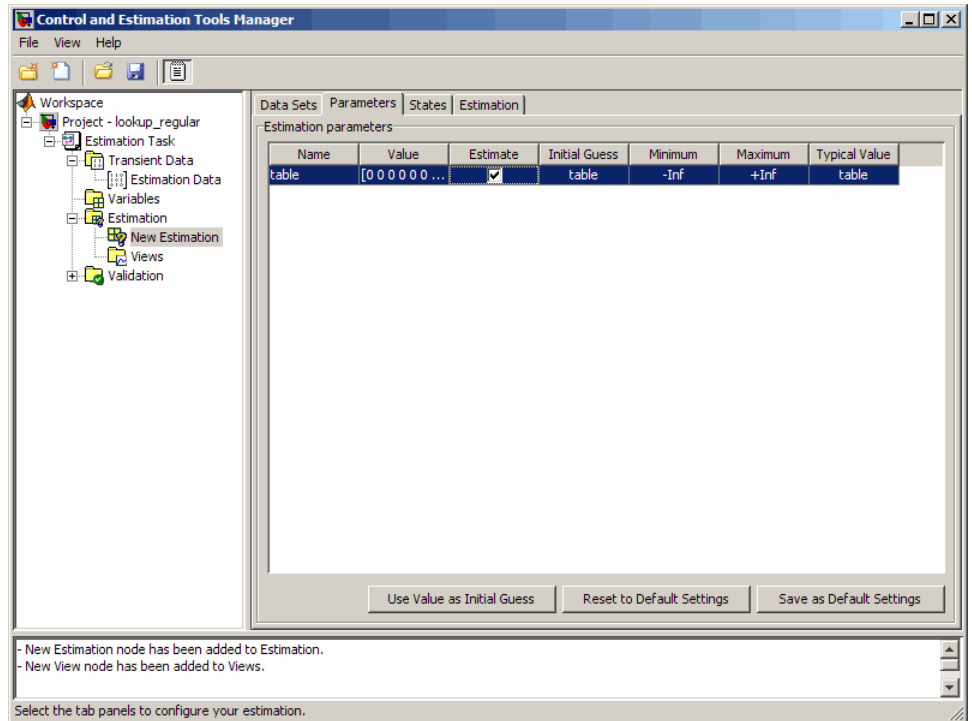


The **Default settings** area of the GUI displays the default settings for the table values. The **Value** field displays the initial table values, which comprise a vector of ten 0s.

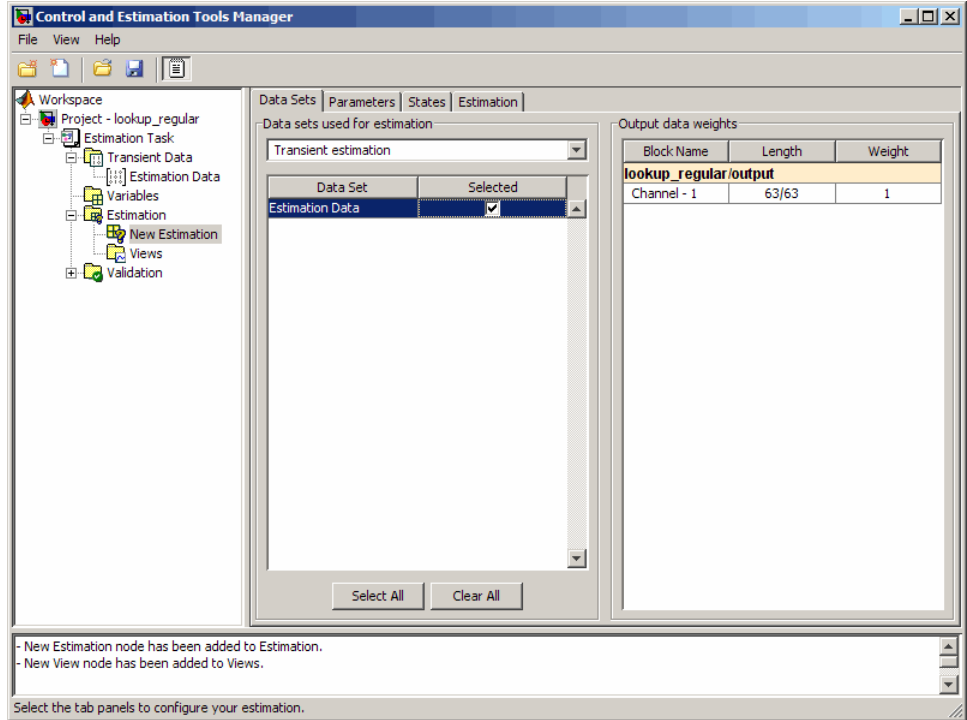
- d Select the **Estimation** node, and click **New** to add a **New Estimation** node.



- e Select the **New Estimation** node. In the **Parameters** tab, select the **Estimate** check box to specify the lookup table values, table, for estimation.



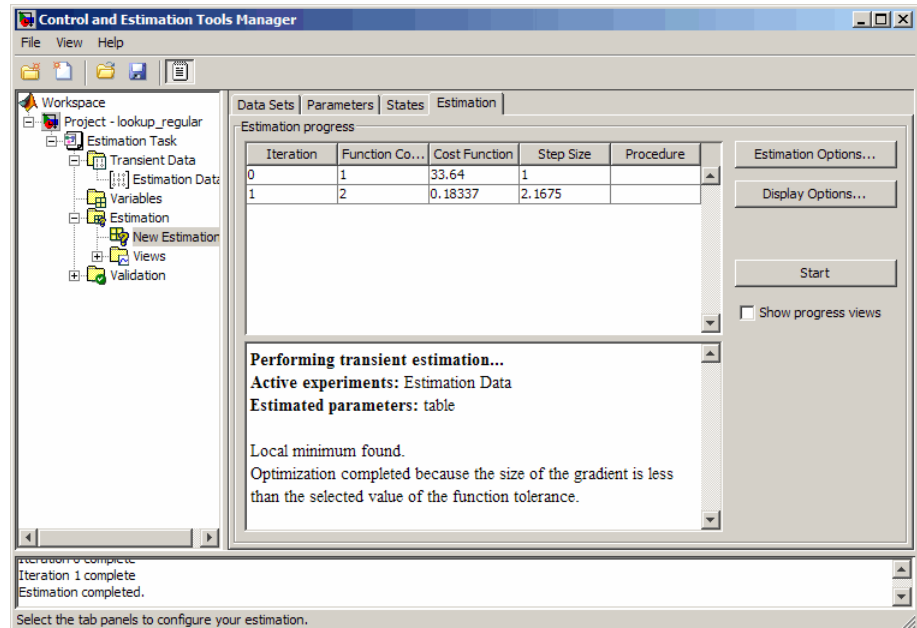
- 4 In the **Data Sets** tab of the **New Estimation** node, select the **Selected** check box to specify the estimation data set.



