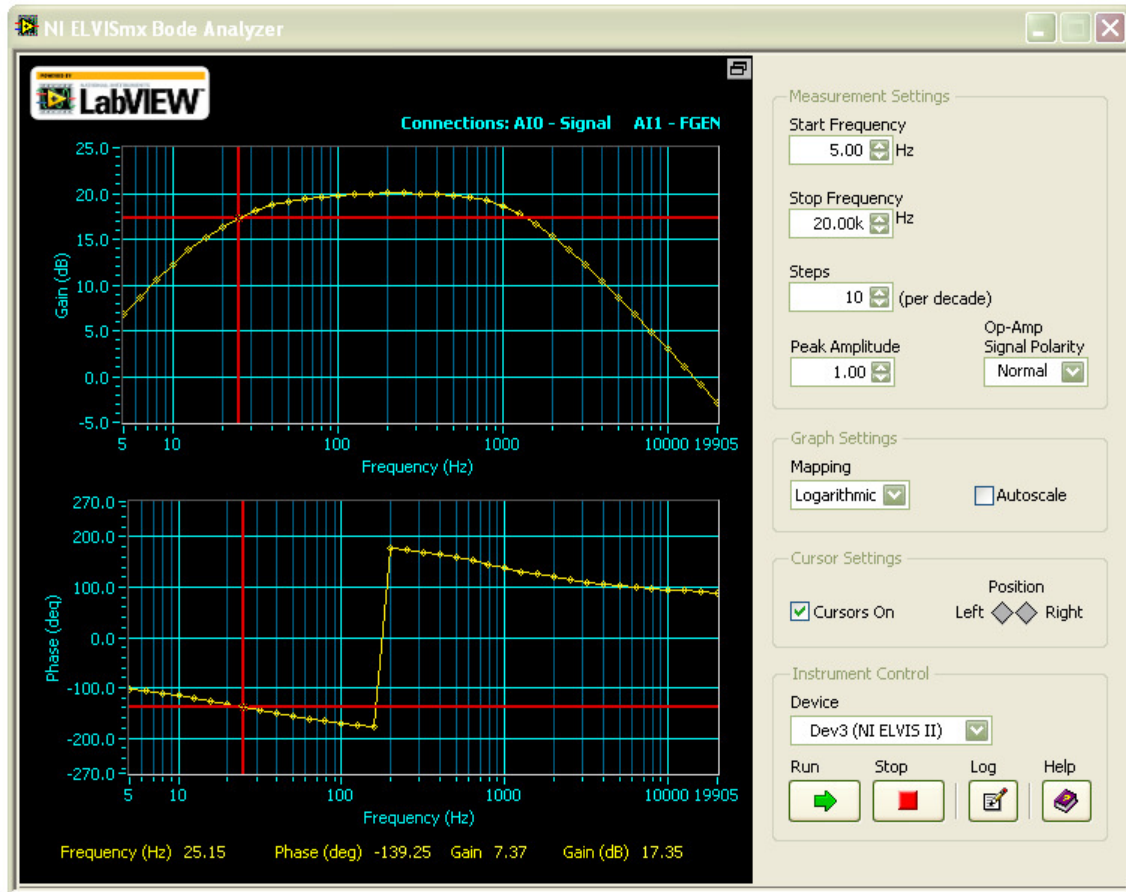# Lab 4 – Op Amp Filters

Figure 4.0. Frequency Characteristics of a BandPass Filter

Adding a few capacitors and resistors to the basic operational amplifier (op amp) circuit can yield many interesting analog circuits such as active filters, integrators, and differentiators. Filters are used to pass specific frequency bands, integrators are used in proportional control, and differentiators are used in noise suppression and waveform generation circuits.

Goal: This lab uses the NI ELVIS II suite of instruments to measure the characteristics of lowpass, highpass, and bandpass filters. Simulate these filters using Multisim with the measured component values. In the lab challenge at the end of this chapter, Multisim is used to design a second order active filter.

Required Soft Front Panels (SFPs)
Digital multimeter (DMM[Ω,C])
Function generator (FGEN)
Oscilloscope (Scope)
Impedance analyzer (Imped)
Bode analyzer (Bode)

Required Components
10 kΩ resistor R_1, (brown, black, orange)
100 kΩ resistor R_f, (brown, black, yellow)
1 µF capacitor C_1
0.01 µF capacitor C_f
741 op amp

Exercise 4.1: Measuring the Circuit Component Values

Complete the following steps to measure the values of the individual components:

1. Launch NI ELVIS II.
2. Select the DMM icon from the Instrument Measurement strip.
3. Select DMM[Ω] to measure the resistors.
4. Select DMM[C] to measure the capacitors.
5. Fill in the following information.

