In [ ]:
```
cd matlab
pwd
```

Introduction to Filters

Scope and Background Reading

This session is Based on the section **Filtering** from Chapter 5 of Benoit Boulet, Fundamentals of Signals and Systems (https://ebookcentral.proquest.com/lib/swansea-ebooks/reader.action?ppg=221&docID=3135971&tm=1518715953782) from the **Recommended Reading List**.

This material is an introduction to analogue filters. You will find much more in-depth coverage on Pages 11-1—11-48 of Karris (https://ebookcentral.proquest.com/lib/swansea-ebooks/reader.action?ppg=429&docID=3384197&tm=1518716026573).

Agenda

- Frequency Selective Filters
- Ideal low-pass filter
- Butterworth low-pass filter
- High-pass filter
- Bandpass filter

Introduction

- Filter design is an important application of the Fourier transform
- Filtering is a rich topic often taught in graduate courses so we give only an introduction.
- Our introduction *will* illustrate the usefulness of the frequency domain viewpoint.
- We will explore how filters can shape the spectrum of a signal.

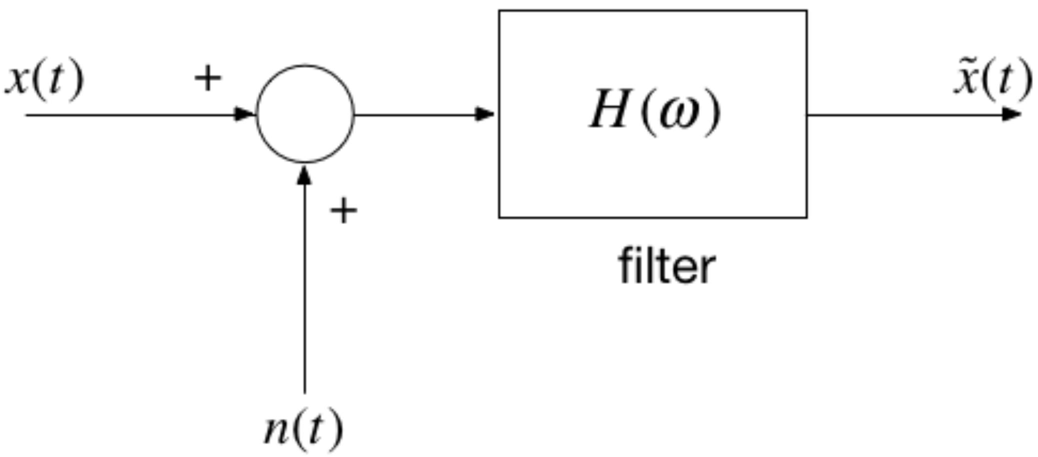
Other applications of the Fourier transform are sampling theory (introduced next week) and modulation.

Frequency Selective Filters

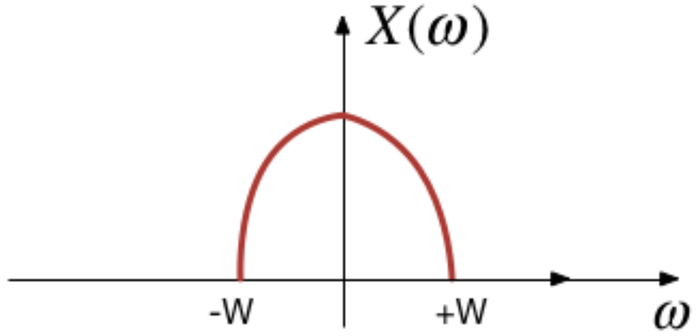
An ideal frequency-selective filter is a system that let's the frequency components of a signal through undistorted while components at other components are completely cut off.

- The range of frequencies which are let through belong to the **pass Band**
- The range of frequencies which are cut-off by the filter are called the **stopband**
- A typical scenario where filtering is needed is when noise $n(t)$ is added to a signal $x(t)$ but that signal has most of its energy outside the bandwidth of a signal.