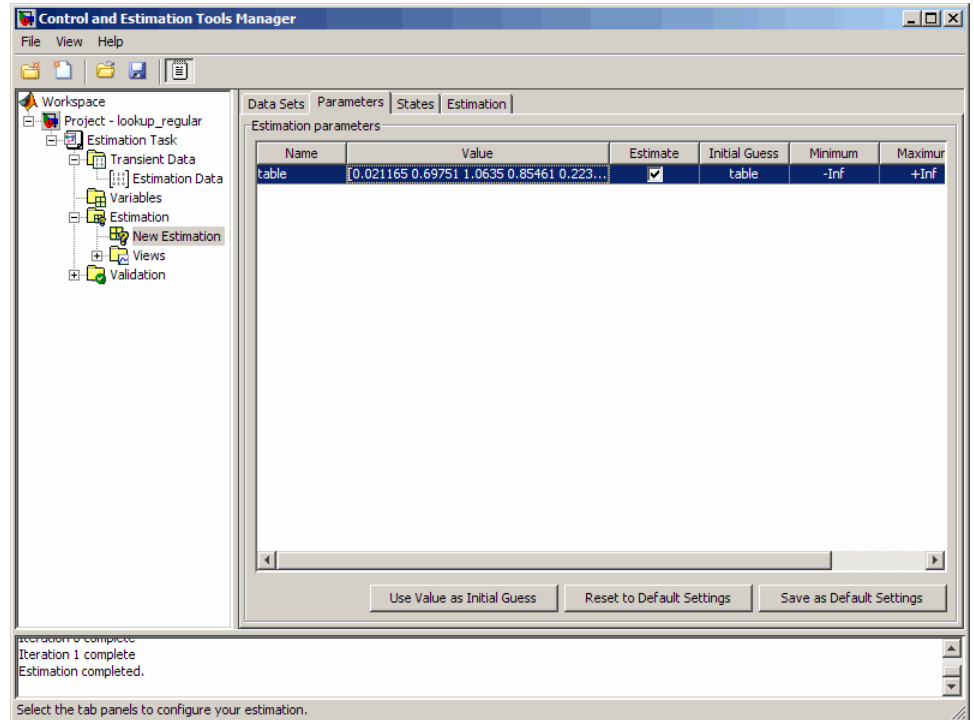
- 5 Estimate the table values using the default settings.

- a In the **Estimation** tab of the **New Estimation** node, click **Start** to start the estimation.

The Control and Tools Manager GUI updates at each iteration, and provides information about the estimation progress. After the estimation completes, the Control and Estimation Tools Manager GUI looks similar to the following figure.



- b Select the **Parameters** tab in the **New Estimation** node to view the estimated table values, which appear in the **Value** field.



## Validating the Estimation Results

After you estimate the table values, as described in “Estimating the Table Values Using Default Settings” on page 6-24, you must use another data set to validate that you have not overfitted the model. You plot and examine the following plots to validate the estimation results:

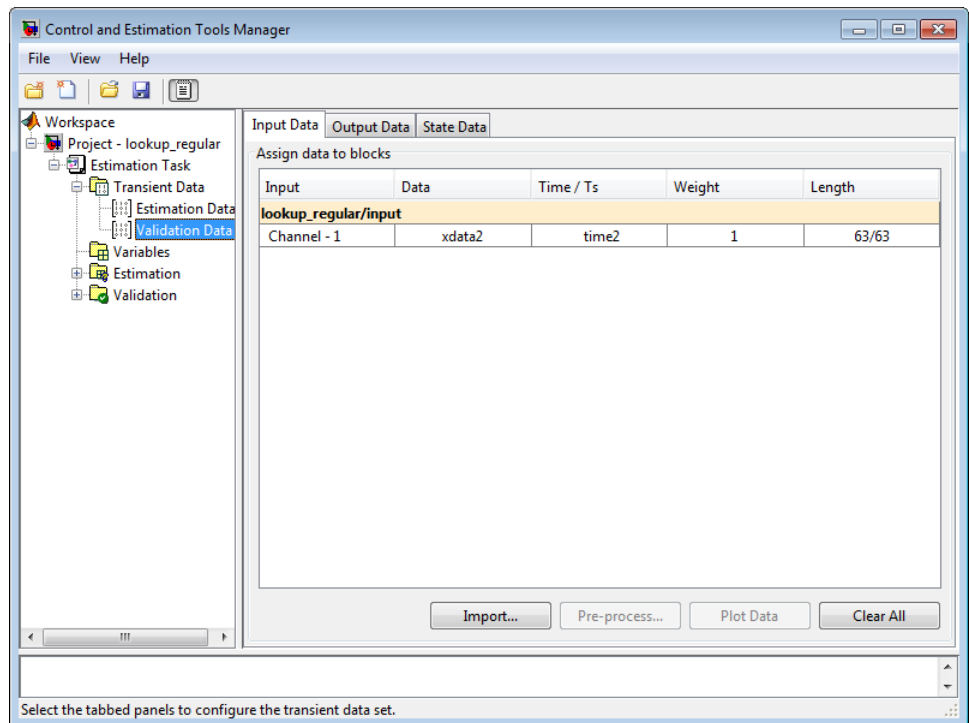
- Residuals plot
- Measured and simulated data plots

To validate the estimation results:

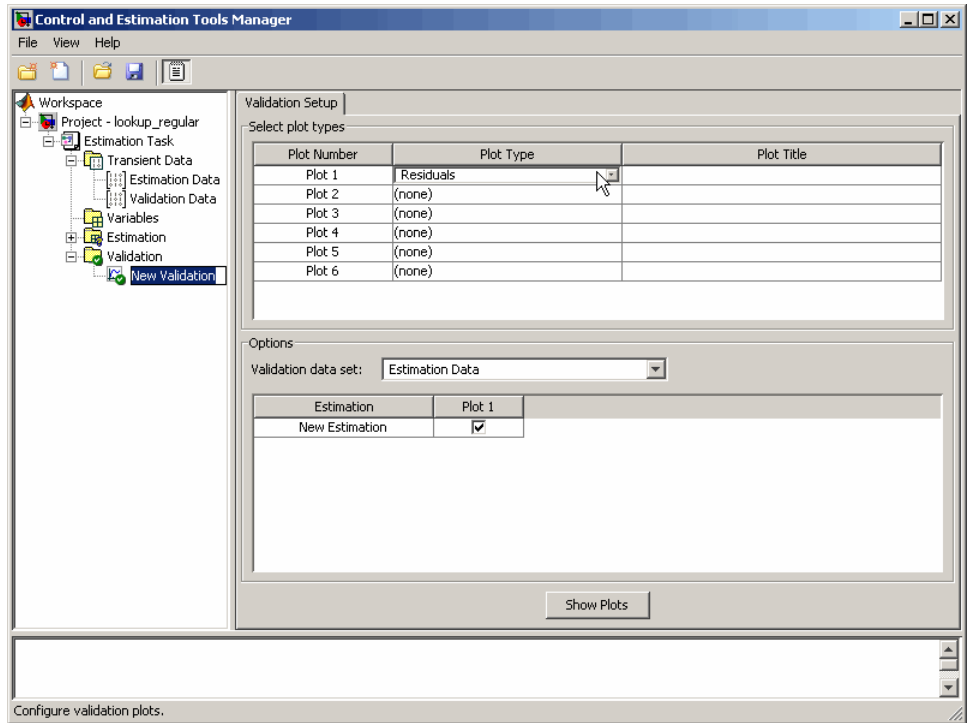
- 1 Import the validation I/O data, `xdata2` and `ydata2`, and time vector, `time2`, in the Control and Estimation Tools Manager GUI.

