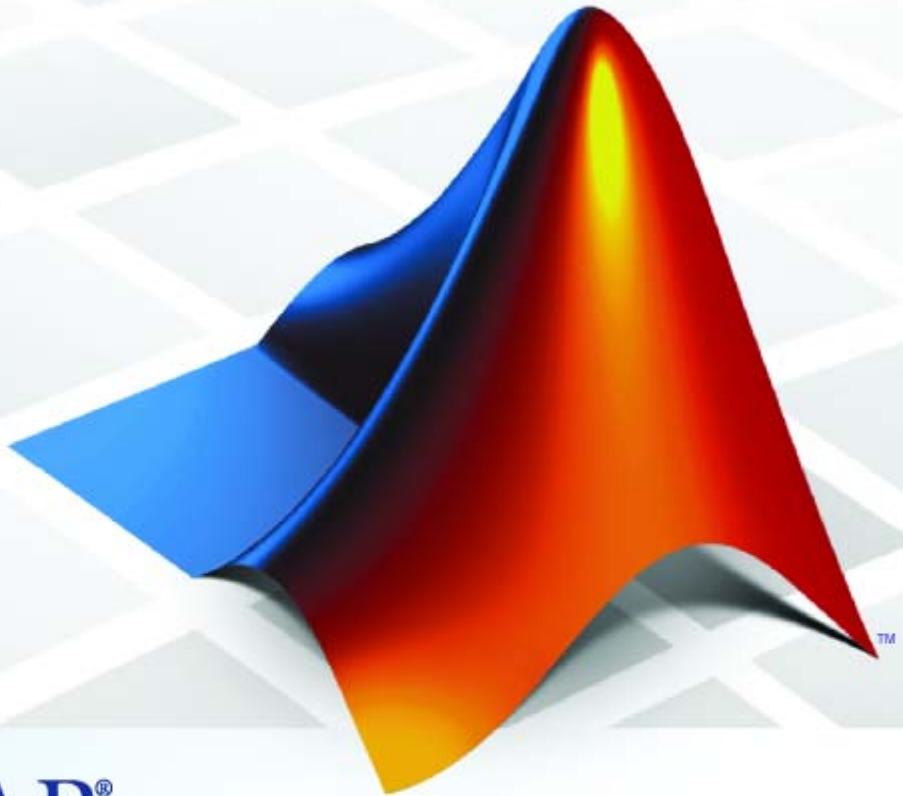


# Signal Processing Toolbox™ 6

## Getting Started Guide



MATLAB®

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## 1

## Overview

<b>Product Overview</b> .....	1-2
Product Summary .....	1-2
Command-Line Functions and Objects .....	1-2
Graphical User Interfaces .....	1-3
Supported Data Types .....	1-3
<b>Central Features</b> .....	1-4
Signal Processing Toolbox Functions .....	1-4
Signals and Systems .....	1-4
Filter Design, Analysis, and Implementation .....	1-5
Linear System Transformations .....	1-5
Windowing Functions .....	1-5
Spectral Analysis .....	1-5
Transforms .....	1-5
Statistical Signal Processing .....	1-5
Parametric Modeling .....	1-6
Linear Prediction .....	1-6
Multirate Signal Processing .....	1-6
Waveform Generation .....	1-6
Other Operations .....	1-6
<b>Interactive Tools</b> .....	1-7
<b>Extensibility</b> .....	1-8
Expanding the Toolbox with M-Files .....	1-8
Expanding the Toolbox with Other Toolboxes .....	1-8
<b>Finding More Information</b> .....	1-9

## Basic Signal Processing Concepts

### 2

<b>Representing Signals</b> .....	2-2
Numeric Arrays .....	2-2
Vector Representation .....	2-2
<b>Waveform Generation: Time Vectors and Sinusoids</b> ...	2-4
Time Vectors .....	2-4
Common Sequences: Unit Impulse, Unit Step, and Unit Ramp .....	2-5
Multichannel Signals .....	2-5
Common Periodic Waveforms .....	2-6
Common Aperiodic Waveforms .....	2-7
The pulstran Function .....	2-8
The Sinc Function .....	2-9
The Dirichlet Function .....	2-10
<b>Working with Data</b> .....	2-12
Importing Data from Within the MATLAB Environment ..	2-12
Importing Data from Outside the MATLAB Environment .....	2-12
Converting Data into a MAT-File .....	2-12
Exporting Data .....	2-13
Data Precision .....	2-13
<b>Selected Bibliography</b> .....	2-14

## Filter Design with Fdesign and Filterbuilder

### 3

<b>Filter Design Process Overview</b> .....	3-2
<b>Basic Filter Design Process</b> .....	3-4
<b>Using Filterbuilder to Design a Filter</b> .....	3-9

## Filter Design with the FDATool GUI

### 4

<b>Introduction</b> .....	4-2
<b>Designing the Filter</b> .....	4-3
<b>Analyzing the Filter</b> .....	4-8
<b>Designing Additional Filters</b> .....	4-10
<b>Viewing and Annotating the Filter</b> .....	4-11
Viewing the Filter in FVTool .....	4-11
Using FVTool for Annotation .....	4-15
<b>Exporting Filters from FDATool</b> .....	4-17
Filtering with dfilt .....	4-18
<b>Designing Filters using Command Line Functions</b> ....	4-21
<b>Where to Find More Information</b> .....	4-24

## Spectral Analysis

### 5

<b>Introduction</b> .....	5-2
Spectral Analysis Examples .....	5-2
Spectral Estimators .....	5-2
Spectral Analysis Algorithms .....	5-2
Spectral Analysis Objects .....	5-3
<b>Creating a Spectral Analysis Object</b> .....	5-4
<b>Generating a Spectrum</b> .....	5-6

<b>Changing Spectral Analysis Object Property Values ..</b>	<b>5-9</b>
Using the set command to Set Property Values .....	<b>5-9</b>
Using Options Objects to Set Property Values .....	<b>5-10</b>
<b>Measuring Signal Power .....</b>	<b>5-11</b>
<b>Where to Find More Information .....</b>	<b>5-15</b>

## **Index**

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# Overview

---

- “Product Overview” on page 1-2
- “Central Features” on page 1-4
- “Interactive Tools” on page 1-7
- “Extensibility” on page 1-8
- “Finding More Information” on page 1-9

## Product Overview

In this section...
“Product Summary” on page 1-2
“Command-Line Functions and Objects” on page 1-2
“Graphical User Interfaces” on page 1-3
“Supported Data Types” on page 1-3

### Product Summary

Signal Processing Toolbox™ software is a collection of tools based on the MATLAB® environment. The toolbox supports a wide range of signal processing operations, from waveform generation to filter design and implementation, parametric modeling, and spectral analysis. The toolbox provides two categories of tools, command-line functions/objects and graphical user interfaces:

### Command-Line Functions and Objects

Command-line functions and objects are available in the following categories:

- Discrete-time filter design, analysis, and implementation
- Analog filter design, analysis, and implementation
- Linear system transformations
- Windowing functions
- Spectral analysis and cepstral analysis
- Transforms
- Statistical signal processing
- Parametric modeling
- Linear prediction
- Multirate signal processing
- Waveform generation

---

**Note** For information on objects, see *Object-Oriented Programming*.

---

## Graphical User Interfaces

A suite of interactive graphical user interfaces are available for

- Filter design and analysis
- Window design and analysis
- Signal plotting and analysis, spectral analysis, and filtering

## Supported Data Types

The Signal Processing Toolbox software supports only double-precision inputs. If you input single-precision floating-point or integer data, you should not expect to receive correct results, and in many cases, an error will occur. The Filter Design Toolbox™ product, in conjunction with the Fixed-Point Toolbox™ product, enables single-precision floating-point and fixed-point support for filtering and filter design.

## Central Features

In this section...
“Signal Processing Toolbox Functions” on page 1-4
“Signals and Systems” on page 1-4
“Filter Design, Analysis, and Implementation” on page 1-5
“Linear System Transformations” on page 1-5
“Windowing Functions” on page 1-5
“Spectral Analysis” on page 1-5
“Transforms” on page 1-5
“Statistical Signal Processing” on page 1-5
“Parametric Modeling” on page 1-6
“Linear Prediction” on page 1-6
“Multirate Signal Processing” on page 1-6
“Waveform Generation” on page 1-6
“Other Operations” on page 1-6

### Signal Processing Toolbox Functions

Signal Processing Toolbox functions are algorithms, expressed mostly in M-files, that implement a variety of signal processing tasks. These toolbox functions are a specialized extension of the MATLAB computational and graphical environment.

### Signals and Systems

The basic entities that toolbox functions work with are signals and systems. The functions emphasize digital (or discrete) signals and filters, as opposed to analog (or continuous) signals. The principal filter type the toolbox supports is the linear, time-invariant digital filter with a single input and a single output. You can represent linear time-invariant systems using one of several models (such as transfer function, state-space, zero-pole-gain, and second-order section), and you can convert between representations.

## **Filter Design, Analysis, and Implementation**

Signal Processing Toolbox software provides customizable support for filter design. The major filter design functions included in the toolbox are FIR and IIR filter design, analysis, and implementation, filter order estimation, and analog filter prototyping and transformations.

## **Linear System Transformations**

The toolbox has a number of transformation functions, including conversions to and from second-order sections, state-space, pole-zero, lattice or ladder, and transfer functions.

## **Windowing Functions**

The toolbox provides many commonly used window functions as well as graphical user interfaces to view and compare windows and design filters using these windows.

## **Spectral Analysis**

Toolbox functions are available for estimating the power spectral density, mean-square spectral estimate, and pseudo spectrum, using parametric and nonparametric techniques. Some of the spectral analysis methods included in the toolbox are Burg, covariance, eigenvector, Thomson multitaper, periodogram, Welch, and Yule-Walker. Other functions are available for computing the average power of a power spectral density, computing a one-sided spectrum, and shifting the DC component to the center of a spectrum.

## **Transforms**

The toolbox includes a variety of transforms and inverse transforms, including Fourier, chirp-Z, discrete cosine, Goertzel, and Hilbert.

## **Statistical Signal Processing**

The toolbox has functions for computing correlation, cross-correlation, covariance, and autocorrelation.

## **Parametric Modeling**

The toolbox includes these methods for autoregressive parametric modeling: Burg, covariance, Yule-Walker, and Steiglitz-McBride (for ARMA modeling). The toolbox also has functions for fitting a frequency response to an analog or discrete-time filter.

## **Linear Prediction**

The toolbox has functions for computing linear prediction coefficients and for converting between autocorrelations and prediction polynomials, reflection coefficients, and line spectral frequencies.

## **Multirate Signal Processing**

The toolbox includes a number of functions for multirate signal processing, including decimation, up- and downsampling, resampling, and spline interpolation.

## **Waveform Generation**

The toolbox has functions to generate many types of periodic and aperiodic waveforms, including chirp, Dirichlet function, Gaussian RF pulse, Gaussian monopulse, pulse train, rectangle, sawtooth, sinc, square wave, triangle, and voltage-controlled oscillator. See “Waveform Generation: Time Vectors and Sinusoids” on page 2-4 for more information.

## **Other Operations**

A number of other operations are also available in the toolbox. Some of these are cepstral analysis, modulation, demodulation, Slepian sequences, and various plotting methods.

## Interactive Tools

The power of Signal Processing Toolbox software is greatly enhanced by its easy-to-use interactive tools.

- The Filter Design and Analysis Tool (`fdatool`) provides a more comprehensive collection of features for addressing filter design. `FDATool` offers seamless access to the additional filter design methods, quantization features, C-code generation and other enhanced filtering features of the Filter Design Toolbox product when that product is installed. If you have the Filter Design HDL Coder™ product installed, you can also generate HDL code from `FDATool`.
- The Filter Visualization Tool (`fvtool`) provides a graphical environment for viewing, annotating, and printing filter response plots.
- The Window Design and Analysis Tool (`wintool`) provides an environment for designing and comparing spectral windows.
- The Window Visualization Tool (`wvtool`) provides a graphical environment for viewing, annotating, and printing window plots.
- The Signal Processing Tool (`sptool`) provides a rich graphical environment for signal viewing, filter design, and spectral analysis.

## Extensibility

In this section...
“Expanding the Toolbox with M-Files” on page 1-8
“Expanding the Toolbox with Other Toolboxes” on page 1-8

### Expanding the Toolbox with M-Files

One of the most important features of the MATLAB environment is that it is extensible. MATLAB lets you create your own M-files to meet numeric computation needs for research, design, or engineering of signal processing systems. Simply copy the M-files provided with the Signal Processing Toolbox product and modify them as needed, or create new functions to expand the functionality of the toolbox.

### Expanding the Toolbox with Other Toolboxes

A number of other MATLAB products expand and enhance the Signal Processing Toolbox product. These include:

- Filter Design Toolbox — Toolbox for advanced filter design
- Signal Processing Blockset™ — Product based on Simulink® for creating and analyzing signal processing models
- Fixed-Point Toolbox — Toolbox for using fixed-point arithmetic
- Filter Design HDL Coder — Toolbox for creating and exporting HDL code
- Embedded IDE Link™ CC — Toolbox for working with embedded software on Texas Instruments™ DSPs



## Finding More Information

This Getting Started guide provides an introduction to Signal Processing Toolbox software and examples, which give you a quick start at using some of the commands and graphical user interfaces. It is assumed that you have basic knowledge and understanding of signals and systems, including such topics as filter and linear system theory and basic Fourier analysis.