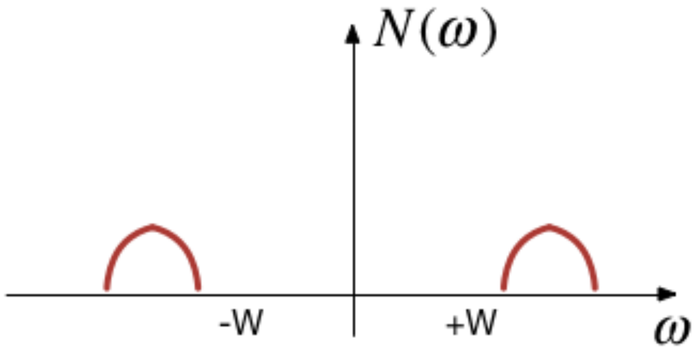
Typical filtering problem



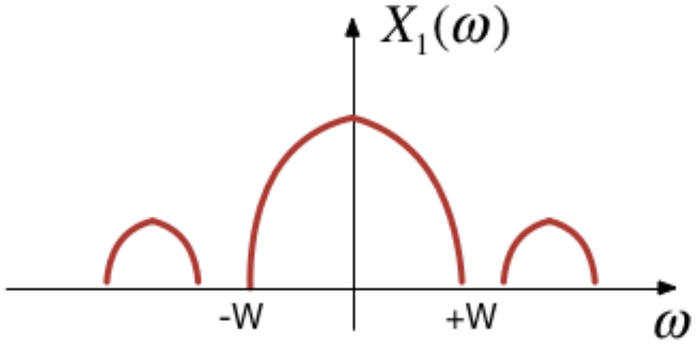
Signal



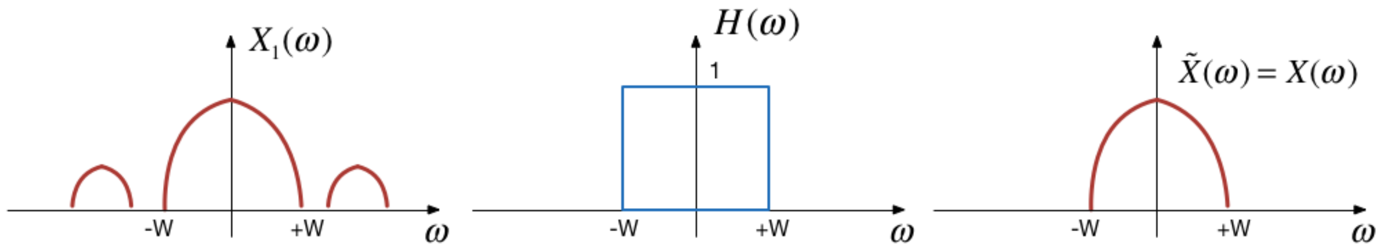
Out-of Bandwidth Noise



Signal plus Noise



Filtering



Motivating example

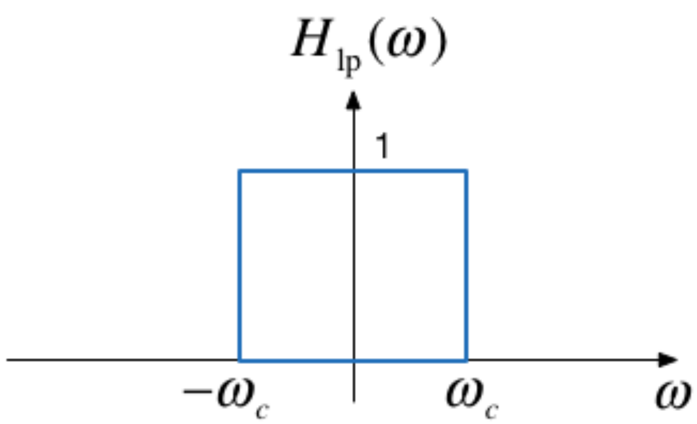
See the notes in the [OneNote Class Room notebook (https://swanseauniversity-my.sharepoint.com/personal/c_p_jobling_swansea_ac_uk/_layouts/15/WopiFrame.aspx?sourcedoc={540d6da0-390f-4f0a-914e-b6445f76b02a}&action=edit&wd=target%28%2F%2F_Content%20Library%2FClasses%2FWeek%207.on ba94-4714-b276-8eb1269b0b5b%2FBefore%20Class%7Ce5ad343a-e348-0141-8096-60e0ca201e57%2F%29)] or on Blackboard.

Ideal Low-Pass Filter

An ideal low pass filter cuts-off frequencies higher than its *cutoff frequency*, ω_c.