You can also load a project that already contains the estimated parameters, and the validation data set. To do so, type the following commands at the MATLAB prompt:

```
lookup_regular;
explorer.loadProject('lookup_regular_val',...
    'Project - lookup_regular', 'Validation Data');
```

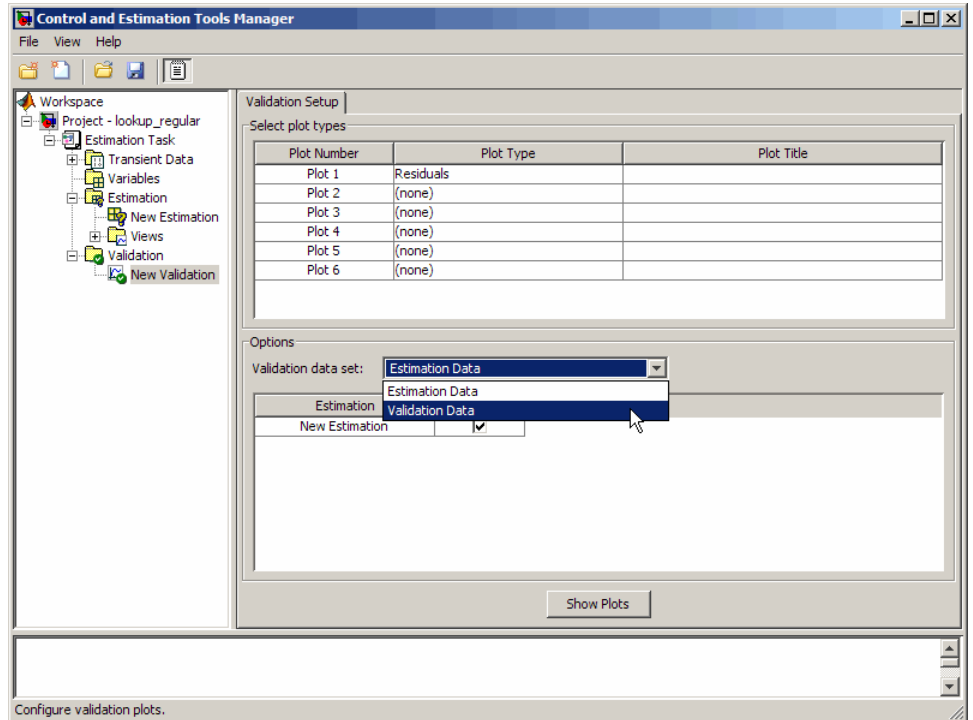


This project also contains the **Residuals** plot already configured in the **Select plot types** area of the GUI, as shown in the next figure. For more information on how to configure this plot, see “Compare Measured and Simulated Responses” on page 2-47.

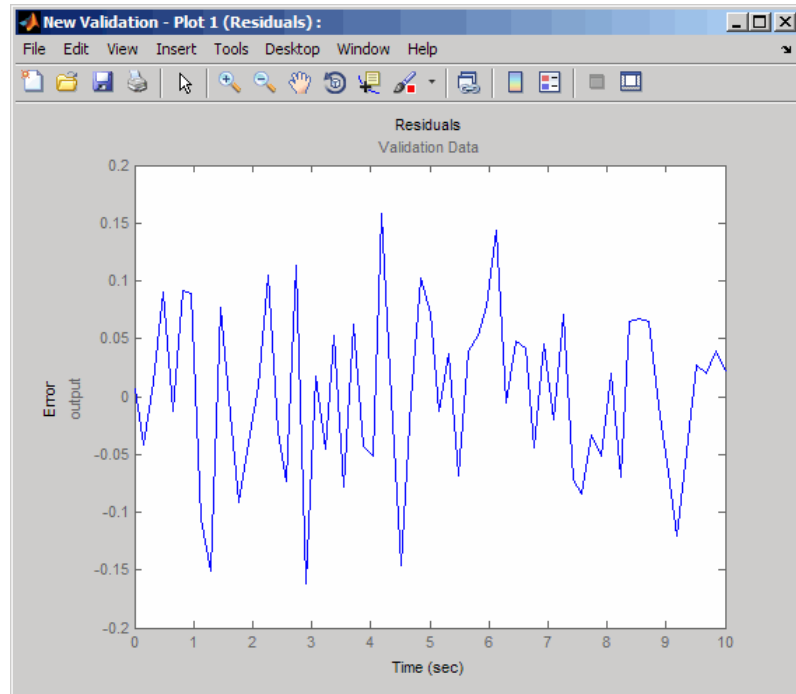


- 2 Plot and examine the residuals:
  - a Select the **New Validation** node under the **Validation** node.

- b** In the **Options** area, select **Validation Data** from the **Validation data set** drop-down list.



- c Click **Show Plots** to open the residuals plot.

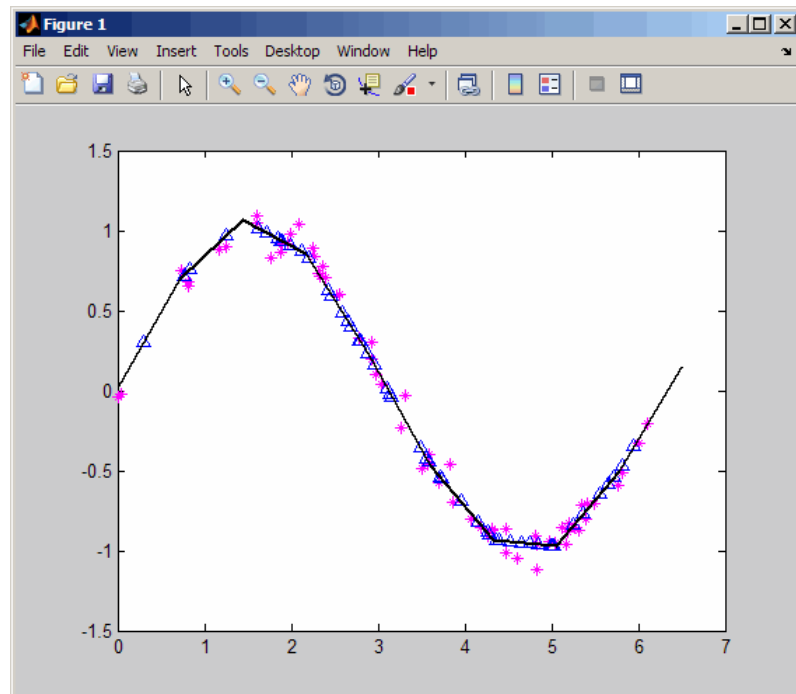


The residuals, which show the difference between the simulated and measured data, lie in the range  $[-0.15, 0.15]$ — within 15% of the maximum output variation. This indicates a good match between the measured and the simulated table data values.