R_1	_____	Ω (10 kΩ nominal)
R_f	_____	Ω (100 kΩ nominal)
C_1	_____	µF (1 µf nominal)
C_f	_____	µF (0.01 µf nominal)

6. Close the DMM.

End of Exercise 4.1

Exercise 4.2: Frequency Response of the Basic Op Amp Circuit

Complete the following steps to build and perform measurements on an op amp.

1. On the workstation protoboard, build a simple 741 inverting op amp circuit with a gain of 10 as shown in Figure 4.1.
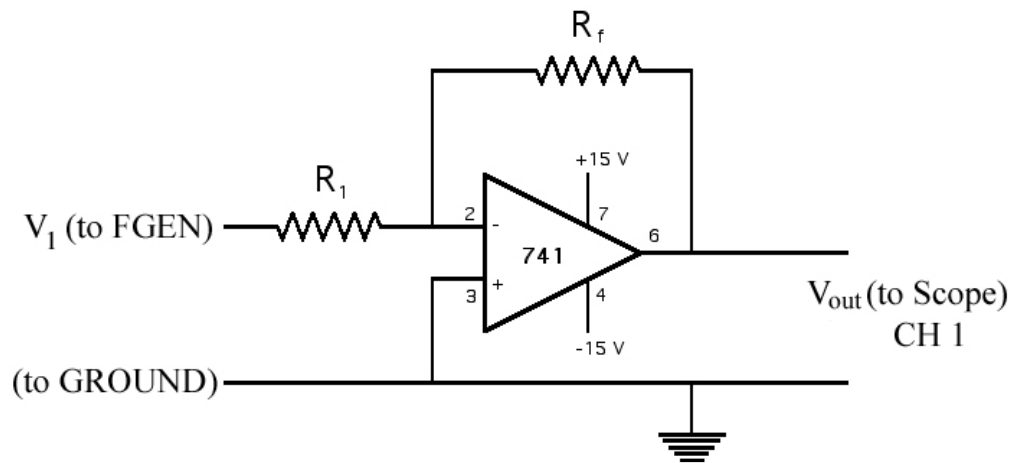
Figure 4.1. Schematic Diagram of a 741 Inverting Op Amp Circuit with a Gain of 10

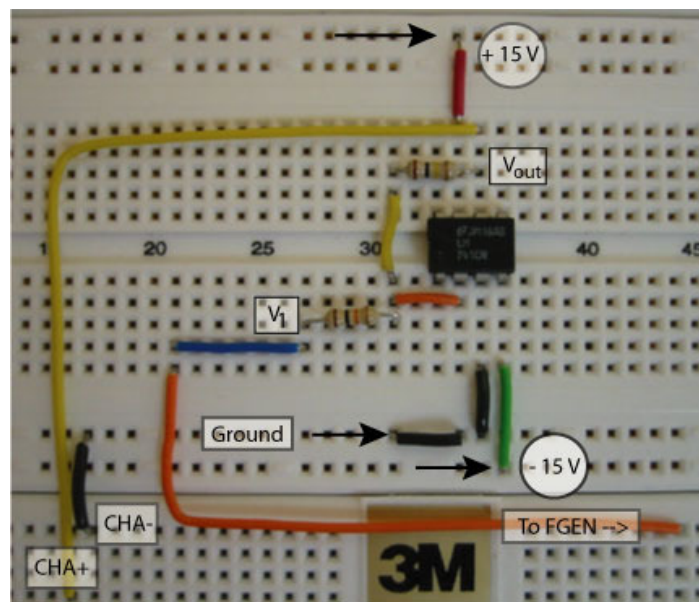The circuit looks like Figure 4.1 on the NI ELVIS II protoboard.

Figure 4.2. 741 Inverting Op Amp Circuit with a Gain of 10 on an NI ELVIS protoboard

Note: The op amp uses both the +15 and -15 VDC power supplies. These are found on the protoboard pin sockets labeled as "DC Power Supplies +15V, -15V & GROUND."

2. Connect the function generator [FGEN] pin socket to the input resistor R_1, and the input resistor to the op amp input.