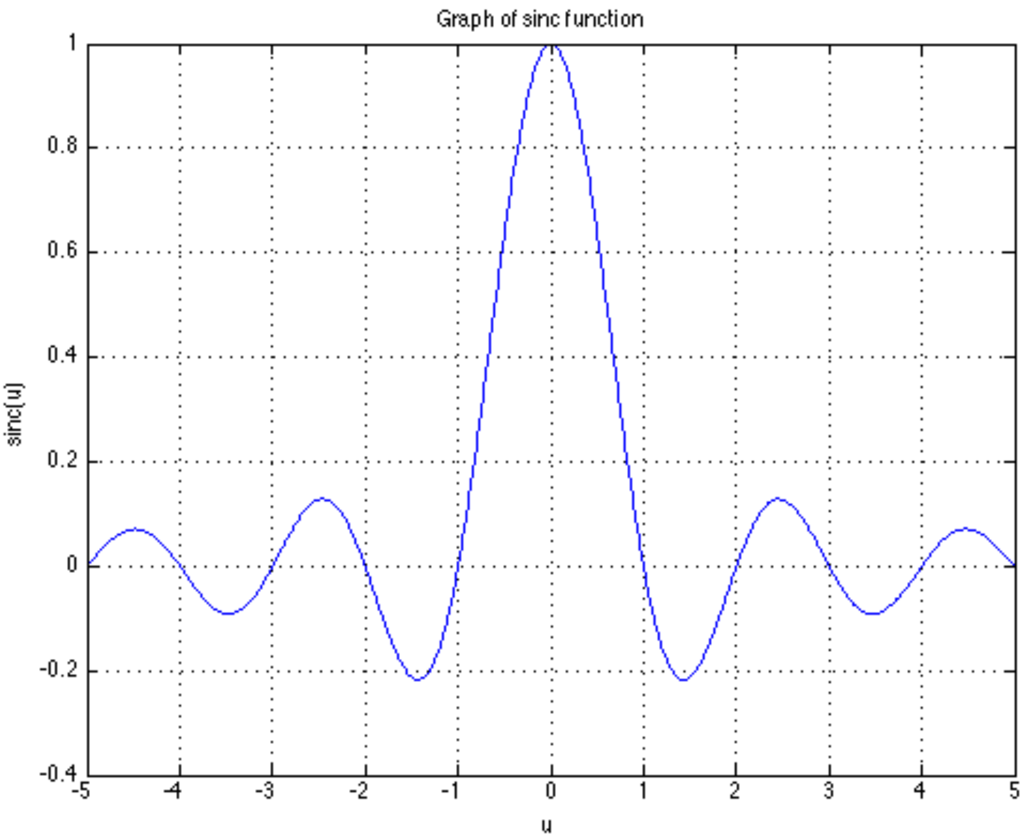
$$H_{\mathrm{lp}}(\omega) = \begin{cases} 1, & |\omega| < \omega_c \\ 0, & |\omega| \geq \omega_c \end{cases}$$

Frequency response



Impulse response

$$h_{\text{lp}}(t) = \frac{\omega_c}{\pi}\text{sinc}\left(\frac{\omega_c}{\pi}t\right)$$



Filtering is Convolution

The output of an LTI system with impulse response

$$h(t) \Leftrightarrow H(\omega)$$

subject to an input signal

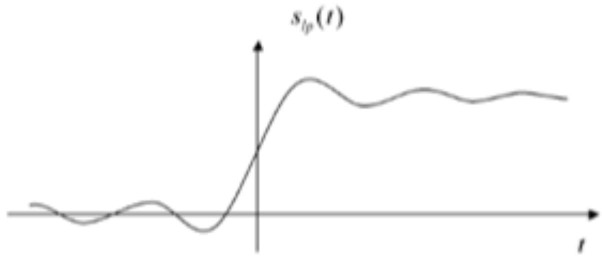
$$x(t) \Leftrightarrow X(\omega)$$

is given by

$$y(t) = h(t) * x(t) \Leftrightarrow Y(\omega) = H(\omega)X(\omega)$$

Issues with the "ideal" filter

This is the step response:



(reproduced from Boulet Fig. 5.23 p. 205)

Ripples in the impulse resonse would be undesireable, and because the impulse response is non-causal it cannot actually be implemented.

Butterworth low-pass filter

N-th Order Butterworth Filter

$$|H_B(\omega)| = \frac{1}{\left(1 + \left(\frac{\omega}{\omega_c}\right)^{2N}\right)^{\frac{1}{2}}}$$

Remarks

- DC gain is $|H_B(j0)| = 1$
- Attenuation at the cut-off frequency is $|H_B(j\omega_c)| = 1/\sqrt{2}$ for any N

More about the Butterworth filter: Wikipedia Article (http://en.wikipedia.org/wiki/Butterworth_filter)

Example 5: Second-order BW Filter

The second-order butterworth Filter is defined by is Charecteristic Equation (CE):

$$p(s) = s^2 + \omega_c\sqrt{2}s + \omega_c^2 = 0^*$$

Calculate the roots of $p(s)$ (the poles of the filter transfer function) in both Cartesian and polar form.

Note: This has the same characteristic as a control system with damping ratio $\zeta = 1/\sqrt{2}$ and $\omega_n = \omega_c$!

Solution

Example 6

Derive the differential equation relating the input $x(t)$ to output $y(t)$ of the 2nd-Order Butterworth Low-Pass Filter with cutoff frequency ω_c.