More detailed and advanced information on using the toolbox is available in the online help system by typing `doc` at the MATLAB command line or by viewing the documentation on the MathWorks Web site ([www.mathworks.com](http://www.mathworks.com)). The toolbox also includes a number of introductory and advanced demos which you can access by typing `demos` at the MATLAB command line.



# Basic Signal Processing Concepts

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- “Representing Signals” on page 2-2
- “Waveform Generation: Time Vectors and Sinusoids” on page 2-4
- “Working with Data” on page 2-12
- “Selected Bibliography” on page 2-14

## Representing Signals

### In this section...

“Numeric Arrays” on page 2-2

“Vector Representation” on page 2-2

### Numeric Arrays

The central data construct in the MATLAB environment is the *numeric array*, an ordered collection of real or complex numeric data with two or more dimensions. The basic data objects of signal processing (one-dimensional signals or sequences, multichannel signals, and two-dimensional signals) are all naturally suited to array representation.

### Vector Representation

MATLAB represents ordinary one-dimensional sampled data signals, or sequences, as *vectors*. Vectors are 1-by- $n$  or  $n$ -by-1 arrays, where  $n$  is the number of samples in the sequence. One way to introduce a sequence is to enter it as a list of elements at the command prompt. The statement

```
x = [4 3 7 -9 1]
```

creates a simple five-element real sequence in a row vector. Transposition turns the sequence into a column vector

```
x = x'
```

resulting in

```
x =  
 4  
 3  
 7  
-9  
 1
```

Column orientation is preferable for single channel signals because it extends naturally to the multichannel case. For multichannel data, each column of a

matrix represents one channel. Each row of such a matrix then corresponds to a sample point. A three-channel signal that consists of  $x$ ,  $2x$ , and  $x/\pi$  is

$$y = [x \ 2*x \ x/\pi]$$

This results in

$$y = \begin{array}{ccc} 4.0000 & 8.0000 & 1.2732 \\ 3.0000 & 6.0000 & 0.9549 \\ 7.0000 & 14.0000 & 2.2282 \\ -9.0000 & -18.0000 & -2.8648 \\ 1.0000 & 2.0000 & 0.3183 \end{array}$$

## Waveform Generation: Time Vectors and Sinusoids

### In this section...

“Time Vectors” on page 2-4

“Common Sequences: Unit Impulse, Unit Step, and Unit Ramp” on page 2-5

“Multichannel Signals” on page 2-5

“Common Periodic Waveforms” on page 2-6

“Common Aperiodic Waveforms” on page 2-7

“The pulstran Function” on page 2-8

“The Sinc Function” on page 2-9

“The Dirichlet Function” on page 2-10

### Time Vectors

Most toolbox functions require you to begin with a vector representing a time base. Consider generating data with a 1000 Hz sample frequency, for example. An appropriate time vector is

```
t = (0:0.001:1)';
```

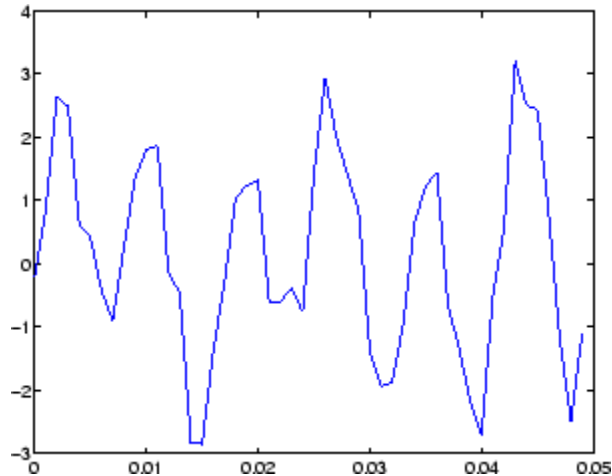
where the MATLAB colon operator creates a 1001-element row vector that represents time running from 0 to 1 s in steps of 1 ms. The transpose operator ( ' ) changes the row vector into a column; the semicolon (;) tells MATLAB to compute, but not display the result.

Given  $t$ , you can create a sample signal  $y$  consisting of two sinusoids, one at 50 Hz and one at 120 Hz with twice the amplitude.

```
y = sin(2*pi*50*t) + 2*sin(2*pi*120*t);
```

The new variable  $y$ , formed from vector  $t$ , is also 1001 elements long. You can add normally distributed white noise to the signal and plot the first 50 points using

```
randn('state',0);  
yn = y + 0.5*randn(size(t));  
plot(t(1:50),yn(1:50))
```



## Common Sequences: Unit Impulse, Unit Step, and Unit Ramp

Since MATLAB is a programming language, an endless variety of different signals is possible. Here are some statements that generate several commonly used sequences, including the unit impulse, unit step, and unit ramp functions:

```
t = (0:0.001:1)';
y = [1; zeros(99,1)]; % impulse
y = ones(100,1);     % step (filter assumes 0 initial cond.)
y = t;               % ramp
y = t.^2;
y = square(4*t);
```

All of these sequences are column vectors. The last three inherit their shapes from `t`.

## Multichannel Signals

Use standard MATLAB array syntax to work with multichannel signals. For example, a multichannel signal consisting of the last three signals generated above is

```
z = [t t.^2 square(4*t)];
```

You can generate a multichannel unit sample function using the outer product operator. For example, a six-element column vector whose first element is one, and whose remaining five elements are zeros, is

```
a = [1 zeros(1,5)]';
```

To duplicate column vector `a` into a matrix without performing any multiplication, use the MATLAB colon operator and the ones function:

```
c = a(:,ones(1,3));
```

### Common Periodic Waveforms

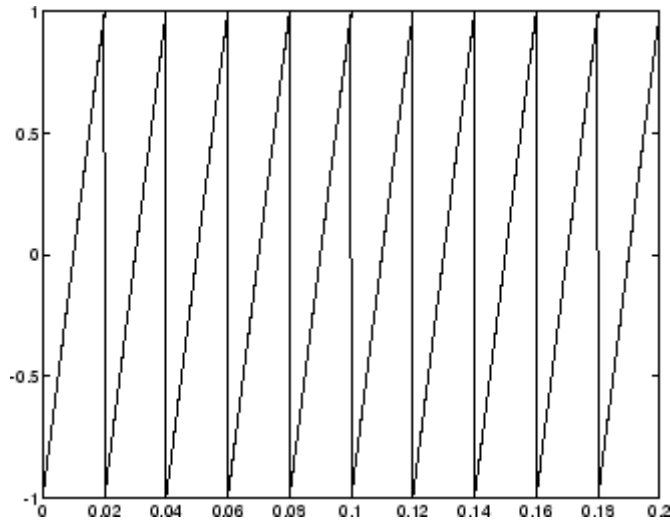
The toolbox provides functions for generating widely used periodic waveforms:

- `sawtooth` generates a sawtooth wave with peaks at  $\pm 1$  and a period of  $2\pi$ . An optional `width` parameter specifies a fractional multiple of  $2\pi$  at which the signal's maximum occurs.
- `square` generates a square wave with a period of  $2\pi$ . An optional parameter specifies *duty cycle*, the percent of the period for which the signal is positive.

To generate 1.5 s of a 50 Hz sawtooth wave with a sample rate of 10 kHz and plot 0.2 s of the generated waveform, use

```
fs = 10000;  
t = 0:1/fs:1.5;  
x = sawtooth(2*pi*50*t);  
plot(t,x), axis([0 0.2 -1 1])
```





## Common Aperiodic Waveforms

The toolbox also provides functions for generating several widely used aperiodic waveforms:

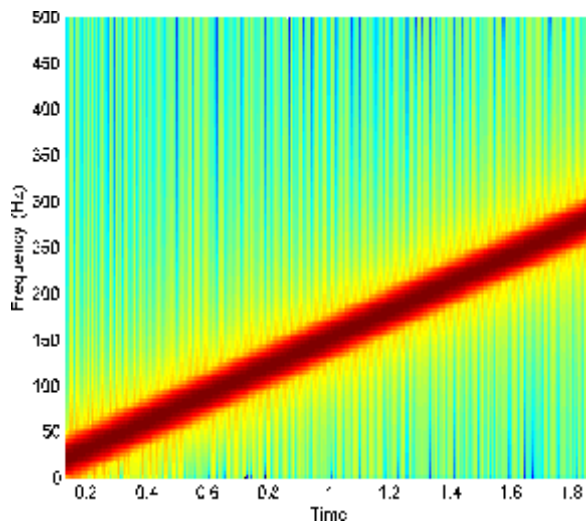
- `gauspuls` generates a Gaussian-modulated sinusoidal pulse with a specified time, center frequency, and fractional bandwidth. Optional parameters return in-phase and quadrature pulses, the RF signal envelope, and the cutoff time for the trailing pulse envelope.
- `chirp` generates a linear, log, or quadratic swept-frequency cosine signal. An optional parameter specifies alternative sweep methods. An optional parameter `phi` allows initial phase to be specified in degrees.

To compute 2 s of a linear chirp signal with a sample rate of 1 kHz, that starts at DC and crosses 150 Hz at 1 s, use

```
t = 0:1/1000:2;
y = chirp(t,0,1,150);
```

To plot the spectrogram, use

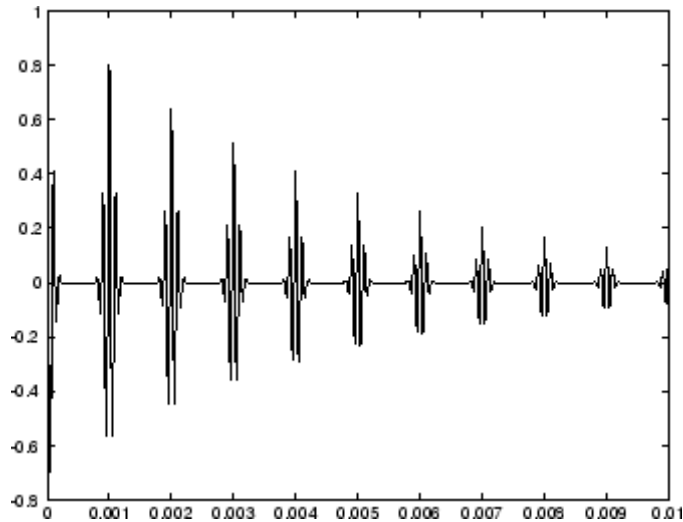
```
spectrogram(y,256,250,256,1000,'yaxis')
```



### The pulstran Function

The pulstran function generates pulse trains from either continuous or sampled prototype pulses. The following example generates a pulse train consisting of the sum of multiple delayed interpolations of a Gaussian pulse. The pulse train is defined to have a sample rate of 50 kHz, a pulse train length of 10 ms, and a pulse repetition rate of 1 kHz; D specifies the delay to each pulse repetition in column 1 and an optional attenuation for each repetition in column 2. The pulse train is constructed by passing the name of the gauspuls function to pulstran, along with additional parameters that specify a 10 kHz Gaussian pulse with 50% bandwidth:

```
T = 0:1/50E3:10E-3;  
D = [0:1/1E3:10E-3;0.8.^(0:10)]';  
Y = pulstran(T,D,'gauspuls',10E3,0.5);  
plot(T,Y)
```



## The Sinc Function

The sinc function computes the mathematical sinc function for an input vector or matrix  $x$ . The sinc function is the continuous inverse Fourier transform of the rectangular pulse of width  $2\pi$  and height 1.

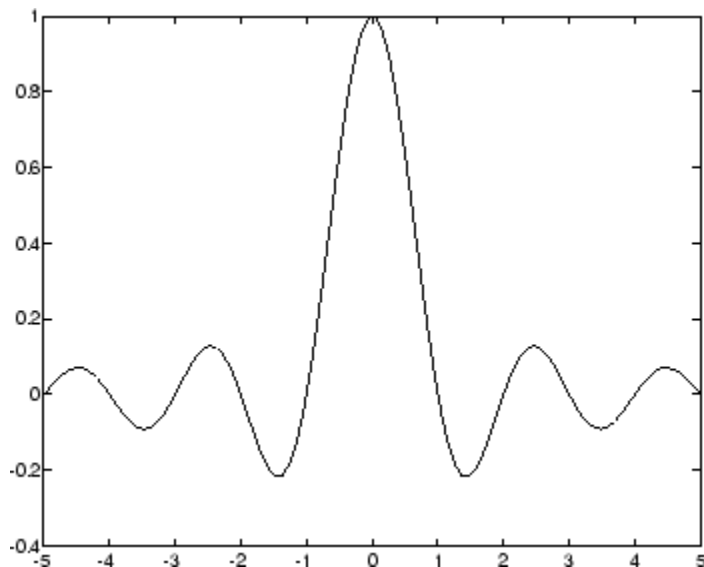
The sinc function has a value of 1 where  $x$  is zero, and a value of

$$\frac{\sin(\pi x)}{\pi x}$$

for all other elements of  $x$ .