3. Connect the [Ground] pin socket to pin 3 of the op amp.

4. Connect the op amp output voltage, V_{out}, to the oscilloscope BNC input connector [BNC 2 +] and the function generator output to BNC input [BNC 1 +]. Connect the ground to the pin sockets [BNC 1 -] and [BNC 2 -]. Using BNC cables, connect the BNC 1 and BNC 2 sockets to the CH0 and CH1 (respectively) inputs on the left side of the ELVIS.

Note: If you do not have BNC Cables, connect the circuit input and output into AI0 and AI1 respectively.

5. From the NI ELVIS II Instrument Launcher strip, select the function generator (**FGEN**) icon and the oscilloscop**e** (**Scope**) icon.

Note: By default, on the oscilloscope, the Channel 0 Settings Source is set to Scope Ch 0 and the Channel 1 Settings Source is set to Scope Ch 1. These are your op amp input and output signals, respectively. If you used the analog input channels instead, select the appropriate channels in the drop down menu under "Source".

6. To view the signals, click on the enable boxes.

7. On the function generator panel, set the following parameters:

Waveform:	**Sine wave**
Peak Amplitude:	**0.2 pp**
Frequency:	**1000 Hz**
DC Offset:	**0.0 V**

8. Check your circuit and then apply power to the NI ELVIS II protoboard.

9. Click on [Run] for both the FGEN and Scope SFPs.

10. Set the trigger to Edge, CH 0, Level 0.0 and the Time/Div to 1 ms.

11. Measure the amplitude of the op amp input (CH 0) and output (CH 1) on the oscilloscope window.
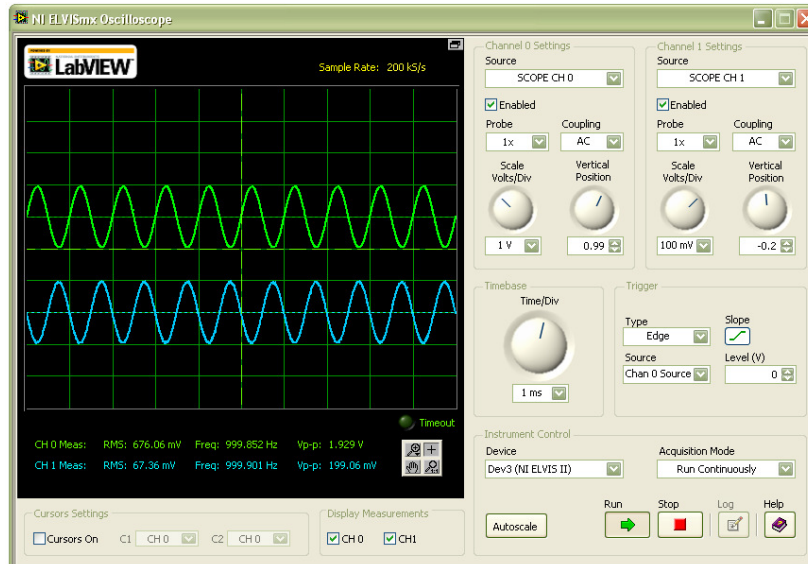
Figure 4.3. Inverting Op Amp input and output signals

Note the output signal is inverted as expected with respect to the input signal.

12. Calculate the voltage gain (the amplitude ratio, CH1/CH0).

13. Try a range of frequencies from 100 Hz to 10 kHz.

How do your measurements agree with the theoretical gain of (R_f/R_1)?

Is the ratio still the same at 100 kHz?

14. Close the FGEN and Scope windows.

End of Exercise 4.2

Exercise 4.3: Measuring the Op Amp Frequency Characteristic

The best way to study the AC characteristic response curve of an op amp is to measure its Bode plot. The Bode plot is basically a plot of gain (dB) and phase (degrees) as a function of log frequency. The transfer function for an inverting op amp circuit is given by:

$$V_{out} = - (R_f/R_1) \, V_1$$

where V_{out} is the op amp output and V_1 is the circuit input. The gain is the quantity (R_f/R_1). The minus sign inverts the output signal with respect to the input signal. On a Bode plot, one expects a straight line with a magnitude of 20 x log (gain). For a gain of 10, the Bode amplitude should be 20 dB.