- d Plot and examine the estimated table values against the validation data set and the simulated table values by typing the following commands at the MATLAB prompt.

```
sim('lookup_regular')  
figure(2); plot(xdata2,ydata2, 'm*', xout, yout,'b^')  
hold on; plot(linspace(0,6.5,10), table, 'k', 'LineWidth', 2)
```



The plot shows that the table values, displayed as the black line, match both the validation data and the simulated table values. The table data values cover the entire range of input values, which indicates that all the lookup table values have been estimated.

## Building Models Using Adaptive Lookup Table Blocks

Simulink Design Optimization software provides blocks for modeling systems as adaptive lookup tables. You can use the adaptive lookup table blocks to create lookup tables from measured or simulated data. You build a model using the adaptive lookup table blocks, and then simulate the model to adapt the lookup table values to the time-varying I/O data. During simulation, the software uses the input data to locate the table values, and then uses the output data to recalculate the table values. The updated table values are stored in the adaptive lookup table block. For more information, see “What are Adaptive Lookup Tables?” on page 6-2.

The Adaptive Lookup Table library has the following blocks:

- Adaptive Lookup Table (1D Stair-Fit) — One-dimensional adaptive lookup table
- Adaptive Lookup Table (2D Stair-Fit) — Two-dimensional adaptive lookup table
- Adaptive Lookup Table (nD Stair-Fit) — Multidimensional adaptive lookup table

---

**Note** Use the Adaptive Lookup Table (nD Stair-Fit) block to create lookup tables of three or more dimensions.

---

To access the Adaptive Lookup Tables library:

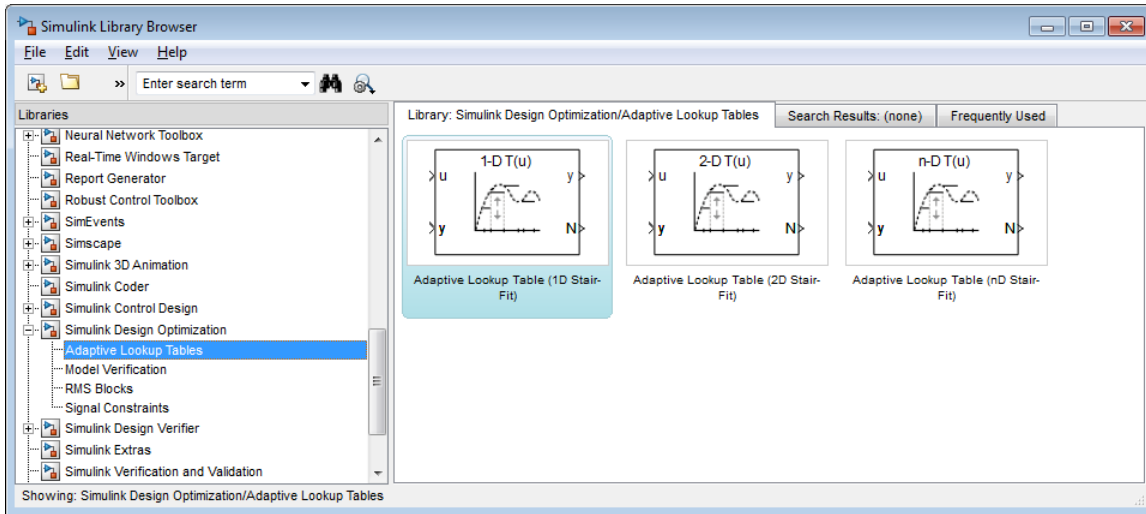
- 1 Open the Simulink Library Browser.

At the MATLAB prompt, enter `simulink`.

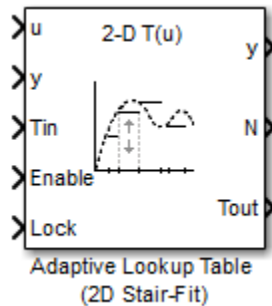
- 2 Open the Simulink Design Optimization library.

In the **Libraries** pane, expand the **Simulink Design Optimization** node.

- 3 In the Simulink Design Optimization library tree, click **Adaptive Lookup Tables**.



By default, the Adaptive Lookup Table blocks have two inputs and outputs. You can display additional inputs and outputs in a block by selecting the corresponding options in the Function Block Parameters dialog box. To learn more about the options, see the block reference pages.



### Adaptive Lookup Table Block Showing Inputs and Outputs

The 2-D Adaptive Lookup Table block has the following inputs and outputs:

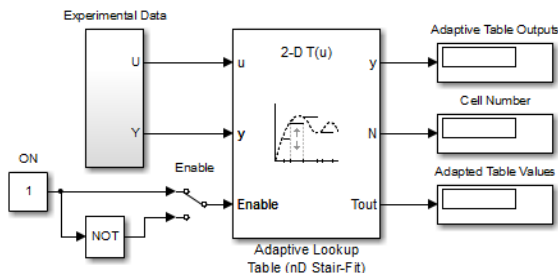
- $u$  and  $y$  — Input and output data of the system being modeled, respectively.

For example, to model an engine's efficiency as a function of engine rpm and manifold pressure, specify  $u$  as the rpm,  $y$  as the pressure, and  $y$  as the efficiency signals.

- $T_{in}$  — The initial table data.
- $Enable$  — Signal to enable, disable, or reset the adaptation process.
- $Lock$  — Signal to update only specified cells in the table.
- $y$  — Value of the cell currently being adapted.
- $N$  — Number of the cell currently being adapted.
- $T_{out}$  — Values of the adapted table data.

For more information on how to use adaptive lookup tables, see “Model Engine Using n-D Adaptive Lookup Table” on page 6-42.

A typical Simulink diagram using an adaptive lookup table block is shown in the next figure.



### Simulink® Diagram Using an Adaptive Lookup Table

In this figure, the Experiment Data block imports a set of experimental data into Simulink through MATLAB workspace variables. The initial table is specified in the block mask parameters. When the simulation runs, the initial table begins to adapt to new data inputs and the resulting table is copied to the block's output.

### See Also

Adaptive Lookup Table (1D Stair-Fit) | Adaptive Lookup Table (2D Stair-Fit)  
| Adaptive Lookup Table (nD Stair-Fit)

## **Related Examples**

- “Model Engine Using n-D Adaptive Lookup Table” on page 6-42

## **Concepts**

- “What are Adaptive Lookup Tables?” on page 6-2
- “Selecting an Adaptation Method” on page 6-40

## Selecting an Adaptation Method

You specify the algorithm using the **Adaptation Method** drop-down list in the Function Block Parameters dialog box of an adaptive lookup table block. This section discusses the details of these algorithms.

### Sample Mean

Sample mean provides the average value of  $n$  output data samples and is defined as:

$$\hat{y}(n) = \frac{1}{n} \sum_{i=1}^n y(i)$$

where  $y(i)$  is the  $i^{\text{th}}$  measurement collected within a particular *cell*. For each input data  $u$ , the sample mean at the corresponding cell is updated using the output data measurement,  $y$ . Instead of accumulating  $n$  samples of data for each cell, a recursive relation is used to calculate the sample mean. The recursive expression is obtained by the following equation:

$$\hat{y}(n) = \frac{1}{n} \left[ \sum_{i=1}^{n-1} y(i) + y(n) \right] = \frac{n-1}{n} \left[ \frac{1}{n-1} \sum_{i=1}^{n-1} y(i) \right] + \frac{1}{n} y(n) = \frac{n-1}{n} \hat{y}(n-1) + \frac{1}{n} y(n)$$

where  $y(n)$  is the  $n^{\text{th}}$  data sample.