To plot the sinc function for a linearly spaced vector with values ranging from -5 to 5, use the following commands:

```
x = linspace(-5,5);  
y = sinc(x);  
plot(x,y)
```



## The Dirichlet Function

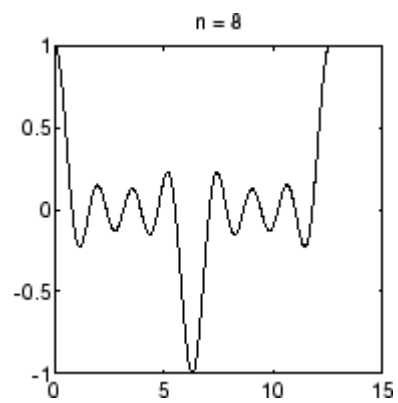
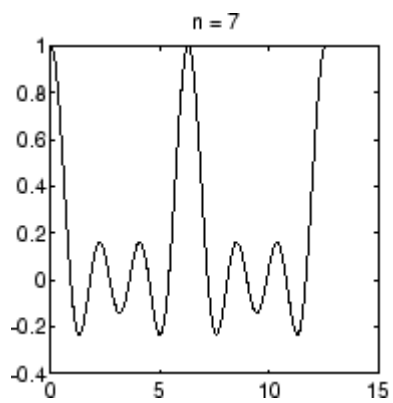
The toolbox function `diric` computes the Dirichlet function, sometimes called the *periodic sinc* or *aliased sinc* function, for an input vector or matrix  $x$ . The Dirichlet function is

$$\text{diric}(x) = \begin{cases} -1^{k(n-1)} & x = 2\pi k, k = 0, \pm 1, \pm 2, \dots \\ \frac{\sin(nx/2)}{n \sin(x/2)} & \text{otherwise} \end{cases}$$

where  $n$  is a user-specified positive integer. For  $n$  odd, the Dirichlet function has a period of  $2\pi$ ; for  $n$  even, its period is  $4\pi$ . The magnitude of this function is  $(1/n)$  times the magnitude of the discrete-time Fourier transform of the  $n$ -point rectangular window.

To plot the Dirichlet function over the range 0 to  $4\pi$  for  $n = 7$  and  $n = 8$ , use

```
x = linspace(0,4*pi,300);
plot(x,diric(x,7)); axis tight;
plot(x,diric(x,8)); axis tight;
```



## Working with Data

In this section...
“Importing Data from Within the MATLAB Environment” on page 2-12
“Importing Data from Outside the MATLAB Environment” on page 2-12
“Converting Data into a MAT-File” on page 2-12
“Exporting Data” on page 2-13
“Data Precision” on page 2-13

### Importing Data from Within the MATLAB Environment

The examples in the preceding sections obtain data in one of two ways:

- By direct input, that is, entering the data manually at the keyboard
- By using a MATLAB or toolbox function, such as `sin`, `cos`, `sawtooth`, `square`, or `sinc`

### Importing Data from Outside the MATLAB Environment

Some applications, however, may need to import data from outside MATLAB. Depending on your data format, you can do this in the following ways:

- Load data from an ASCII file or MAT-file with the MATLAB `load` command.
- Read the data into MATLAB with a low-level file I/O function, such as `fopen`, `fread`, and `fscanf`.
- Develop a MEX-file to read the data.

### Converting Data into a MAT-File

Other resources are also useful, such as a high-level language program (in Fortran or C, for example) that converts your data into MAT-file format. See the “Manually Converting Data Passed to Functions” documentation for details. MATLAB reads such files using the `load` command.

## **Exporting Data**

Similar techniques are available for exporting data generated within MATLAB. See the “Importing and Exporting Data” documentation for more details.

## **Data Precision**

All Signal Processing Toolbox functions accept double-precision inputs. If you input single-precision floating-point or integer data types, you should not expect to receive correct results and in many cases, an error will occur. Filter Design Toolbox and Fixed-Point Toolbox products enable single-precision floating-point and fixed-point support for most `dfilt` structures.

## Selected Bibliography

Algorithm development for Signal Processing Toolbox functions has drawn heavily upon the references listed below. All are recommended to the interested reader who needs to know more about signal processing than is covered in this manual.

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[10] Rabiner, L.R., and B. Gold. *Theory and Application of Digital Signal Processing*. Englewood Cliffs, NJ: Prentice Hall, 1975.

[11] Welch, P.D. "The Use of Fast Fourier Transform for the Estimation of Power Spectra: A Method Based on Time Averaging Over Short, Modified



Periodograms." *IEEE Trans. Audio Electroacoust.* Vol. AU-15 (June 1967).  
Pgs. 70-73.



# Filter Design with Fdesign and Filterbuilder

---

- “Filter Design Process Overview” on page 3-2
- “Basic Filter Design Process” on page 3-4
- “Using Filterbuilder to Design a Filter” on page 3-9

## Filter Design Process Overview

---

**Note** You must have the Signal Processing Toolbox installed to use and filterbuilder. Some of the features described and displayed in this tutorial may be unavailable if your installation does not additionally include the Filter Design Toolbox license. You can verify the presence of both toolboxes by typing `ver` at the command prompt.

---

Filter design through user-defined specifications is the core of the `fdesign` approach. This specification-centric approach places less emphasis on the choice of specific filter algorithms, and more emphasis on performance during the design a good working filter. For example, you can take a given set of design parameters for the filter, such as a stopband frequency, a passband frequency, and a stopband attenuation, and— using these parameters— design a specification object for the filter. You can then implement the filter using this specification object. Using this approach, it is also possible to compare different algorithms as applied to a set of specifications.

There are two distinct objects involved in filter design:

- Specification Object — Captures the required design parameters of a filter
- Implementation Object — Describes the designed filter; includes the array of coefficients and the filter structure

The distinction between these two objects is at the core of the filter design methodology. The basic attributes of each of these objects are outlined in the following table.

Specification Object	Implementation Object
High-level specification	Filter coefficients
Algorithmic properties	Filter structure

You can run the code in the following examples from the Help browser (select the code, right-click the selection, and choose **Evaluate Selection** from the context menu), or you can enter the code on the MATLAB command line. Before you begin this example, start MATLAB and verify that you

have installed the Signal Processing Toolbox. If you wish to access the full functionality of `fdesign` and `filterbuilder`, you should additionally obtain the Filter Design Toolbox software. You can verify the presence of these products by typing `ver` at the command prompt.

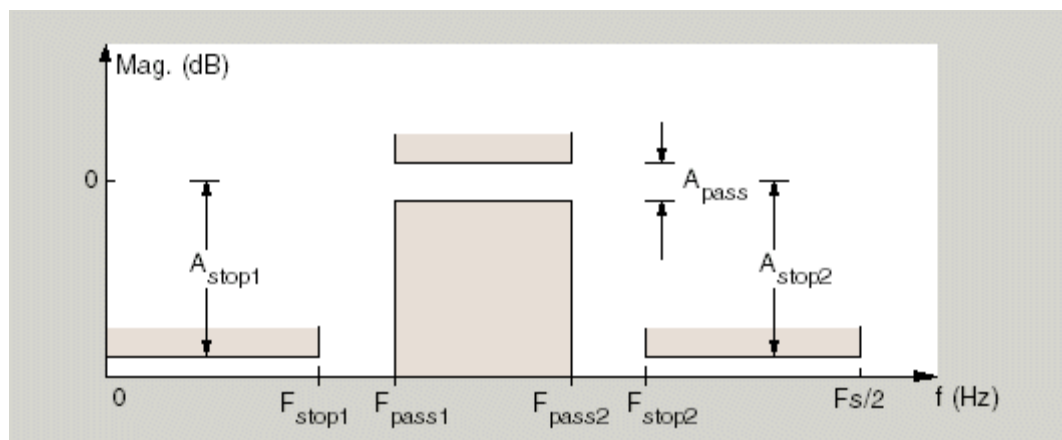
## Basic Filter Design Process

Use the following two steps to design a simple filter.

- 1 Create a filter specification object.
- 2 Design your filter.

### Example – Design a Filter in Two Steps

Assume that you want to design a bandpass filter. Typically a bandpass filter is defined as shown in the following figure.



In this example, a sampling frequency of  $F_s = 48$  kHz is used. This bandpass filter has the following specifications, specified here using MATLAB code:

```
A_stop1 = 60; % Attenuation in the first stopband = 60 dB
F_stop1 = 8400; % Edge of the stopband = 8400 Hz
F_pass1 = 10800; % Edge of the passband = 10800 Hz
F_pass2 = 15600; % Closing edge of the passband = 15600 Hz
F_stop2 = 18000; % Edge of the second stopband = 18000 Hz
A_stop2 = 60; % Attenuation in the second stopband = 60 dB
A_pass = 1; % Amount of ripple allowed in the passband = 1 dB
```

In the following two steps, these specifications are passed to the `fdesign.bandpass` method as parameters. For more information about

passing specifications to the `fdesign` filter specification object, refer to the reference.

### Step 1

To create a filter specification object, evaluate the following code at the MATLAB prompt:

```
d = fdesign.bandpass
```

Now, pass the filter specifications that correspond to the default Specification — `fst1,fp1,fp2,fst2,ast1,ap,ast2`. This example adds `fs` as the final input argument to specify the sampling frequency of 48 kHz.

```
>> BandPassSpecObj = ...  
    fdesign.bandpass('Fst1,Fp1,Fp2,Fst2,Ast1,Ap,Ast2', ...  
    F_stop1, F_pass1, F_pass2, F_stop2, A_stop1, A_pass, ...  
    A_stop2, 48000)
```

```
BandPassSpecObj =
```

```
    Response: 'Bandpass'  
    Specification: 'Fst1,Fp1,Fp2,Fst2,Ast1,Ap,Ast2'  
    Description: {7x1 cell}  
    NormalizedFrequency: false  
           Fs: 48000  
    Fstop1: 8400  
    Fpass1: 10800  
    Fpass2: 15600  
    Fstop2: 18000  
    Astop1: 60  
    Apass: 1  
    Astop2: 60
```

---

**Note** The order of the filter is not specified, allowing a degree of freedom for the algorithm design in order to achieve the specification. The design will be a minimum order design.

---

The specification parameters, such as `Fstop1`, are all given default values when none are provided. You can change the values of the specification parameters after the filter specification object has been created. For example, if there are two values that need to be changed, `Fpass2` and `Fstop2`, use the `set` command, which takes the object first, and then the parameter value pairs. Evaluate the following code at the MATLAB prompt:

```
>> set(BandPassSpecObj, 'Fpass2', 15800, 'Fstop2', 18400)
```

`BandPassSpecObj` is the new filter specification object which contains all the required design parameters, including the filter type.

You may also change parameter values in filter specification objects by accessing them as if they were elements in a `struct` array.

```
>> BandPassSpecObj.Fpass1=15800;
```

#### Step 2

Design the filter by using the `design` command. You can access the design methods available for your specification object by calling the `designmethods` function. For example, in this case, you can execute the command

```
>> designmethods(BandPassSpecObj)
```

```
Design Methods for class
fdesign.bandpass (Fst1,Fp1,Fp2,Fst2,Ast1,Ap,Ast2):
```

```
butter
cheby1
cheby2
ellip
equiripple
kaiserwin
```

After choosing a design method use, you can evaluate the following at the MATLAB prompt (this example assumes you've chosen 'equiripple'):



```
>> BandPassFilt = design(BandPassSpecObj, 'equiripple')

BandPassFilt =

    FilterStructure: 'Direct-Form FIR'
      Arithmetic: 'double'
      Numerator: [1x44 double]
 PersistentMemory: false
```

---

**Note** If you do not specify a design method, a default method will be used. For example, you can execute the command

```
>> BandPassFilt = design(BandPassSpecObj)

BandPassFilt =

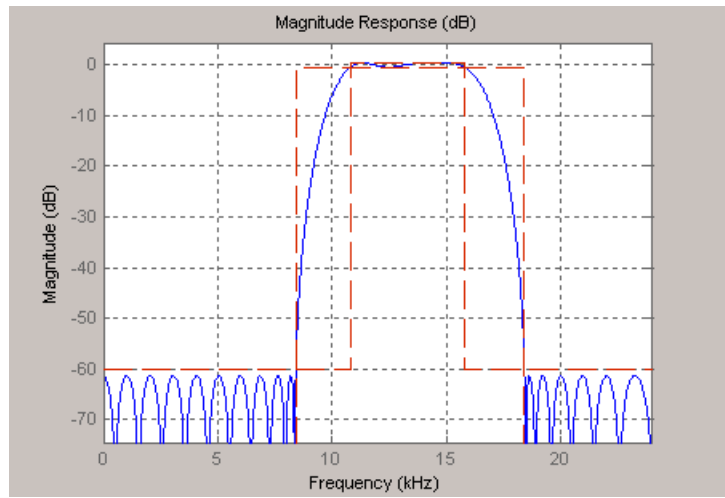
    FilterStructure: 'Direct-Form FIR'
      Arithmetic: 'double'
      Numerator: [1x44 double]
 PersistentMemory: false
```

and a design method will be selected automatically.