Solution

Example 7

Determine the frequency response $H_B(\omega) = Y(\omega)/X(\omega)$

Solution

Magnitude of frequency response of a 2nd-order Butterworth Filter

In [2]:
```
wc = 100;
```

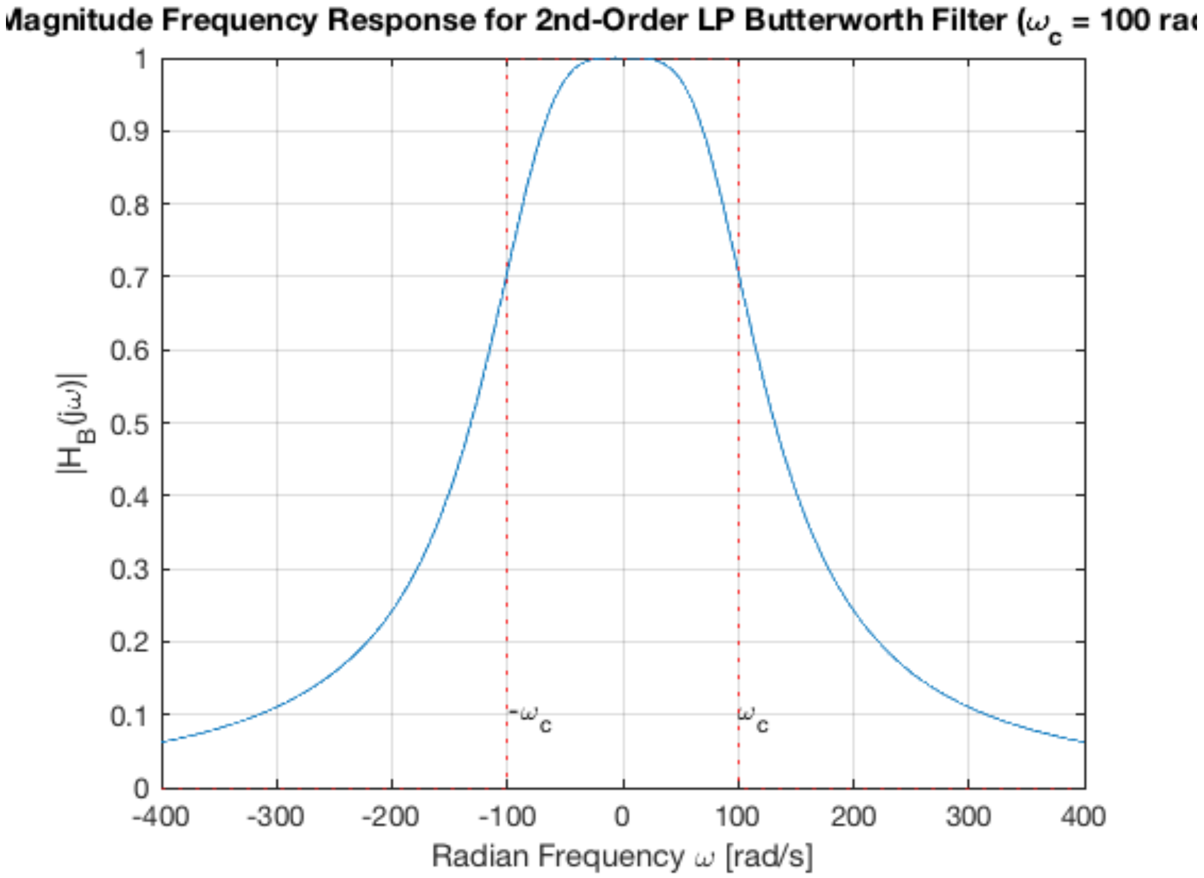
Transfer function

In [3]:
```
H = tf(wc^2,[1, wc*sqrt(2), wc^2])
```

```
H =

          10000
  ---------------------
  s^2 + 141.4 s + 10000

Continuous-time transfer function.
```