Defining *a priori estimation error* as  $e(n) = y(n) - \hat{y}(n-1)$ , the recursive relation can be written as:

$$\hat{y}(n) = \hat{y}(n-1) + \frac{1}{n} e(n)$$

where  $n \geq 1$  and the initial estimate  $\hat{y}(0)$  is arbitrary.

In this expression, only the number of samples,  $n$ , for each cell—rather than  $n$  data samples—is stored in memory.

## Sample Mean with Forgetting

The adaptation method “Sample Mean” on page 6-40 has an *infinite memory*. The past data samples have the same weight as the final sample in calculating the sample mean. Sample mean (with forgetting) uses an algorithm with a *forgetting factor* or **Adaptation gain** that puts more weight on the more recent samples. This algorithm provides robustness against initial response transients of the plant and an adjustable speed of adaptation. Sample mean (with forgetting) is defined as:

$$\begin{aligned}\hat{y}(n) &= \frac{1}{\sum_{i=1}^n \lambda^{n-i}} \sum_{i=1}^n \lambda^{n-i} y(i) \\ &= \frac{1}{\sum_{i=1}^n \lambda^{n-i}} \left[ \sum_{i=1}^{n-1} \lambda^{n-i} y(i) + y(n) \right] = \frac{s(n-1)}{s(n)} \hat{y}(n-1) + \frac{1}{s(n)} y(n)\end{aligned}$$

where  $\lambda \in [0,1]$  is the **Adaptation gain** and  $s(k) = \sum_{i=1}^k \lambda^{n-i}$ .

Defining *a priori estimation error* as  $e(n) = y(n) - \hat{y}(n-1)$ , where  $n \geq 1$  and the initial estimate  $\hat{y}(0)$  is arbitrary, the recursive relation can be written as:

$$\hat{y}(n) = \hat{y}(n-1) + \frac{1}{s(n)} e(n) = \hat{y}(n-1) + \frac{1-\lambda}{1-\lambda^n} e(n)$$

A small value of  $\lambda$  results in faster adaptation. A value of 0 indicates short memory (last data becomes the table value), and a value of 1 indicates long memory (average all data received in a cell).

## Model Engine Using n-D Adaptive Lookup Table

### In this section...

“Objectives” on page 6-42

“About the Data” on page 6-42

“Building a Model Using Adaptive Lookup Table Blocks” on page 6-43

“Adapting the Lookup Table Values Using Time-Varying I/O Data” on page 6-52

### Objectives

In this example, you learn how to capture the time-varying behavior of an engine using an n-D adaptive lookup table. You accomplish the following tasks using the Simulink software:

- Configure an adaptive lookup table block to model your system.
- Simulate the model to update the lookup table values dynamically.
- Export the adapted lookup table values to the MATLAB workspace.
- Lock a specific cell in the table during adaptation.
- Disable the adaptation process and use the adaptive lookup table as a static lookup table.

### About the Data

In this example, you use the data in `vedata.mat` which contains the following variables measured from an engine:

- X — 10 input breakpoints for intake manifold pressure in the range [10,100]
- Y — 36 input breakpoints for engine speed in the range [0,7000]
- Z — 10x36 matrix of table data for engine volumetric efficiency

To learn more about breakpoints and table data, see “Anatomy of a Lookup Table” in the Simulink documentation.



The output volumetric efficiency of the engine is time varying, and a function of two inputs—intake manifold pressure and engine speed. The data in the MAT-file is used to generate the time-varying input and output (I/O) data for the engine.

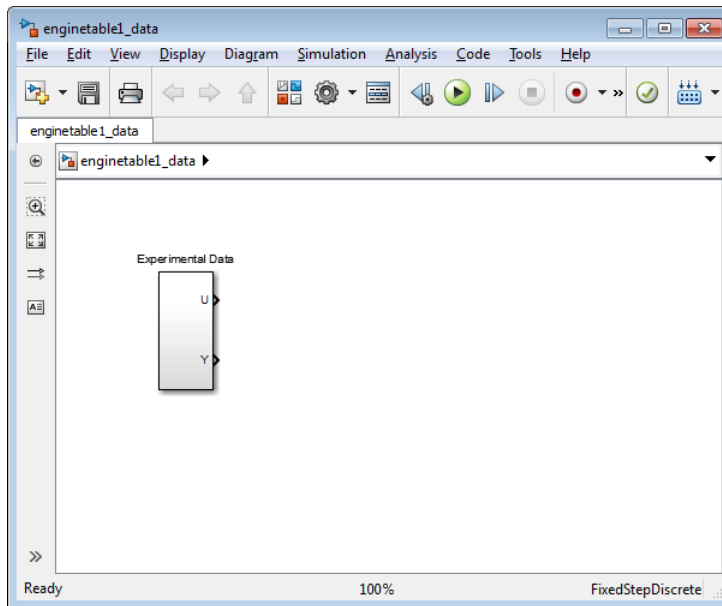
## Building a Model Using Adaptive Lookup Table Blocks

In this portion of the tutorial, you learn how to build a model of an engine using an Adaptive Lookup Table block.

- 1 Open a preconfigured Simulink model by typing the model name at the MATLAB prompt:

```
enginetable1_data
```

The Experimental Data subsystem in the Simulink model generates time-varying I/O data during simulation.



This command also loads the variables  $X$ ,  $Y$  and  $Z$  into the MATLAB workspace. To learn more about this data, see “About the Data” on page 6-42.

2 Add an Adaptive Lookup Table block to the Simulink model.

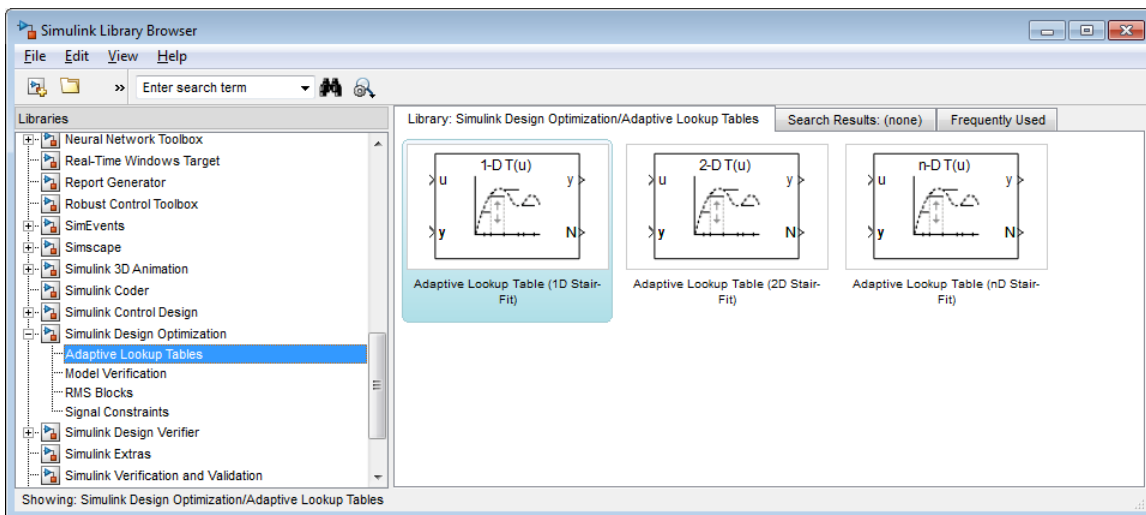
- a Open the Simulink Library Browser.