---

To check your work, you can plot the filter magnitude response using the Filter Visualization tool. Verify that all the design parameters are met:

```
>> fvtool(BandPassFilt) %plot the filter magnitude response
```



## Using Filterbuilder to Design a Filter

Filterbuilder presents the option of designing a filter using a GUI dialog box as opposed to the command line instructions. You can use Filterbuilder to design the same bandpass filter designed in the previous section, “Basic Filter Design Process” on page 3-4

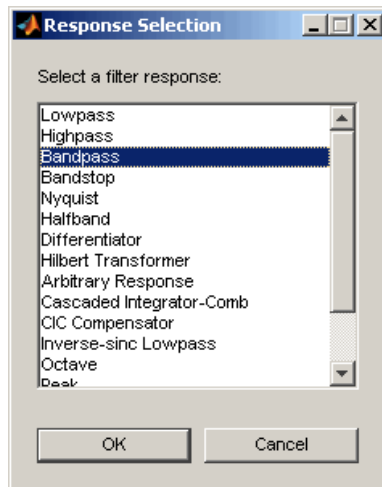
### Example – Using Filterbuilder to Design a Simple Filter

To design the filter using FilterBuilder:

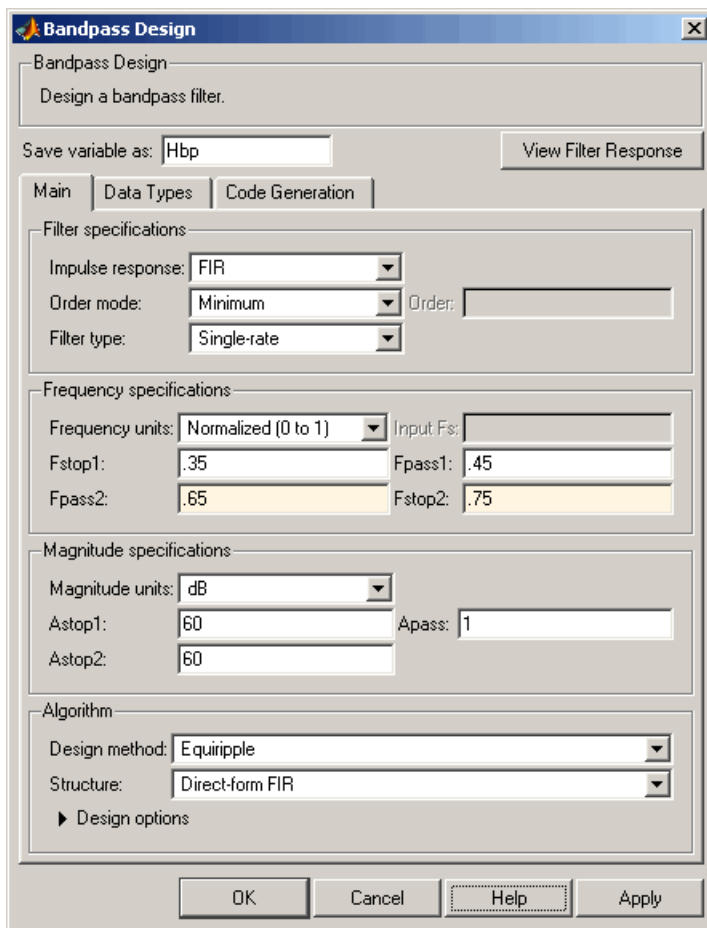
- 1 Type the following at the MATLAB prompt:

```
filterbuilder
```

The following dialog box opens:



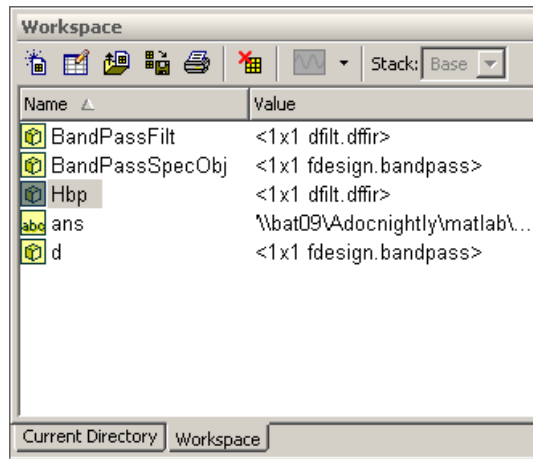
- 2 Select Bandpass filter response from the list in the dialog box, and hit the **OK** button. The following dialog box opens:



- 3** Enter the correct frequencies for **Fpass2** and **Fstop2**, as shown in the preceding figure, then click **OK**. Here the specification uses normalized frequency, so that the passband and stopband edges are expressed as a fraction of the Nyquist frequency (in this case,  $48/2$  kHz). The following message appears at the MATLAB prompt:

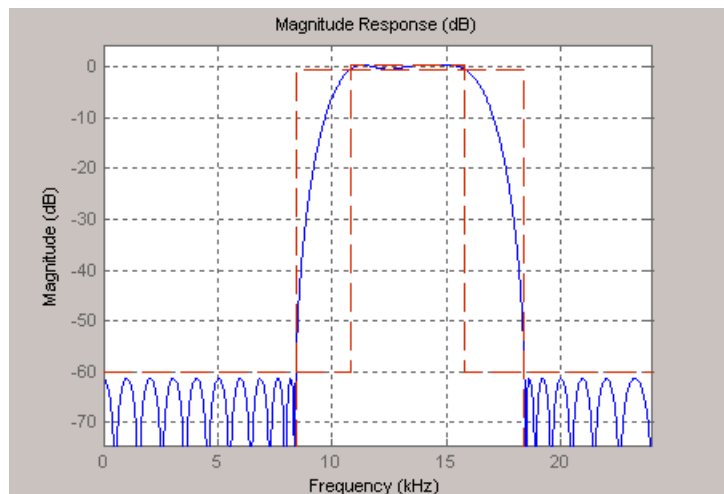
The variable 'Hbp' has been exported to the command window.

If you display the Workspace tab, as shown in the following figure, you see the object Hbp has been placed on your workspace.



- 4** To check your work, plot the filter magnitude response using the Filter Visualization tool. Verify that all the design parameters are met:

```
fvtool(Hbp) %plot the filter magnitude response
```





# Filter Design with the FDATool GUI

---

- “Introduction” on page 4-2
- “Designing the Filter” on page 4-3
- “Analyzing the Filter” on page 4-8
- “Designing Additional Filters” on page 4-10
- “Viewing and Annotating the Filter” on page 4-11
- “Exporting Filters from FDATool” on page 4-17
- “Designing Filters using Command Line Functions” on page 4-21
- “Where to Find More Information” on page 4-24

# Introduction

This section describes how to graphically design and implement digital filters using the Signal Processing Toolbox FDATool GUI. Filter design is the process of creating the filter coefficients to meet specific frequency specifications. Filter implementation involves choosing and applying a particular filter structure to those coefficients. Only after both design and implementation have been performed can your data be filtered.

This section includes a brief discussion of applying the completed filter design and filter implementation using MATLAB command line functions, such as `filter`.

For an interactive FDATool demo, type `demod` at the MATLAB command line, and select **Toolboxes**. Expand the tree, scroll down, and select **Signal Processing Toolbox**. Under Filter Design and Analysis, click **Introduction to Filter Design and Analysis Tool**.



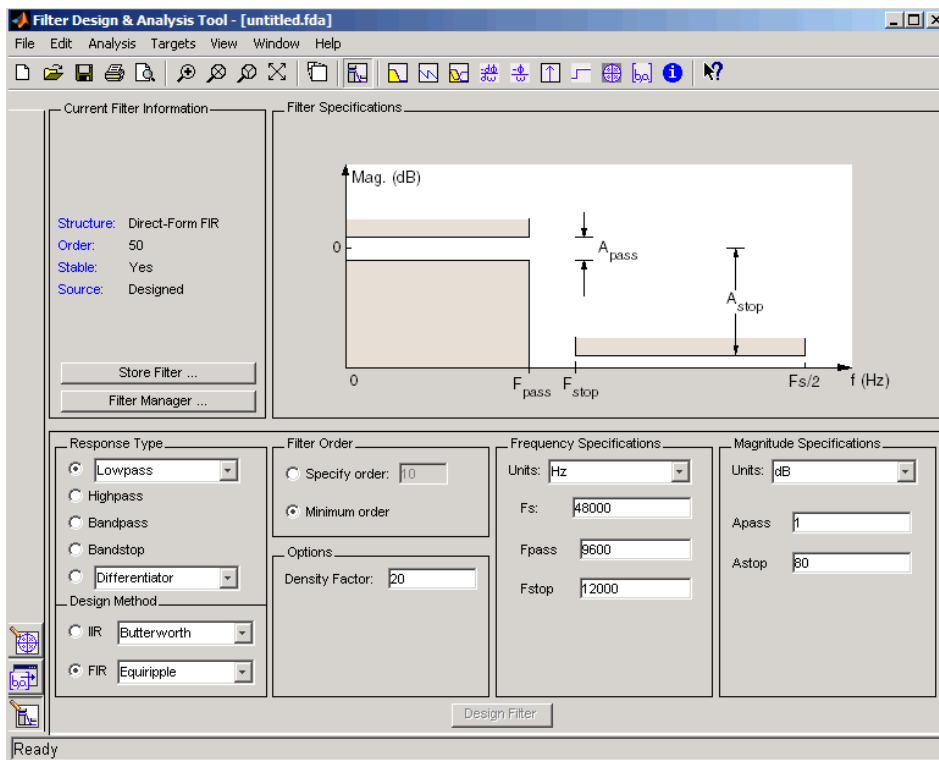
## Designing the Filter

This section is a step-by-step introduction to using the Filter Design and Analysis Tool (FDATool) to design an octave-band filter. An octave is the interval between two frequencies having a ratio of 2:1. An octave-band filter is a bandpass filter with high cutoff frequency approximately twice that of the low cutoff frequency. The class of an octave filter is determined by its allowable passband ripple and its stopband attenuation. Refer to the ANSI S1.11–2004 standard for more information. For more information on designing filters, see “FDATool: A Filter Design and Analysis GUT” in the Signal Processing Toolbox User’s Guide. (Note that you can also access FDATool from SPTool).

- 1 Start FDATool from the MATLAB command line.

```
fdatool
```

The FDATool dialog opens with a default filter. Its filter information is summarized in the upper left (**Current Filter Information**) and its filter specifications are depicted in the upper right. In addition to displaying filter specification, this upper right pane displays filter responses and filter coefficients.



The bottom half of FDATool shows the Filter Design panel, where you specify the filter parameters. Other panels, such as Import filter from workspace and Pole/Zero Editor, which you access with the buttons on the lower left, are also displayed in this area. If you have other products installed, you may see additional buttons.

- 2** In the **Response Type** pane, select **Bandpass**.
- 3** In the **Design Method** pane, select **IIR**, and then select Butterworth from the selection list.

Response Type

Lowpass

Highpass

Bandpass

Bandstop

Differentiator

Design Method

IIR Butterworth

FIR Equiripple

- 4 For the Filter Order, select **Specify order**, and then enter 6.

Filter Order

Specify order: 6

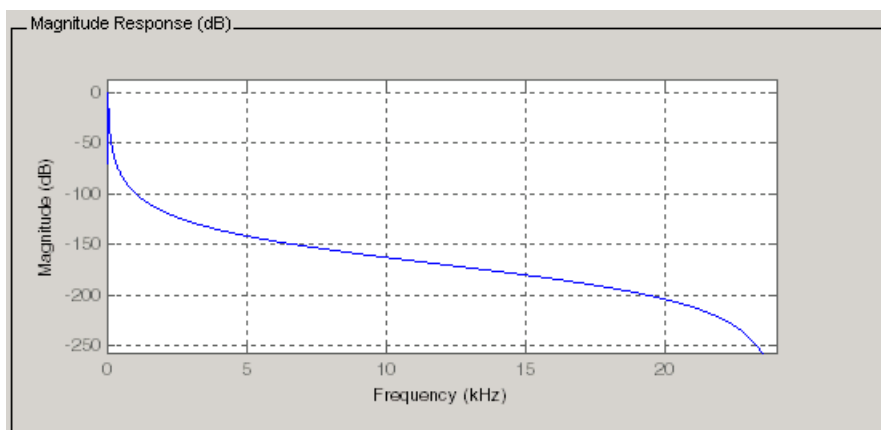
Minimum order

- 5 Set the Frequency Specifications as follows:

Parameter	Setting	Description
Units	Hz	Units for the parameters
Fs	48000	Sampling frequency
Fc1	22	First cutoff frequency (i.e., the frequency preceding the passband at which the magnitude response is 3 dB below the passband gain)
Fc2	45	Second cutoff frequency (i.e., the frequency following the passband at which the magnitude response is 3 dB below the passband gain)

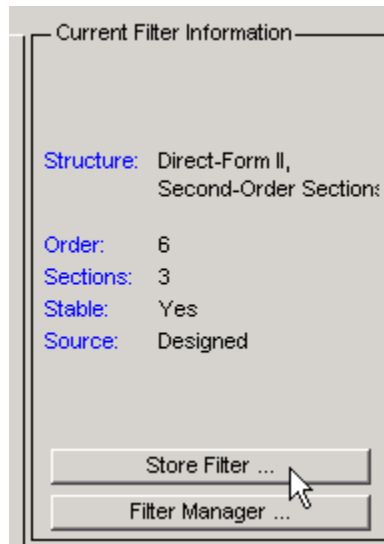
Frequency Specifications	Magnitude Specifications
Units: <input type="text" value="Hz"/>	
Fs: <input type="text" value="48000"/>	The attenuation at cutoff
Fc1: <input type="text" value="22"/>	frequencies is fixed at 3 dB
Fc2: <input type="text" value="45"/>	(half the passband power)

- 6 After specifying the filter design parameters, click the **Design Filter** button at the bottom of the design panel to compute the filter coefficients. The display updates to show the magnitude response of the designed filter.