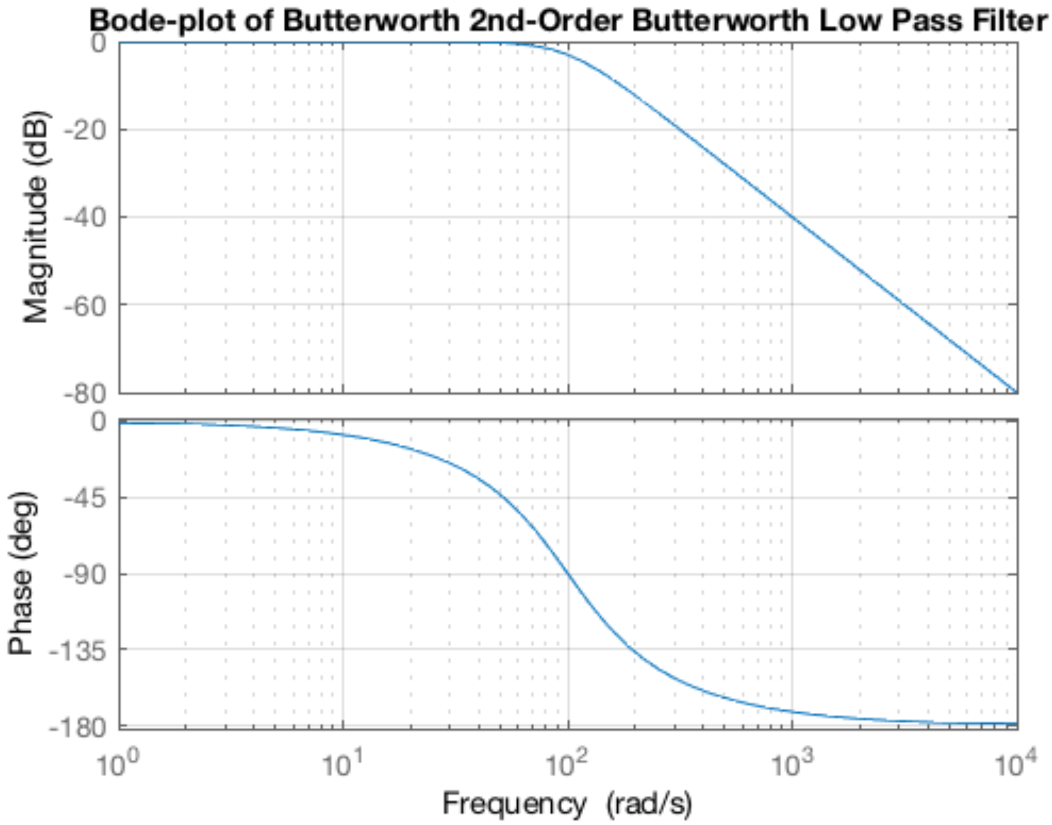
Magnitude frequency response

In [4]:
```
w = -400:400;
mHlp = 1./(sqrt(1 + (w./wc).^4));
plot(w,mHlp)
grid
ylabel('|H_B(j\omega)|')
title('Magnitude Frequency Response for 2nd-Order LP Butterworth Fi
lter (\omega_c = 100 rad/s)')
xlabel('Radian Frequency \omega [rad/s]')
text(100,0.1,'\omega_c')
text(-100,0.1,'-\omega_c')
hold on
plot([-400,-100,-100,100,100,400],[0,0,1,1,0,0],'r:')
hold off
```



Bode plot

In [5]:
```
bode(H)
grid
title('Bode-plot of Butterworth 2nd-Order Butterworth Low Pass Filt
er')
```



Example 8

Determine the impulse and step responsew of a butterworth low-pass filter.

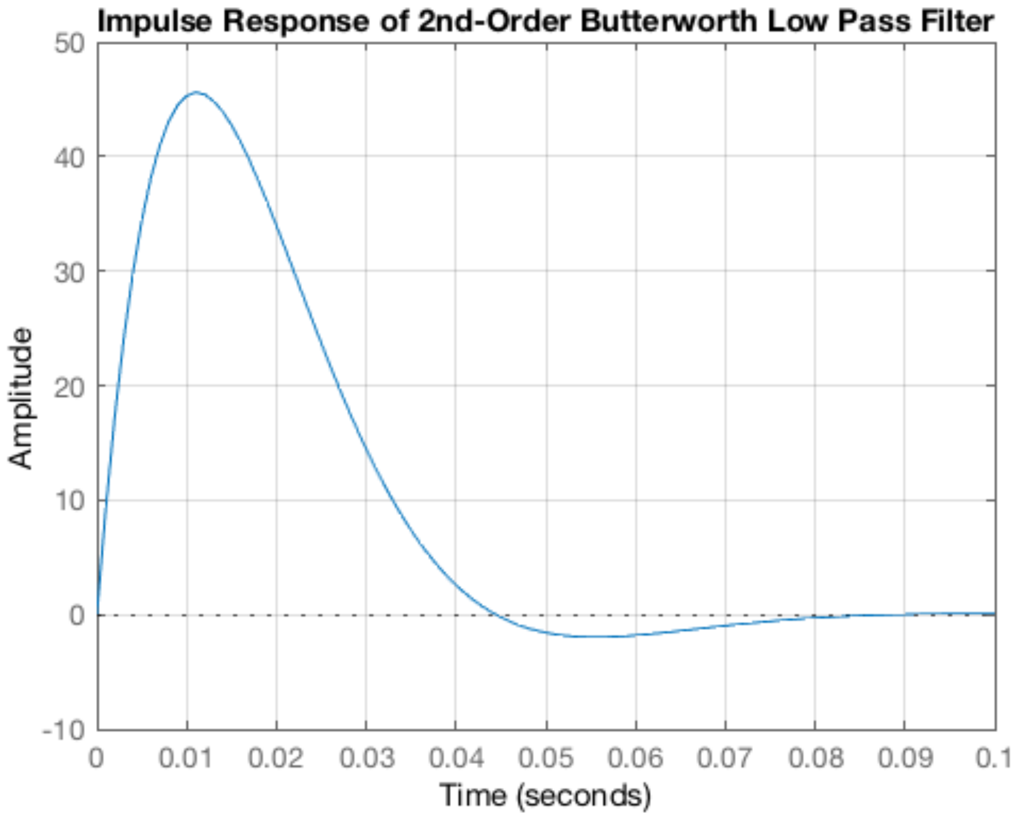
You will find this Fourier transform pair useful:

$$e^{-at}\sin\omega_0 t\; u_0(t) \Leftrightarrow \frac{\omega_0}{(j\omega + a)^2 + \omega_0^2}$$