At the MATLAB prompt, enter `simulink`.

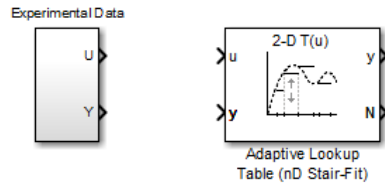
- b Open the Simulink Design Optimization library.

In the **Libraries** pane, expand the **Simulink Design Optimization** node.

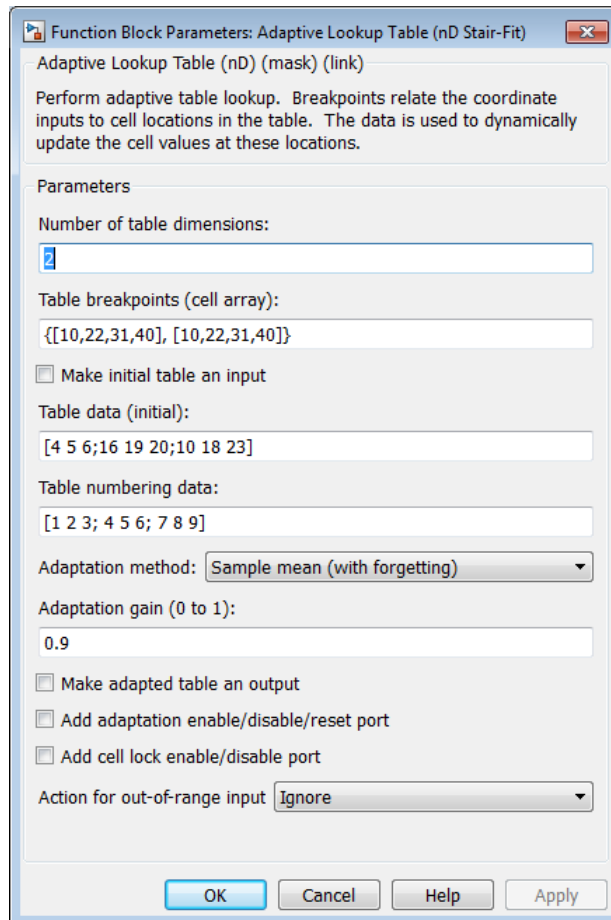
- c In the Simulink Design Optimization library tree, click **Adaptive Lookup Tables**.



- d Drag and drop the Adaptive Lookup Table (nD Stair-Fit) block from the Adaptive Lookup Tables library to the Simulink model window.



- 3 Double-click the Adaptive Lookup Table (nD Stair-Fit) block to open the Function Block Parameters: Adaptive Lookup Table (nD Stair-Fit) dialog box.



- 4 In the Function Block Parameters dialog box:
  - a Specify the following block parameters:
    - **Table breakpoints (cell array)** — Enter `{[X; 110], [Y; 7200]}` to specify the range of input breakpoints.
    - **Table data (initial)** — Enter `rand(10,36)` to specify random numbers as the initial table values for the volumetric efficiency.
    - **Table numbering data** — Enter `reshape(1:360,10,36)` to specify a numbering scheme for the table cells.
  - b Verify that **Sample mean (with forgetting)** is selected in the **Adaptation method** drop-down list.
  - c Enter `0.98` in the **Adaptation gain (0 to 1)** field to specify the *forgetting factor* for the **Sample mean (with forgetting)** adaptation algorithm.

An adaptation gain close to 1 indicates high robustness of the lookup table values to input noise. To learn more about the adaptation gain, see “Sample Mean with Forgetting” on page 6-41 in “Selecting an Adaptation Method” on page 6-40.

- d Select the **Make adapted table an output** check box.

This action adds a new port named **Tout** to the Adaptive Lookup Table block. You use this port to plot the table values as they are being adapted.

- e Select the **Add adaptation enable/disable/reset port** check box.

This action adds a new port named **Enable** to the Adaptive Lookup Table block. You use this port to enable or disable the adaptation process.

- f Select the **Add cell lock enable/disable port** check box.

This action adds a new port named **Lock** to the Adaptive Lookup Table block. You use this port to lock a cell during the adaptation process.

- g Verify that **Ignore** is selected in the **Action for out-of-range** drop-down list.

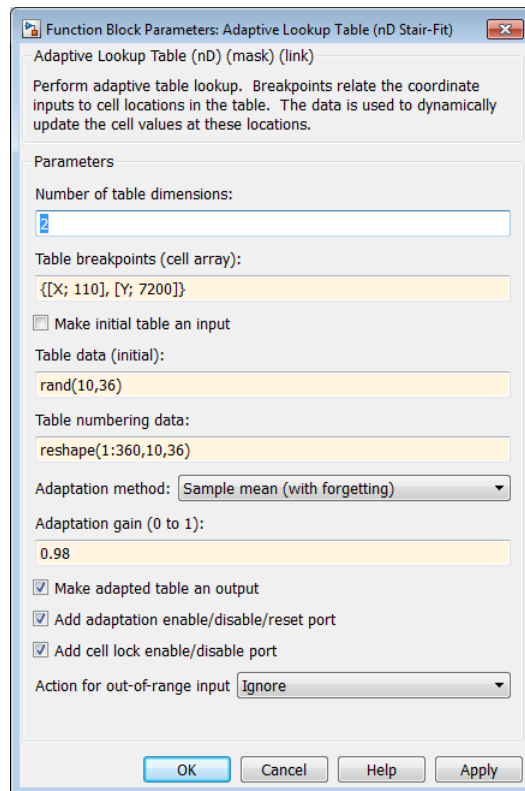
This selection specifies that the software ignores any time-varying inputs outside the range of input breakpoints during adaptation.

---

**Tip** To learn more, see Adaptive Lookup Table (nD Stair-Fit) block reference page.

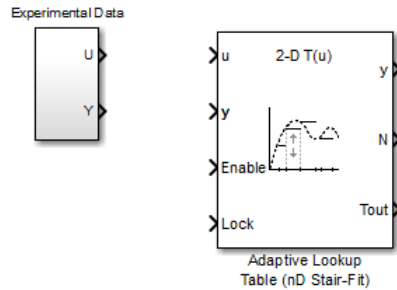
---

After you configure the parameters, the block parameters dialog box looks like the following figure.

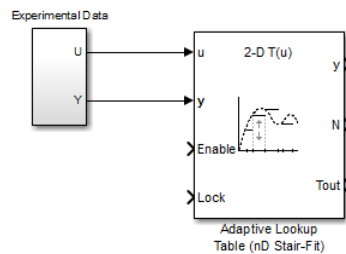


**h** Click **OK** to close the Function Block Parameters dialog box.

The Simulink model now looks similar to the following figure.