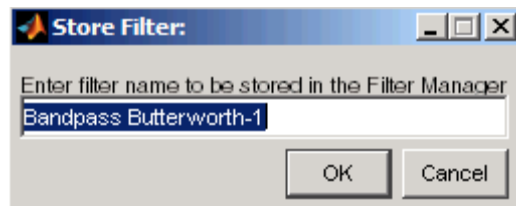


Notice that the **Design Filter** button is disabled after you compute the coefficients for your filter design. This button is enabled again if you make any changes to the filter specifications.

- 7 Click the **Store Filter** button.













- 8 In the Store Filter dialog, change the filter name to **Bandpass Butterworth-1** and click **OK** to save the filter in the Filter Manager.



## Analyzing the Filter

After designing the filter, you can view the following filter responses in the display region by clicking on the associated toolbar button or by selecting the desired response from the **Analysis** menu.

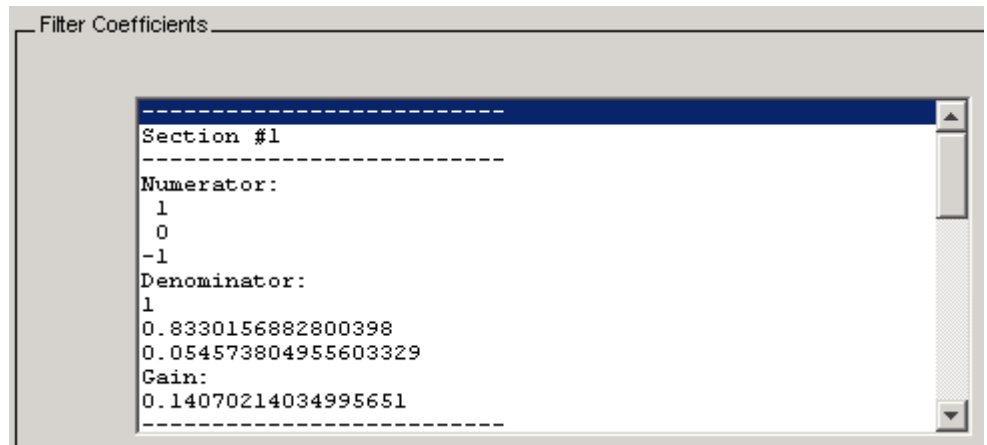
<b>Response</b>	<b>Toolbar Button Image</b>
Magnitude response	
Phase response	
Magnitude and Phase responses	
Group delay	
Phase delay	
Impulse response	
Step response	
Pole-zero plot	
Filter coefficients	
Filter information	
<b>Zero-phase response</b> —only available from a context menu. Right-click on the y-axis of a Magnitude or Magnitude and Phase response plot or select <b>Analysis &gt; Analysis Parameters</b> .	

---

**Note** Other analyses are available if you have the Filter Design Toolbox product installed.

---

- 1 Examine the displayed magnitude response of the filter.
- 2 Display other responses, as desired. Click the appropriate buttons, shown in the table above or select the desired response from the **Analysis** menu.
- 3 Click the **Filter coefficients** button to display the filter coefficients.



```
Filter Coefficients
-----
Section #1
-----
Numerator:
  1
  0
 -1
Denominator:
  1
 0.8330156882800398
 0.054573804955603329
Gain:
0.14070214034995651
-----
```

## Designing Additional Filters

You have designed one of the bands of an octave filter bank. This section shows you how to design and save the other nine bands. The following table defines the parameters for the remaining bands. Note that all of the bands use these parameters: **Bandpass, IIR – Butterworth** , **order = 6, Fs = 48000 Hz** .

<b>Fc1</b>	<b>Fc2</b>	<b>Filter Name</b>
45	89	Bandpass Butterworth-2
89	178	Bandpass Butterworth-3
178	355	Bandpass Butterworth-4
355	708	Bandpass Butterworth-5
708	1413	Bandpass Butterworth-6
1413	2818	Bandpass Butterworth-7
2818	5623	Bandpass Butterworth-8
5623	11220	Bandpass Butterworth-9
11220	22387	Bandpass Butterworth-10

- 1** Using the parameters listed in the table above, for each table row, set the appropriate the **Fc1** and **Fc2** values.
- 2** Design the filter by clicking the **Design Filter** button.
- 3** Click **Store Filter** to save the filter.
- 4** Change the name to the appropriate filter name shown in the table above.
- 5** Repeat these steps until all 10 filters are designed and stored.



## Viewing and Annotating the Filter

### In this section...

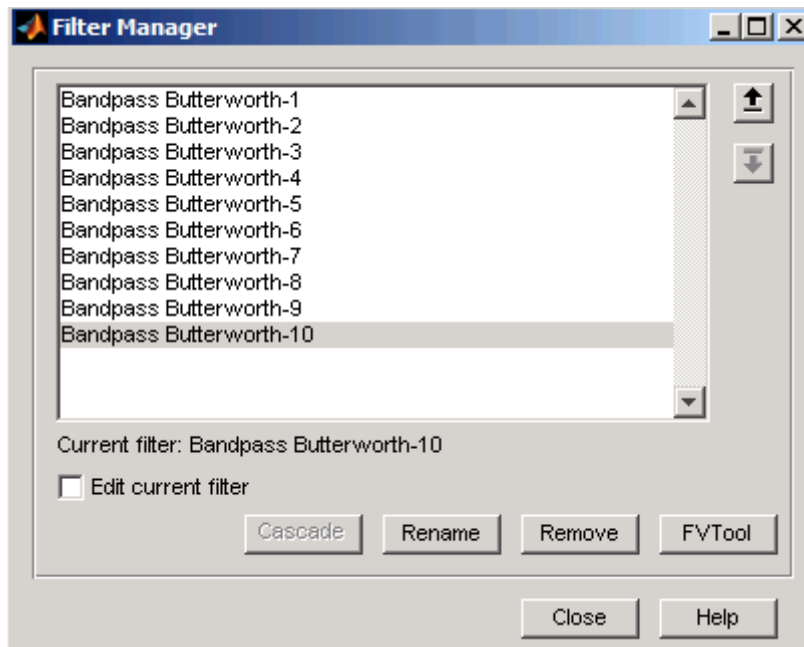
“Viewing the Filter in FVTool” on page 4-11

“Using FVTool for Annotation” on page 4-15

### Viewing the Filter in FVTool

This section teaches you how to use the Filter Visualization Tool (FVTool) to view the octave-band filter. It also describes how to annotate your filter.

- 1 Click the **Filter Manager** button to display the Filter Manager, which lists your saved filters.

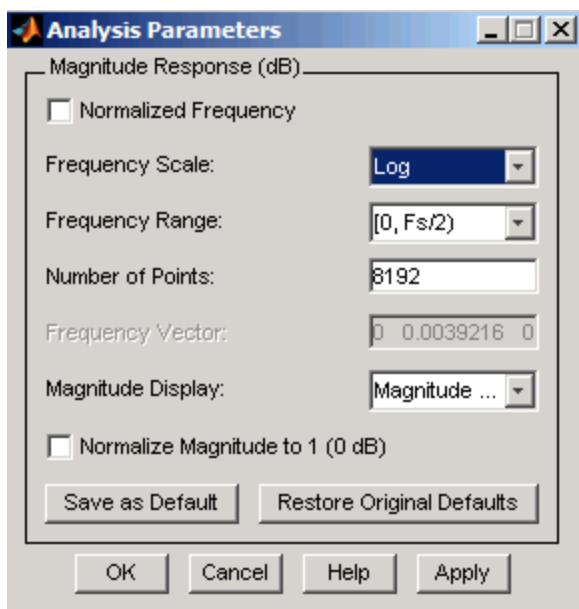


- 2 Press Ctrl+click on each filter name to select all the filters, and then click **FVTool**. FVTool opens with the filter responses overlaid for easy comparison. (If you want to view a single filter in FVTool, click the **Full**

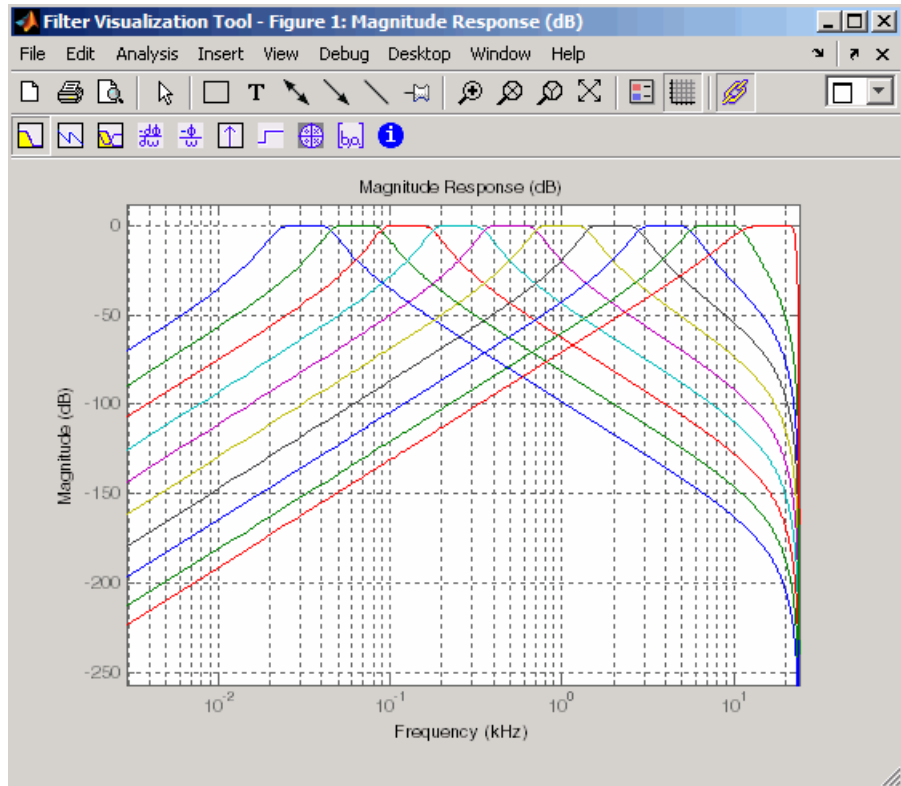
**View Analysis** button when that filter is shown in the FDATool display panel or select **View > Filter Visualization Tool**).


**3** Change the x-axis scale to logarithmic by selecting **Analysis > Analysis Parameters** to display the Analysis Parameters dialog.

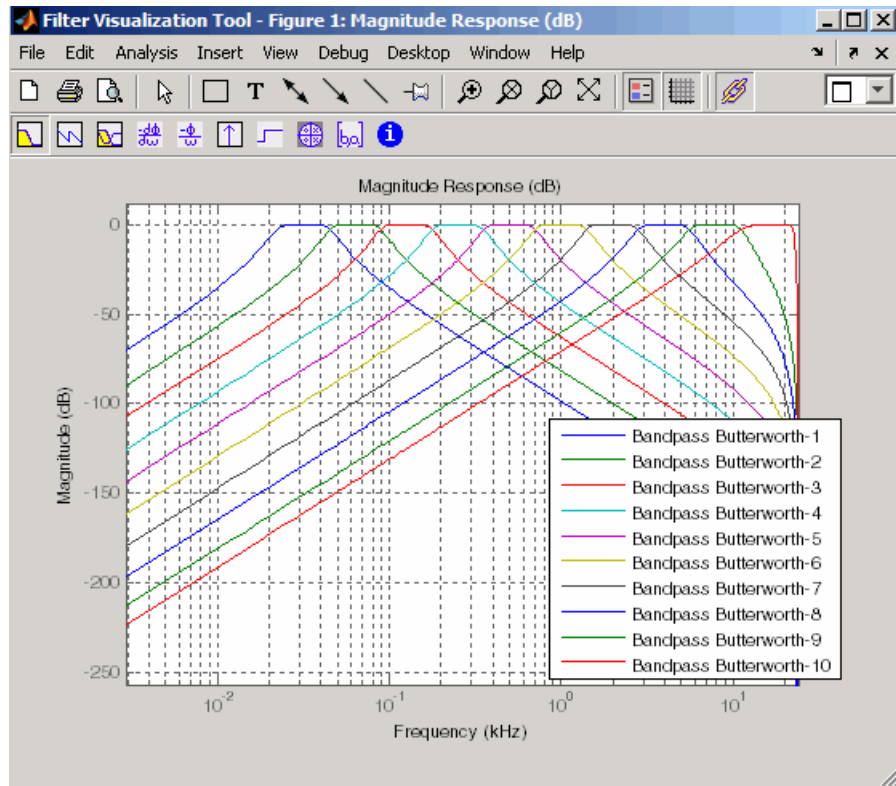
**4** Change the **Frequency Scale** to Log.