Solution

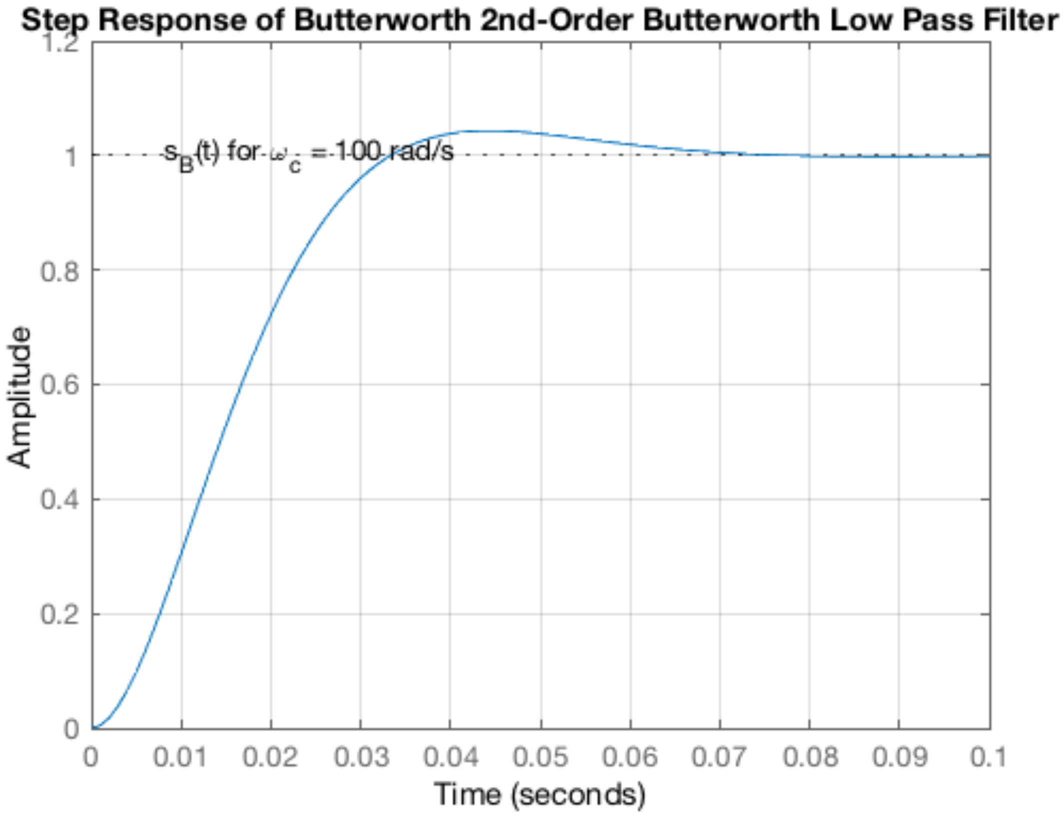
Impulse response

In [6]:
```
impulse(H,0.1)
grid
title('Impulse Response of 2nd-Order Butterworth Low Pass Filter')
```



Step response

In [7]:
```
step(H,0.1)
title('Step Response of Butterworth 2nd-Order Butterworth Low Pass Filter')
grid
text(0.008,1,'s_B(t) for \omega_c = 100 rad/s')
```

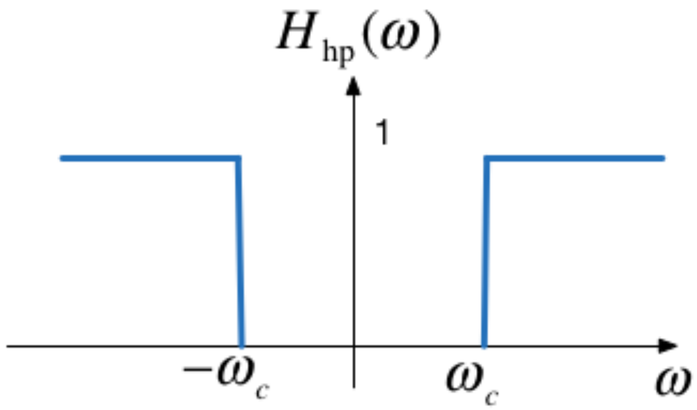


High-pass filter

An ideal highpass filter cuts-off frequencies lower than its *cutoff frequency*, ω_c.

$$H_{\mathrm{hp}}(\omega) = \begin{cases} 0, & |\omega| \leq \omega_c \\ 1, & |\omega| > \omega_c \end{cases}$$