- 5 Assign the input and output data to the engine model by connecting the U and Y ports of the Experimental Data block to the u and y ports of the Adaptive Lookup Table block, respectively.

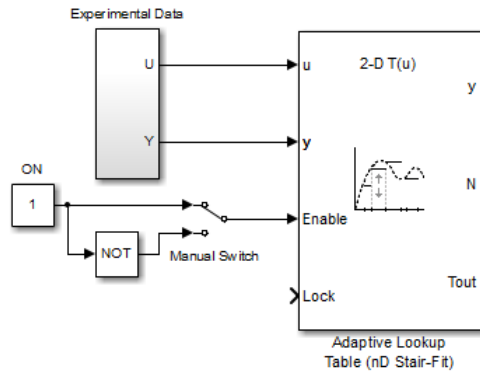



---

**Tip** To learn how to connect blocks in the Simulink model window, see “Connect Blocks” in the Simulink documentation.

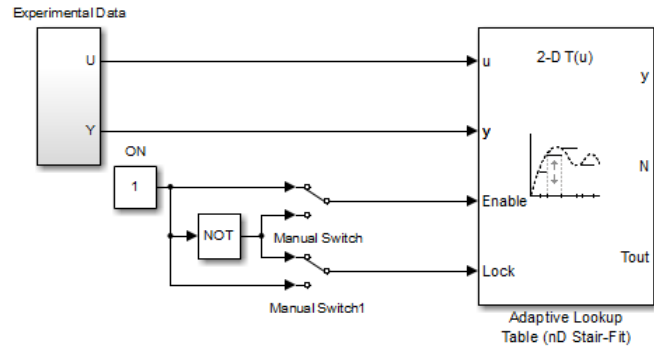
---

- 6 Design a logic using Simulink blocks to enable or disable the adaptation process. Connect the logic to the Adaptive Lookup Table block, as shown in the following figure.

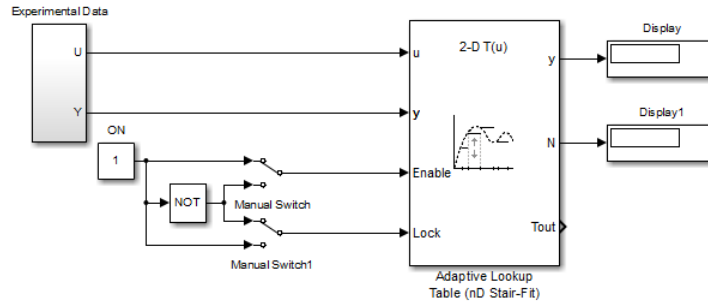


This logic outputs an initial value of 1 which enables the adaptation process.

- 7** Design a logic to lock a cell during adaptation. Connect the logic to the Adaptive Lookup Table block, as shown in the following figure.



- 8** In the Simulink Library Browser, select the **Simulink > Sinks** library, and drag Display blocks to the model window. Connect the blocks, as shown in the following figure.

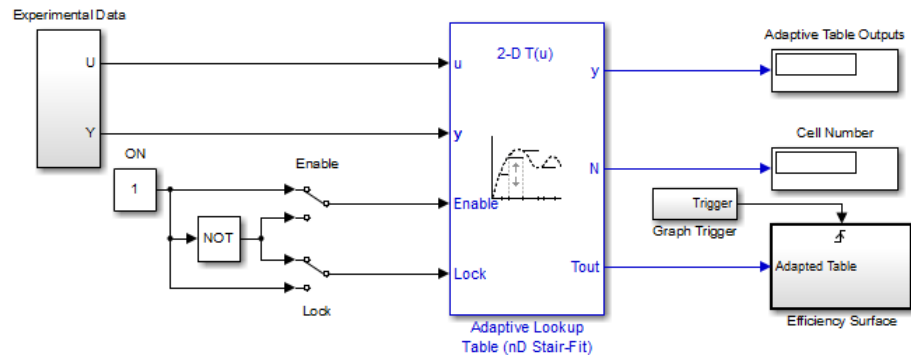


During simulation, the Display blocks show the following:

- Display block — Shows the value of the current cell being adapted.
- Display1 block — Shows the number of the current cell being adapted.

9 Write a MATLAB function to plot the lookup table values as they adapt during simulation.

Alternatively, type `enginetable` at the MATLAB prompt to open a preconfigured Simulink model. The Efficiency Surface subsystem contains a function to plot the lookup table values, as shown in the next figure.



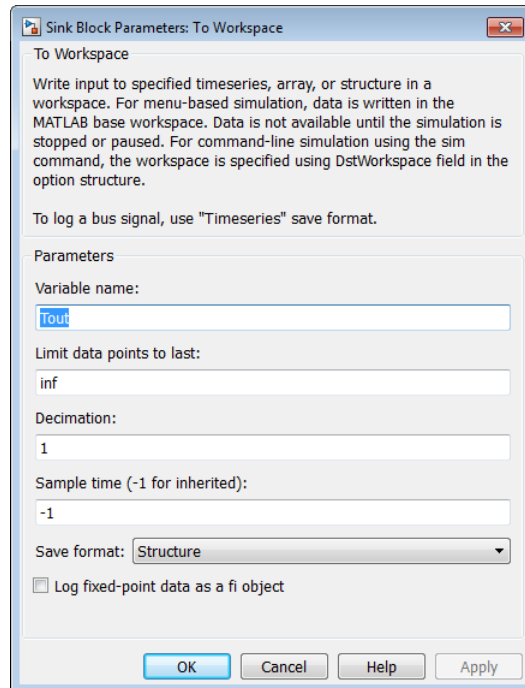
10 Connect a To Workspace block to export the adapted table values:

- In the Simulink Library Browser, select the **Simulink > Sinks** library, and drag the To Workspace block to the model window.

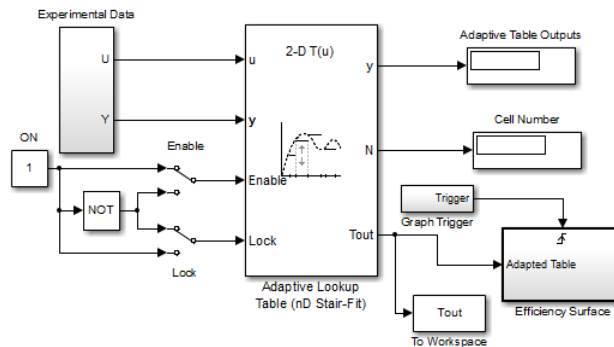


To learn more about this block, see the To Workspace block reference page in the Simulink documentation.

- b** Double-click the To Workspace block to open the Sink Block Parameters dialog box, and type `Tout` in the **Variable name** field.



- c** Click **OK**.
- d** Connect the To Workspace block to the adaptive lookup table output signal `Tout`, as shown in the next figure.



You have now built the model for updating and viewing the adaptive lookup table values. You must now simulate the model to start the adaptation, as described in “Adapting the Lookup Table Values Using Time-Varying I/O Data” on page 6-52.