**5** Click **OK**.

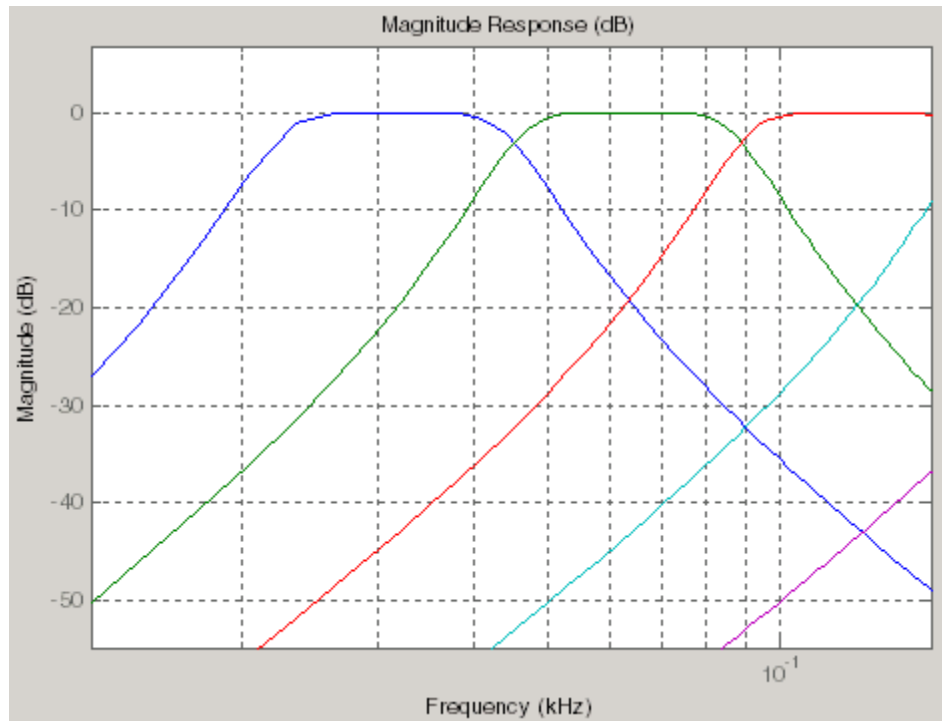



- 6 Click the **Legend** button  to turn on the legend, which you can drag to the desired location.



7 Click the **Legend** button again to turn off the legend.

Use the **Zoom** button  and drag a rectangle around the first few passbands to zoom in.



- 8 Click the **Restore Default View** button  to return to the full view.
- 9 Display other responses, as desired. (The FVTool Analysis toolbar buttons and **Analysis** menu are the same as in FDATool. See “Analyzing the Filter” on page 4-8 for descriptions of the buttons.)

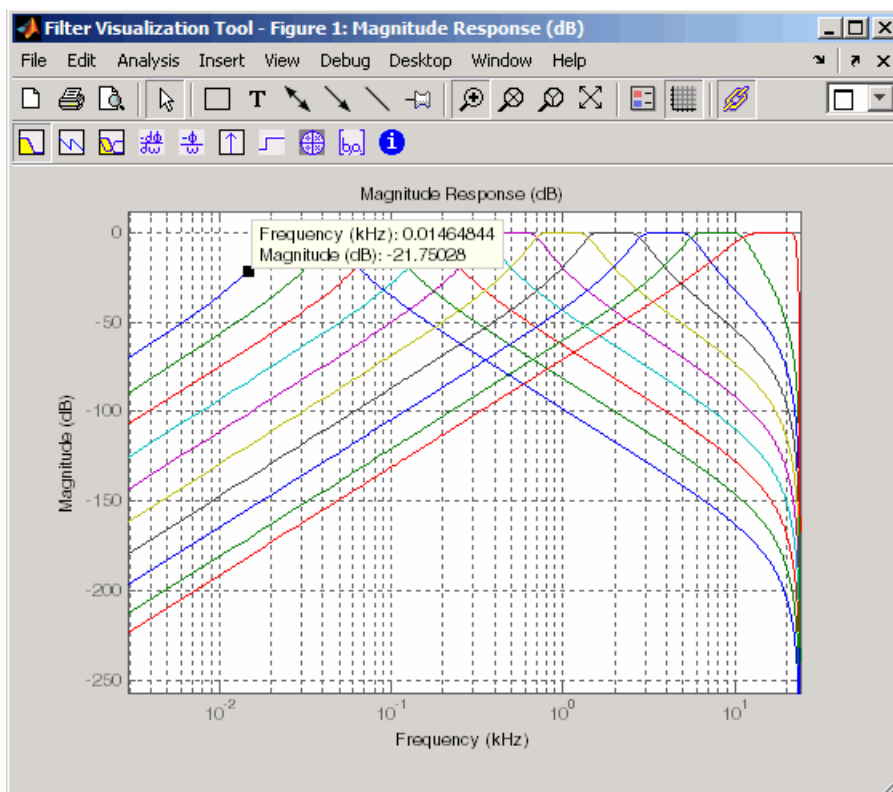
## Using FVTool for Annotation

FVTool is also useful for doing further analysis, adding annotations, and printing. Available annotations include adding rectangles, text boxes, arrows and lines, and adding data tips.

For a demo about FVTool, type **demos** at the MATLAB command line, and select **Toolboxes**. Expand the tree, scroll down, and select **Signal Processing Toolbox**. Under Filter Design and Analysis, click **Filter Analysis using FVTool and its API**.

**Note** Do not close FDATool at this time. You will use it in future sections.

- 1 Use the toolbar buttons to annotate your response plot. Add a line by clicking one of the line buttons, and then use your mouse to draw the line on your plot.
- 2 Add a data tip by clicking on a plot at the desired point. The data tip shows the frequency and magnitude at that point.

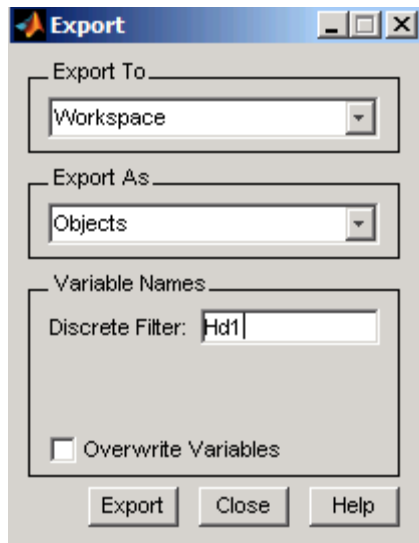


- 3 Close FVTool by selecting **File > Close**.

## Exporting Filters from FDATool

FDATool provides a simple way to create filter objects (dfilt) from your filter designs. This is particularly useful for saving your filter design to the MATLAB workspace for use with command line functions. You can also save your filters to M-files using **File > Generate M-file** to run in scripts or batch files.

- 1 In FDATool, click **Filter Manager** and highlight only the Bandpass Butterworth-1 filter.
- 2 Select **File > Export**.
- 3 Set **Export to** to Workspace. Set **Export as** to Objects. In **Discrete Filter** type Hd1. Click **Export** to export the first filter in your filter bank to an Hd1 dfilt object in the workspace.



- 4 Repeat steps 1 through 3 for each of the remaining nine filters. Highlight each filter individually to make it the active filter and change the **Discrete Filter** name to match the filter number. When you finish you will have 10 dfilt objects in the workspace.

**5** Close FDATool by selecting **File > Close**.

**6** On the MATLAB command line, verify that your objects were exported by using the whos command.

```
whos
      Name      Size      Bytes  Class      Attributes
      Hd1       1x1           48  dfilt.df2sos
      Hd10      1x1           48  dfilt.df2sos
      Hd2       1x1           48  dfilt.df2sos
      Hd3       1x1           48  dfilt.df2sos
      Hd4       1x1           48  dfilt.df2sos
      Hd5       1x1           48  dfilt.df2sos
      Hd6       1x1           48  dfilt.df2sos
      Hd7       1x1           48  dfilt.df2sos
      Hd8       1x1           48  dfilt.df2sos
      Hd9       1x1           48  dfilt.df2sos
```

## Filtering with dfilt

**1** Type the following on the MATLAB command line to concatenate your filter bank filter objects into a single dfilt object.

```
Hd = [Hd1 Hd2 Hd3 Hd4 Hd5 Hd6 Hd7 Hd8 Hd9 Hd10];
```

**2** To view the first filter, type Hd(1).

```
Hd(1)
ans =
  FilterStructure: 'Direct-Form II, Second-Order Sections'
      sosMatrix: [3x6 double]
      ScaleValues: [3.40097054256801e-009;1;1;1]
 PersistentMemory: false
```

**3** A number of methods can be used to view and manipulate the Hd1 dfilt object. Try the info command:

```
info(Hd1)           % Displays filter information

Discrete-Time IIR Filter (real)
```



```

-----
Filter Structure      : Direct-Form II, Second-Order Sections
Number of Sections  : 3
Stable               : Yes
Linear Phase        : No

```

- 4** You can open FVTool from the MATLAB command line and specify display parameters as follows.

```

F = fvtool(Hd, 'Analysis', 'magnitude') % Open FVTool with
                                         % magnitude display
set(F, 'FrequencyScale', 'Log')        % Change to log scale

```

This produces the same display as step 5 of “Viewing the Filter in FVTool” on page 4-11 above.

- 5** Now using the MATLAB command line, create some discrete white Gaussian noise data, which you can then filter using the filter bank.

```

rand; % Initialize random number generator
Nx = 100000; % Number of noise data points
xw = randn(Nx,1); % Create white noise
for i=1:10,
    yw(:,i)=filter(Hd(i),xw); % Filter the white noise through
end % the entire filter bank.
% (:,i) means all rows of column i

```

---

**Note** Do not delete this filtered data. You will use it in the Spectral Analysis section.

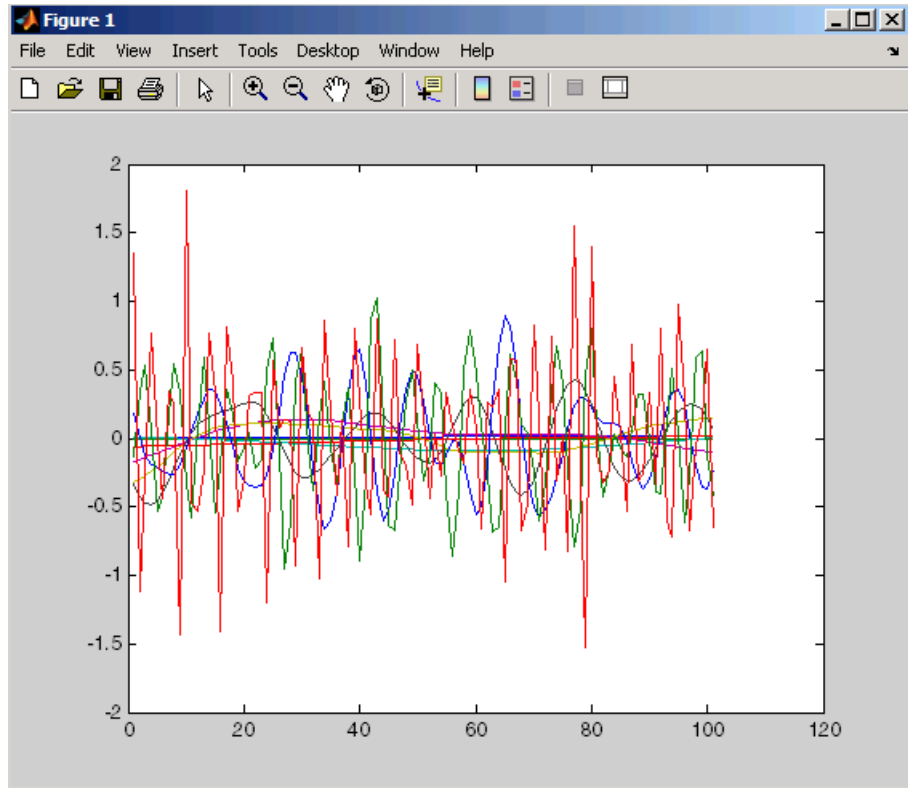
---

- 6** Plot the filtered data.

```

plot(yw)

```



The next section discusses spectral analysis, where you analyze this data.

## Designing Filters using Command Line Functions

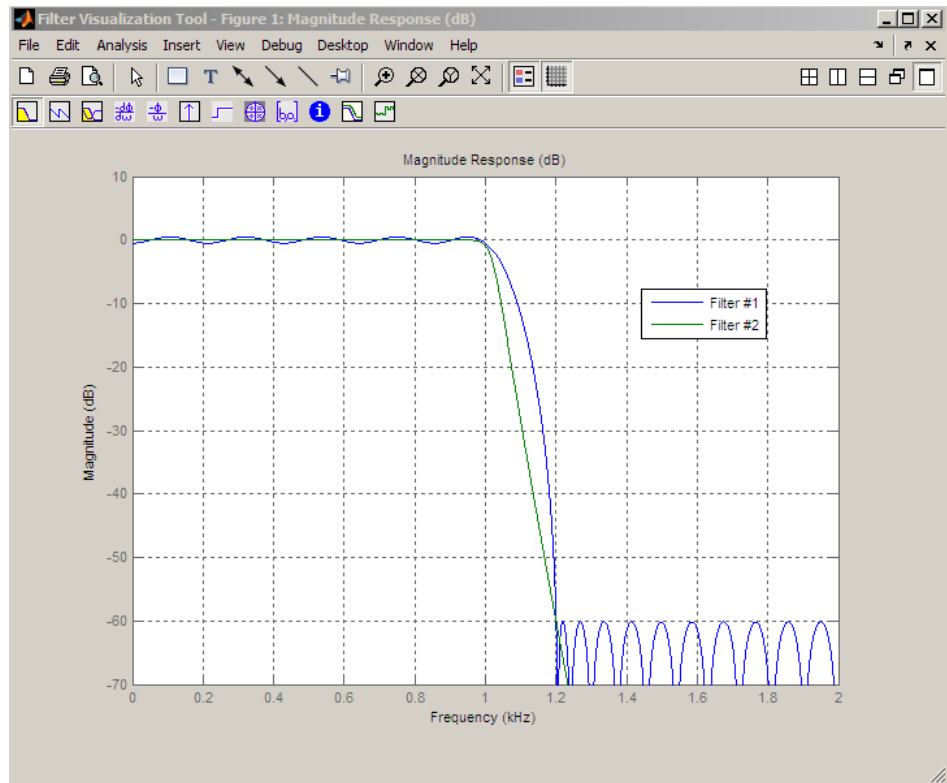
Beginning with R2009a, users can specify and design filters at the command line using `design`. The use of `fdesign` and `design` provides a powerful and efficient way to specify and implement digital filters. With `fdesign` and `design`, digital filter design is a two-step process. In the first step, the user specifies the desired characteristics of the filter and saves those specifications in a Filter Specification Object. In the second step, the user implements the filter as a `dfilt` object, which can then be used to filter data. As an example of this two-step process, we will design a lowpass filter for data sampled at 20 kHz. The desired passband frequency is 1 kHz with a stopband frequency of 1.2 kHz. We will limit the passband ripple to 1 dB and require 60 dB of attenuation between the passband and stopband frequencies.