Frequency response



Responses

Frequency response

$$H_{\mathrm{hp}}(\omega) = 1 - H_{\mathrm{lp}}(\omega)$$

Impulse response

$$h_{\mathrm{hp}}(t) = \delta(t) - h_{\mathrm{lp}}(t)$$

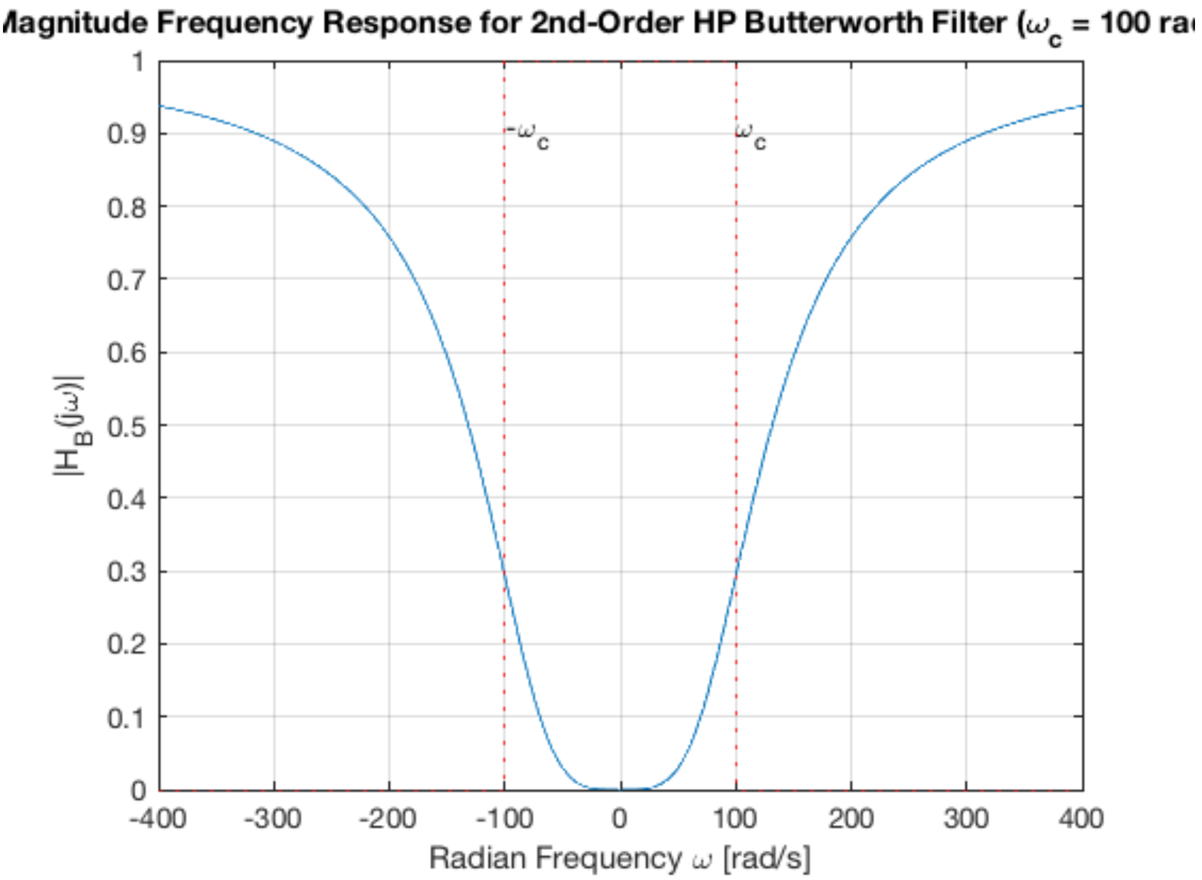
Example 9

Determine the frequency response of a 2nd-order butterworth highpass filter

Solution

Magnitude frequency response

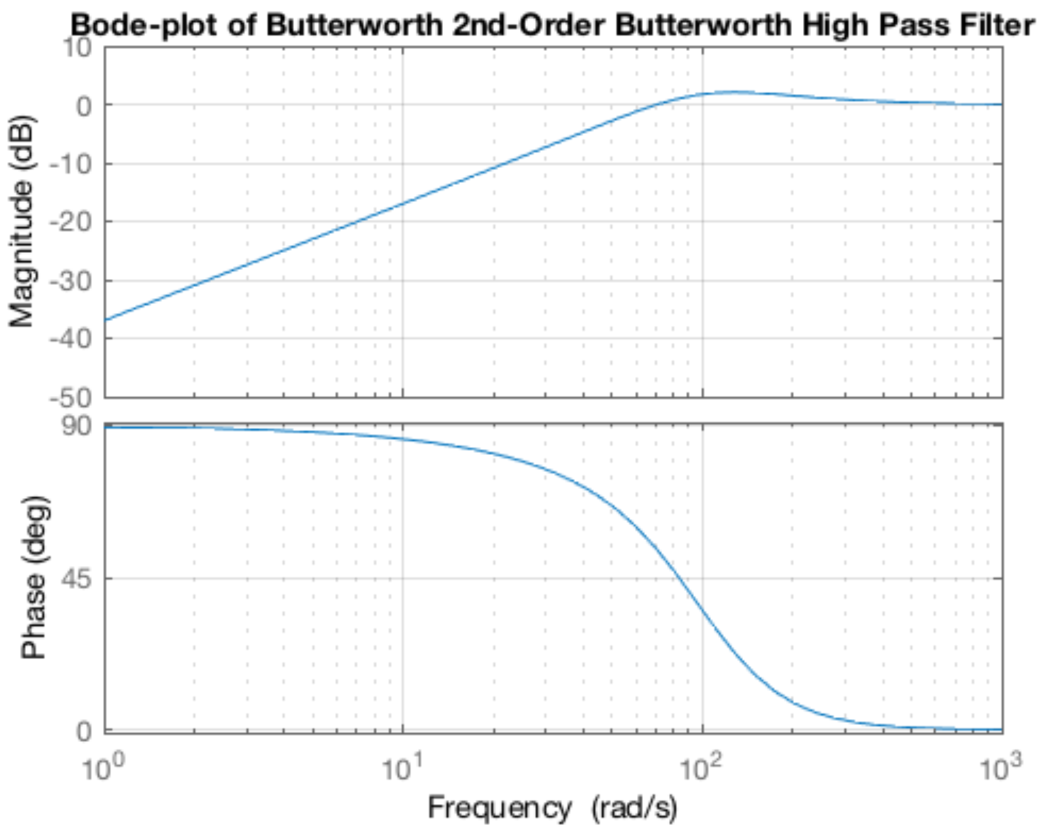
In [8]:
```
w = -400:400;
plot(w,1-mHlp)
grid
ylabel('|H_B(j\omega)|')
title('Magnitude Frequency Response for 2nd-Order HP Butterworth Fi
lter (\omega_c = 100 rad/s)')
xlabel('Radian Frequency \omega [rad/s]')
text(100,0.9,'\omega_c')
text(-100,0.9,'-\omega_c')
hold on
plot([-400,-100,-100,100,100,400],[0,0,1,1,0,0],'r:')
hold off
```



High-pass filter

In [9]:
```
Hhp = 1 - H
bode(Hhp)
grid
title('Bode-plot of Butterworth 2nd-Order Butterworth High Pass Filter')
```

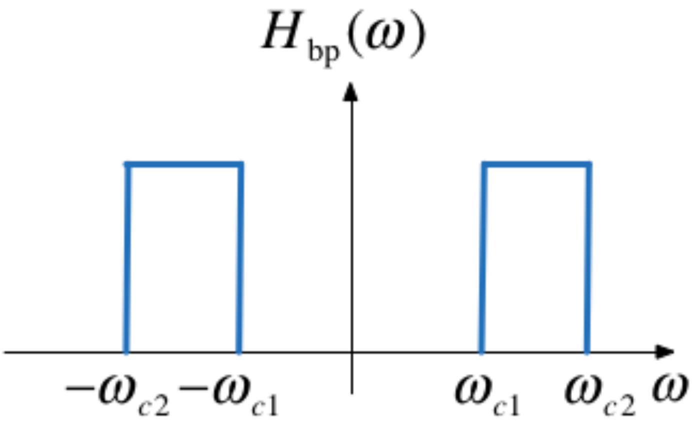
```
Hhp =

       s^2 + 141.4 s
  ---------------------
  s^2 + 141.4 s + 10000

Continuous-time transfer function.
```



Band-pass filter

An ideal bandpass filter cuts-off frequencies lower than its first *cutoff frequency* ω_{c1}, and higher than its second *cutoff frequency* ω_{c2}.

$$H_{\text{bp}}(\omega) = \begin{cases} 1, & \omega_{c1} < |\omega| < \omega_{c2} \\ 0, & \text{otherwise} \end{cases}$$



Bandpass filter design

A bandpass filter can be obtained by multiplying the frequency responses of a lowpass filter by a highpass filter.

$$H_{\mathrm{bp}}(\omega) = H_{\mathrm{hp}}(\omega)H_{\mathrm{lp}}(\omega)$$

- The highpass filter should have cut-off frequency of ω_{c1}

- The lowpass filter should have cut-off frequency of ω_{c2}

To generate all the plots shown in this presentation, you can use butter2_ex.m (matlab/butter2_ex.m)

Summary

- Frequency Selective Filters
- Ideal low-pass filter
- Butterworth low-pass filter
- High-pass filter
- Bandpass filter

Next Lesson – sampling theory