## Adapting the Lookup Table Values Using Time-Varying I/O Data

In this portion of the tutorial, you learn how to update the lookup table values to adapt to the time-varying input and output values.

You must have already built the Simulink model, as described “Building a Model Using Adaptive Lookup Table Blocks” on page 6-43.

To perform the adaptation:

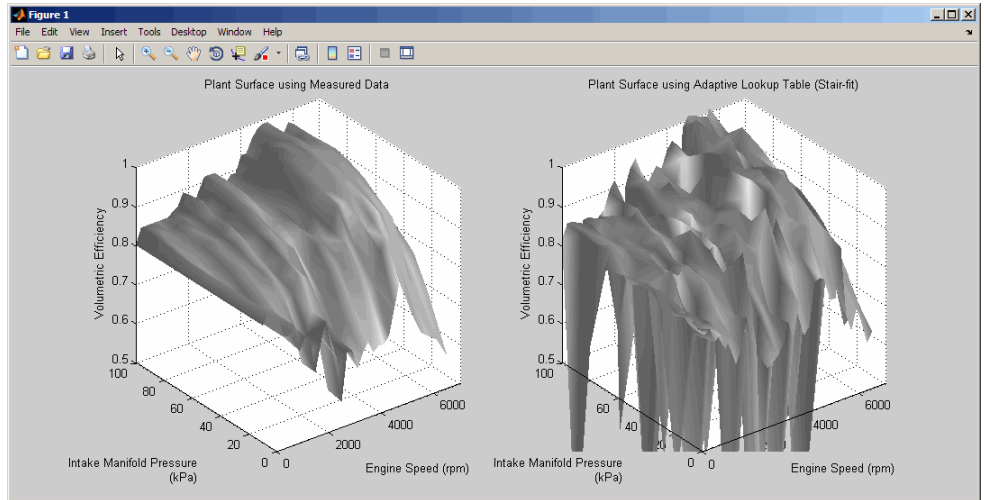
- 1 In the Simulink Editor, specify the simulation time as `inf`.

The simulation time of infinity specifies that the adaptation process continues as long as the input and output values of the engine change.

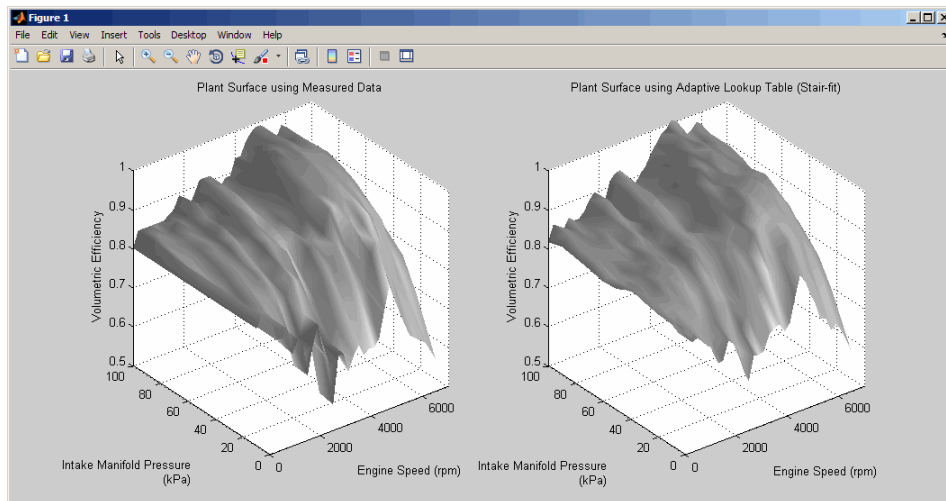
- 2 In the Simulink Editor, select **Simulation > Run** to start the adaptation process.

A figure window opens that shows the volumetric efficiency of the engine as a function of the intake manifold pressure and engine speed:

- The left plot shows the measured volumetric efficiency as a function of intake manifold pressure and engine speed.
- The right plot shows the volumetric efficiency as it adapts with the time-varying intake manifold pressure and engine speed.



During simulation, the lookup table values displayed on the right plot adapt to the variations in the I/O data. The left and the right plots resemble each other after a few seconds, as shown in the next figure.



---

**Tip** During simulation, the **Cell Number** and **Adaptive Table Outputs** blocks in the Simulink model display the cell number, and the adapted lookup table value in the cell, respectively.

---

**3** Pause the simulation by selecting **Simulation > Pause**.

This action also exports the adapted table values  $T_{out}$  to the MATLAB workspace.

---

**Note** After you pause the simulation, the adapted table values are stored in the Adaptive Lookup Table block.

---

**4** Examine that the left and the right plots match. This resemblance indicates that the table values have adapted to the time-varying I/O data.

**5** Lock a table cell so that only one cell adapts. You may find this feature useful if a portion of the data is highly erratic or otherwise difficult for the algorithm to handle.

**a** Select **Simulation > Run** to restart the simulation.

- b** Double-click the **Lock** block. This action toggles the switch and feeds the output of the **ON** block to the **Lock** input port of the **Adaptive Lookup Table (nD Stair-Fit)** block.

You can view the number of the locked cell in the **Cell Number** block in the Simulink model.

- 6** After the table values adapt to the time-varying I/O data, you can continue to use the **Adaptive Lookup Table** block as a static lookup table:
  - a** In the Simulink model window, double-click the **Enable** block. This action toggles the switch, and disables the adaptation.
  - b** Select **Simulation > Run** to restart the simulation, if it is not already running.

During simulation, the **Adaptive Lookup Table** block works like a static lookup table, and continues to estimate the output values as the input values change. You can see the current lookup table value in the **Adaptive Table Outputs** block in the Simulink model window.

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**Note** After you disable the adaptation, the **Adaptive Lookup Table** block does not update the stored table values, and the figure that displays the table values does not update.

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**See Also** Adaptive Lookup Table (nD Stair-Fit)

**Concepts**

- “What are Adaptive Lookup Tables?” on page 6-2

## Using Adaptive Lookup Tables in Real-Time Environment

You can use experimental data from sensor measurements collected by running various tests on a system in real time. The measured data is then sent to the adaptive table block to generate a lookup table describing the relation between the system inputs and output.

You can also use the Adaptive Lookup Table block in a real-time environment, where some time-varying properties of a system need to be captured. To do so, generate C code using Simulink Coder™ code generation software that can then be run in an Simulink Real-Time™ or dSPACE® software. Because you can start, stop, or reset the adaptation if you want, use logic to enable the adaptation of the table data only when it is desired. The cell number output *N*, and the *Enable* and *Lock* inputs facilitate this process. Use the *Enable* input to start and stop the adaptation and the *Lock* input to update only one of the table cells. The *Lock* input combined with some logic using the cell number output *N* provide the means for updating only the desired table cells during a simulation run.

### See Also

Adaptive Lookup Table (1D Stair-Fit) | Adaptive Lookup Table (2D Stair-Fit)  
| Adaptive Lookup Table (nD Stair-Fit)

### Related Examples

- “Model Engine Using n-D Adaptive Lookup Table” on page 6-42

### Concepts

- “What are Adaptive Lookup Tables?” on page 6-2