- 1 To specify the filter use `fdesign.lowpass` with the parameters given above. You can copy and paste the following code at the MATLAB command prompt.

```
d=fdesign.lowpass('Fp,Fst,Ap,Ast',1000,1200,1,60,20000);
```

- 2 To design the filter use `design` with the appropriate design methods. In this example, we create FIR equiripple and IIR Butterworth designs and compare the filters' magnitude responses.

```
Hd1=design(d,'equiripple'); %FIR equiripple design
Hd2=design(d,'butter'); %Butterworth design
Hd=[Hd1 Hd2];%filter object with both designs
%compare filters
fvtool(Hd,'legend','on'); axis([0 2 -70 10])
```



To determine which filter design methods are available for a given Filter Specification Object, use `designmethods`. For the lowpass filter example above, you have a choice of two FIR and four IIR digital filter designs.:

```
designmethods(d)  
Design Methods for class fdesign.lowpass (Fp,Fst,Ap,Ast):
```

```
butter  
cheby1  
cheby2  
ellip  
equiripple  
kaiserwin
```

For more detailed information on filter specification and implementation objects see “Designing a Filter in Fdesign — Process Overview”.

### Where to Find More Information

The previous sections described how to use the fundamental features of FDATool, FVTool, and the `fdesign` and `design` commands. For more advanced information and more complex examples, refer to other sections of Signal Processing Toolbox online help or Signal Processing Toolbox documentation available on The MathWorks Web site ([www.mathworks.com](http://www.mathworks.com)).

# Spectral Analysis

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- “Introduction” on page 5-2
- “Creating a Spectral Analysis Object” on page 5-4
- “Generating a Spectrum” on page 5-6
- “Changing Spectral Analysis Object Property Values” on page 5-9
- “Measuring Signal Power” on page 5-11
- “Where to Find More Information” on page 5-15

## Introduction

In this section...
“Spectral Analysis Examples” on page 5-2
“Spectral Estimators” on page 5-2
“Spectral Analysis Algorithms” on page 5-2
“Spectral Analysis Objects” on page 5-3

### Spectral Analysis Examples

This section has two major examples. The first example shows you how to compute and display a mean-square spectrum. The second example shows you how to measure the average power of a signal.

---

**Note** The examples in this section use filters and data you created in Chapter 4, “Filter Design with the FDATool GUI”.

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### Spectral Estimators

Spectral analysis includes three types of spectral estimators — power spectral density (PSD), mean-square spectrum (MSS) and pseudo spectrum.

- Power spectral density (`psd`) measures power per unit of frequency and has power/frequency units.
- Mean-square (power) spectrum (`msspectrum`) measures power at a specific frequency.
- Pseudospectrum (`pseudospectrum`) returns a pseudo spectrum that does not have any units.

### Spectral Analysis Algorithms

Signal Processing Toolbox software provides algorithms to compute the above spectral estimators. The following table indicates which algorithms are available to compute each type of estimator and produce a spectrum object.



For general information on objects, see *Object-Oriented Programming*. For details on spectrum objects, see the `spectrum` reference page.

<b>Spectral Estimator</b>	<b>Algorithms</b>
Power spectral density ( <code>psd</code> )	Burg ( <code>spectrum.burg</code> ), Covariance ( <code>spectrum.cov</code> ), Modified covariance ( <code>spectrum.mcov</code> ), Thomson multitaper method (MTM) ( <code>spectrum.mtm</code> ), Periodogram ( <code>spectrum.periodogram</code> ), Welch ( <code>spectrum.welch</code> ), Yule-Walker autoregressive ( <code>spectrum.yulear</code> ) See also <code>dspdata.psd</code>
Mean-square spectrum ( <code>msspectrum</code> )	Periodogram ( <code>spectrum.periodogram</code> ), Welch ( <code>spectrum.welch</code> ) See also <code>dspdata.msspectrum</code>
Pseudo spectrum ( <code>pseudospectrum</code> )	Eigenvector ( <code>spectrum.eigenvector</code> ), MUSIC (Multiple Signal Classification) ( <code>spectrum.music</code> ) See also <code>dspdata.pseudospectrum</code>

## Spectral Analysis Objects

Spectral analysis objects contain property values for the particular algorithm. To calculate a spectrum estimate, you first create an estimator object using one of the algorithms (e.g., `h = spectrum.burg`), and then pass it to one of the spectrum estimator objects with your data (e.g., `Hpsd = psd(h, x)`). In this example, `h` is a Burg spectrum object, `x` is the original input data, and `Hpsd` is the resulting PSD.

For more information and examples, see the *Getting Started with Spectral Analysis Objects* demo.

## Creating a Spectral Analysis Object

Continuing the example in Chapter 4, “Filter Design with the FDATool GUI”, you will create a spectral analysis object that uses default property values, and then, use it to generate a mean-square spectrum of the data filtered through the octave-band filter bank.

Create a Welch’s method spectrum object using default values by typing the following at the MATLAB command line.

```
h = spectrum.welch

h =
  EstimationMethod: 'Welch'
    SegmentLength: 64
    OverlapPercent: 50
      WindowName: 'Hamming'
    SamplingFlag: 'symmetric'
```

If you want to specify parameters instead of using default values, you use syntax similar to the following, which uses a Kaiser window and a segment length of 66. Note that the Kaiser window has an additional parameter (Beta). See the `spectrum.welch` reference page for more information.

```
h = spectrum.welch('kaiser',66,50)

h =
  EstimationMethod: 'Welch'
    SegmentLength: 66
    OverlapPercent: 50
      WindowName: 'Kaiser'
      Beta: 0.5000
```

---

**Note** For the rest of this example, use the default `h = spectrum.welch` object.

---

You can also change some of the property values of a created spectrum object. See “Changing Spectral Analysis Object Property Values” on page 5-9 for more information.

## Generating a Spectrum

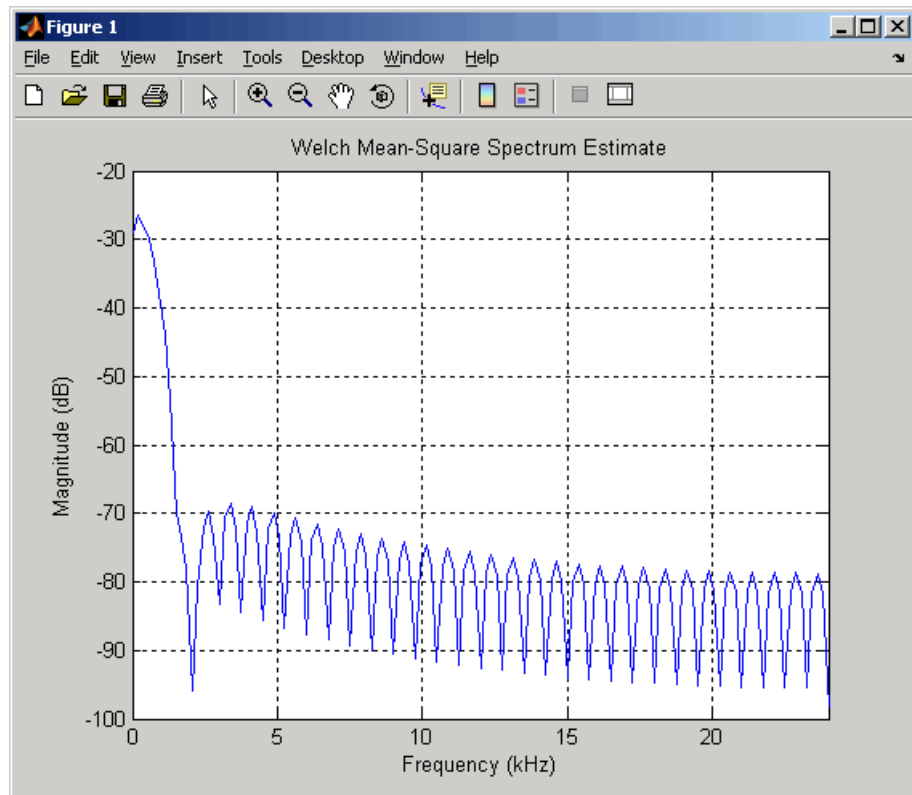
To generate a spectrum, you use a spectral estimation method on your spectrum object and data. Using the data, `yw`, created in Chapter 4, “Filter Design with the FDATool GUI”, create a mean-square spectrum, by typing

```
Fs = 48000;      % Set the sampling frequency

h = spectrum.welch; % Create spectrum object
msPyyw = msspectrum(h,yw(:,1),'Fs',Fs)

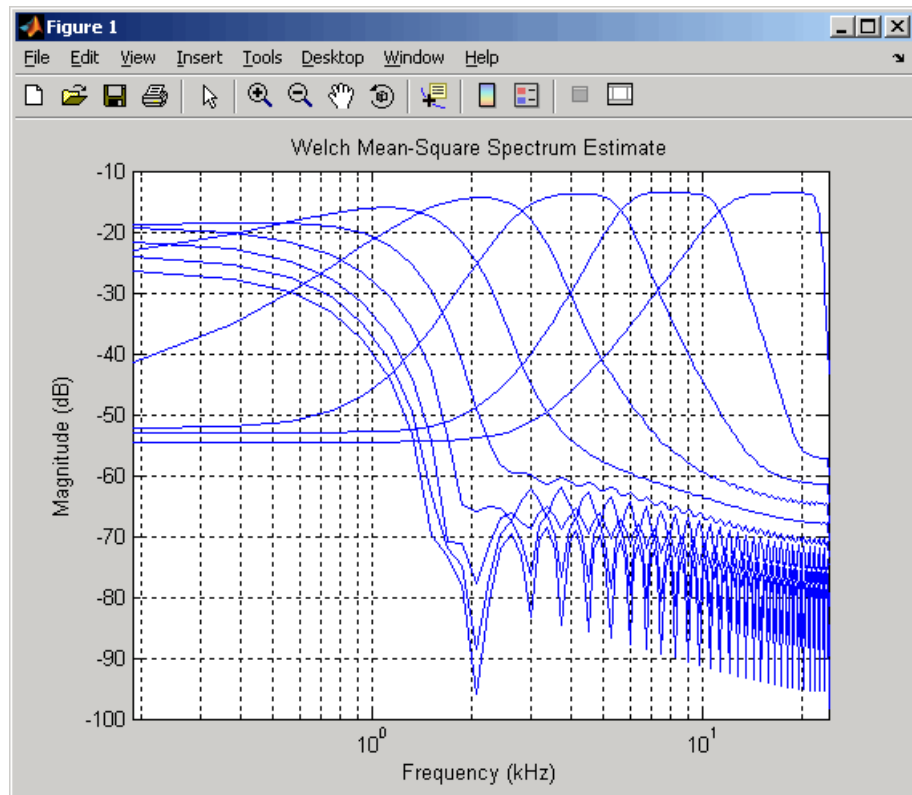
msPyyw =
           Name: 'Mean-Square Spectrum'
           Data: [129x1 double]
      SpectrumType: 'Onesided'
NormalizedFrequency: false
                Fs: 48000
      Frequencies: [129x1 double]

plot(msPyyw)
```



To see the spectra for all the filters, type

```
for i=1:10
    msspectrum(h,yw(:,i),'Fs',Fs);
    hold on;           % Plot each spectrum in the same
end                   % figure window
set(gca,'Xscale','log') % Change to log scale
```



The syntax for using `psd`, `msspectrum`, or `pseudospectrum` is the same. As shown in the example above, the first input is the spectrum object (`h`) and the second input (`yw`) is the signal to measure, followed by any settable properties using property-value pairs (e.g., `'Fs'`, `Fs`). To set property-value pairs, you list the property first and then the value for that property.

## Changing Spectral Analysis Object Property Values

### In this section...

“Using the set command to Set Property Values” on page 5-9

“Using Options Objects to Set Property Values” on page 5-10

### Using the set command to Set Property Values

After you have created a spectrum object, you can use the `set` method or dot notation to change any of its properties, except its `EstimationMethod` property. (Since `EstimationMethod` is the central property of a particular spectrum object, you cannot change it.) To change the window from Hamming (used in the Welch object created above) to Chebyshev, use dot notation as follows:

```
h.WindowName = 'Chebyshev'

h =
  EstimationMethod: 'Welch'
  SegmentLength: 66
  OverlapPercent: 50
  WindowName: 'Chebyshev'
  SidelobeAtten: 100
```

or use the `set` method,

```
set(h, 'WindowName', 'Chebyshev')
```

As illustrated above, Chebyshev windows have a sidelobe attenuation parameter that automatically appears in the list of properties. To change a window parameter, you must use a cell array containing the window name and parameter value, such as,

```
h = spectrum.welch({'Chebyshev', 80})

h =
  EstimationMethod: 'Welch'
  SegmentLength: 64
  OverlapPercent: 50
```

```
WindowName: 'Chebyshev'  
SidelobeAtten: 80
```

To view the amplitude and magnitude responses of various windows, type `wintool` to open the Window Design and Analysis Tool.

## Using Options Objects to Set Property Values

Another way to set properties for a particular estimation method is to use the options object associated with that method. For example, use the following syntax to create an options object from the spectrum object for use with the mean-square spectrum:

```
Hopts = msspectrumopts(h) % Create options object  
  
Hopts =  
          NFFT: 'Nextpow2'  
NormalizedFrequency: true  
          Fs: 'Normalized'  
SpectrumType: 'Onesided'  
CenterDC: false
```

You can then change any of the options properties using `set`, followed by the options object and property-value pair(s), such as

```
set(Hopts, 'Fs', 48000)
```

To pass the options object to the first `msspectrum` in the filtered data, use

```
msspectrum(h, yw(:, 1), Hopts)
```

Options objects that correspond to `psd` and `pseudospectrum` are `psdopts` and `pseudospectrumopts`, respectively.



## Measuring Signal Power

This section shows you how to measure the average power of a deterministic periodic signal. This type of signal is continuous in time, but produces a discrete power spectra. A signal made up of sinusoids is an example of a power signal that has infinite energy, but finite average power. The example below shows how to measure and estimate the average power of a single sinusoidal signal with a peak amplitude of 1 v and a frequency component at 128 Hz.

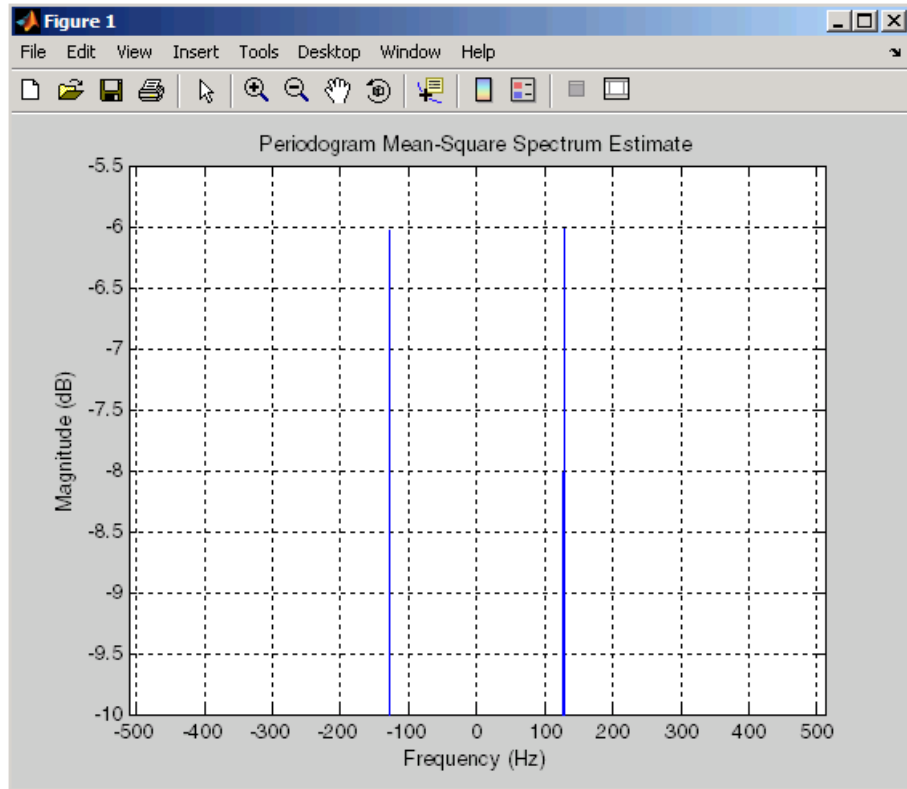
First, you measure the signal's average power using a periodogram spectrum object, and then calculate and plot the mean-square (power) spectrum.

```
Fs = 1024;                % Sampling frequency
t = 0:1/Fs:1-(1/Fs);     % Time vector
A = 1;                   % Peak amplitude
F1 = 128;                 % Hz
x = A*sin(2*pi*t*F1);    % Sinusoidal signal

hp = spectrum.periodogram('hamming'); % Create periodogram

% Create options object and set properties
hpopts = psdopts(hp,x);
set(hpopts,'Fs',Fs,'SpectrumType','twosided','centerdc',true);

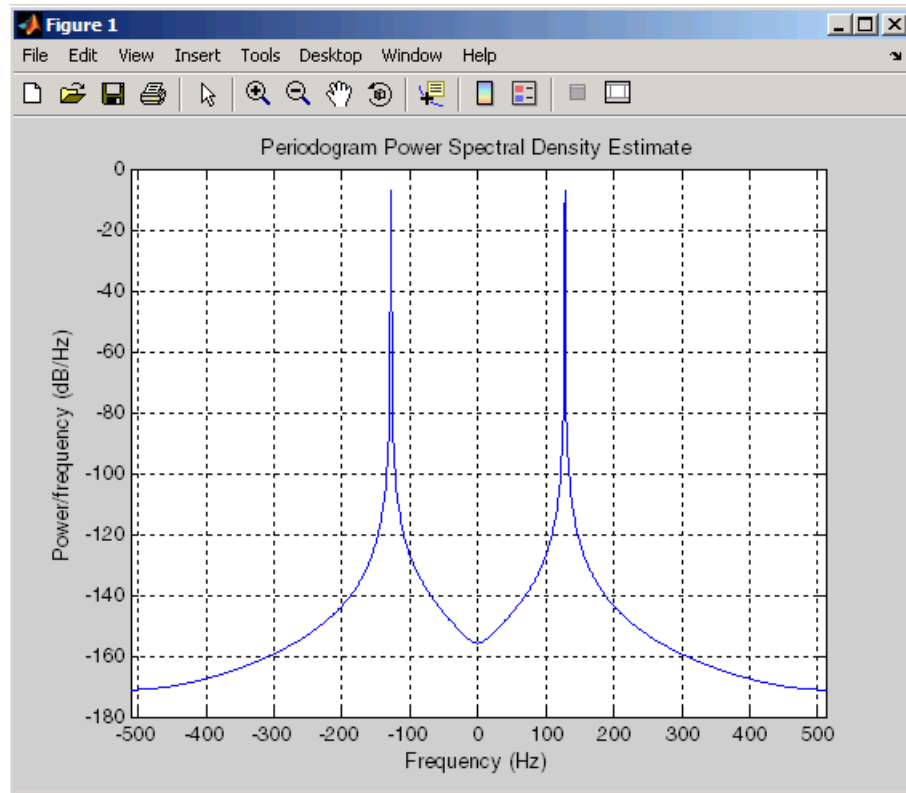
msspectrum(hp,x,hpopts);
v = axis; axis([v(1) v(2) -10 -5.5]); % Zoom in Y.
```



The average power of each complex sinusoid is approximately -6 dB.

Another way to calculate a signal's average power is by "integrating" the area under the power spectral density (PSD) curve. To do this, you use the `psd` method on the spectrum object created above (`hp`) to get a PSD data object, and then use the `avgpower` method.

```
hpsd = psd(hp,x,hopts);  
plot(hpsd);
```



Notice that the peaks of this plot are not the same height as the mean-square spectrum peaks plotted above. The area under the PSD curve is the measure of the average power, not the peak heights. By using the `avgpower` method and converting the result to dB, you can see that the average power is the same for both of them.

```
power_freqdomain = avgpower(hpsd)
```

```
power_freqdomain =
```

```
0.5000
```

According to Parseval's theorem, the total average power in a sinusoid is the same, whether it's computed in the time domain or the frequency domain.

You can verify the signal's estimated total average power by summing the signal in the time domain.

```
power_timedomain = sum(abs(x).^2)/length(x)
```

```
power_timedomain =
```

```
0.5000
```

Now, converting this linear value to a logarithmic value (and taking only the positive frequencies), you see that the average power is the same as that shown in the mean-square spectrum plot above.

```
10*log10(power_freqdomain/2)
```

```
ans =
```

```
-6.0206
```

## Where to Find More Information

The previous sections described how to use the fundamental features of spectral analysis. For more advanced information and more complex examples, refer to other sections of Signal Processing Toolbox online help or Signal Processing Toolbox documentation available on The MathWorks Web site ([www.mathworks.com](http://www.mathworks.com)).



## A

- aliasing
  - sinc functions 2-10
- analog signals. *See* signals
- annotation 4-15
- ASCII files
  - importing 2-12
- average power 5-11

## B

- bandpass filters 4-3
- buttons
  - filter analysis 4-8

## C

- cell array 5-9
- chirp signals 2-7
- continuous signals. *See* signals
- cycles
  - duty 2-6

## D

- data
  - importing 2-12
  - matrices 2-2
  - multichannel matrix 2-2
  - multichannel signals 2-6
  - supported types 1-3
  - time vectors 2-4
  - vectors 2-2
- demos 1-9
  - FDATool 4-2
  - FVTool 4-15
  - spectral analysis 5-3
- design a filter 3-4
  - filterbuilder 3-9
- dfilt 4-18

- digital signals 1-4
- Dirichlet functions
  - definition 2-10
- dot notation 5-9
- double-precision inputs 1-3
- duty cycles 2-6

## E

- export 4-17
- extensibility 1-8

## F

- fdatool GUI
  - analysis buttons 4-8
  - group delay 4-8
  - impulse response 4-8
  - magnitude response 4-8
  - phase delay 4-8
  - phase response 4-8
  - pole-zero plots 4-8
  - step response 4-8
- files
  - M 2-12
  - MAT 2-12
  - MEX 2-12
- filter coefficients
  - icon 4-8
- filter information
  - icon 4-8
- filterbuilder 3-9
- filters
  - linear time-invariant digital 1-4
  - octave-band 4-3
- fopen function 2-12
- fread function 2-12
- functions
  - Dirichlet 2-10
  - sinc 2-9

**G**

gauspuls function  
    pulse trains 2-8  
getting started 3-2  
getting started example 3-2  
graphical user interface (GUI) 1-7  
    *See also* sptool GUI, fdatool GUI, wintool  
    GUI, fvtool GUI, wvtool GUI  
group delay  
    icon 4-8

**I**

import  
    data 2-12  
impulse 2-5  
impulse response  
    icon 4-8  
inverse Fourier transforms  
    *See* sinc function 2-9

**M**

M-files  
    expanding a toolbox 1-8  
magnitude and phase response  
    icon 4-8  
magnitude response  
    icon 4-8  
MAT-files  
    converting to 2-12  
    importing 2-12  
matrices  
    data 2-3  
matrix 2-2  
MEX-files 2-12  
multichannel data 2-6

**N**

noise data 4-19

**O**

octave-band filters 4-3  
options object 5-10

**P**

P-V pairs 5-8  
periodogram 5-11  
phase delay  
    icon 4-8  
phase response  
    icon 4-8  
pole-zero plot  
    icon 4-8  
power spectral density 5-2  
power spectrum 5-2  
property values  
    changing 5-9  
property-value pairs 5-8  
pulse trains  
    example 2-8  
    pulstran function 2-8

**R**

ramp 2-5  
references  
    DSP 2-14

**S**

sawtooth function  
    example 2-6  
sawtooth wave 2-6  
set 5-9  
signal  
    average power 5-11



- signals
    - adding noise 2-4
    - aperiodic 2-7
    - chirp 2-7
    - continuous (analog) 1-4
    - diric function 2-10
    - discrete (digital) 1-4
    - generating 2-5
    - multichannel 2-6
    - periodic 2-6
    - plotting 2-4
    - pulstran function 2-8
    - representing 2-2
    - sawtooth 2-6
    - sinc 2-9
    - sinusoidal 2-4
    - square wave 2-6
  - single-precision inputs 1-3
  - spectrum
    - creating 5-6
    - mean-square spectrum 5-2
    - options object 5-10
    - PSD 5-2
    - pseudo spectrum 5-2
  - spectrum object
    - creating 5-4
    - Welch 5-4
  - sptool GUI
    - data entering 2-12
  - square function
    - example 2-6
  - square wave
    - See* square function 2-6
  - step 2-5
  - step response
    - icon 4-8
- T**
- time vectors 2-4
  - toolbox
    - getting started 3-2
  - tools
    - interactive GUIs 1-7
- U**
- unit impulse function 2-5
  - unit ramp function 2-5
  - unit sample multichannel 2-6
  - unit step function 2-5
- V**
- vectors
    - data representation 2-2
    - waveform generation 2-4
- W**
- waveforms. *See* signals
  - Welch spectrum object
    - example 5-4
  - white noise 2-4
- Z**
- zero-phase response 4-8