Complete the following step to measure the Bode plot of the Op Amp circuit:

1. From the NI ELVIS II Instrument Launcher strip, select Bode Analyzer **(Bode)** icon.

2. Connect the signals, input (V_1) and output (V_{out}), to the analog input pins as follows:

V_1+	AI 0+ (from the FGEN output)
V_1 -	AI 0- (from GROUND)
$V_{out}+$	AI 1+ (from the op amp output)
V_{out} -	AI 1 - (from GROUND)

3. On the Bode analyzer, set the scan parameters as follows:

Start:	**5 (Hz)**
Stop:	**20000 (Hz)**
Steps:	**10 (per decade)**

4. Apply power to the protoboard.

5. Click [Run] and observe the Bode plot for the inverting op amp circuit.
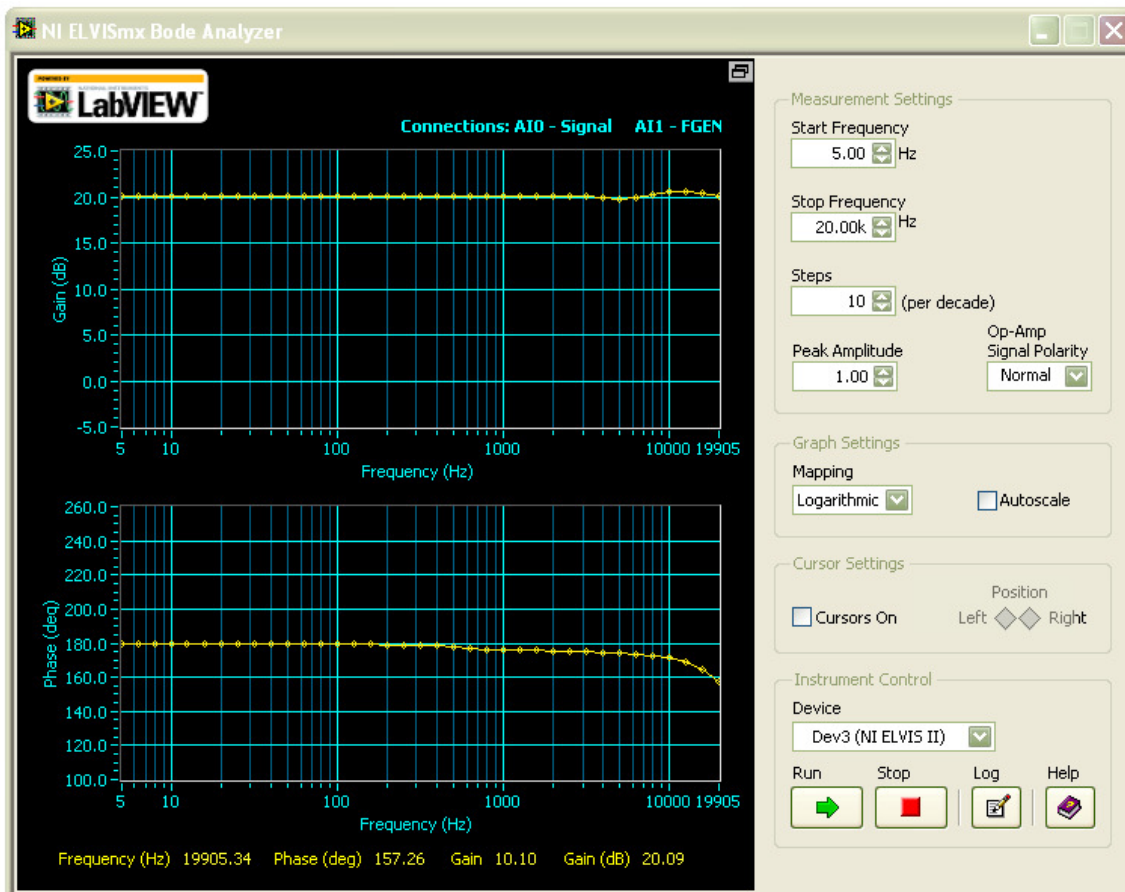
6. Take a close look at the phase response.

The gain (20 dB) is flat and independent of frequency until approximately 10,000 Hz, where it starts to roll off as shown in Figure 4.4. This Bode plot is typical for a 741 op amp inverting circuit. At high frequencies, the amplifier response depends on its internal circuitry as well as any external components.

End of Exercise 4.3

Exercise 4.4: Highpass Filter

A low frequency cutoff point, f_L, for a simple RC series circuit is given by the equation:

$$2\pi f_L = 1/RC$$

where f_L is measured in hertz. The low-frequency cutoff point is the frequency where the gain (dB) has fallen by -3 dB. This (-3 dB) point occurs when the impedance of the capacitor equals that of the resistor.

1. Add a 1 μF capacitor, C_1, in series with the 1 kΩ input resistor, R_1, in the op amp circuit as shown in Figure 4.5.
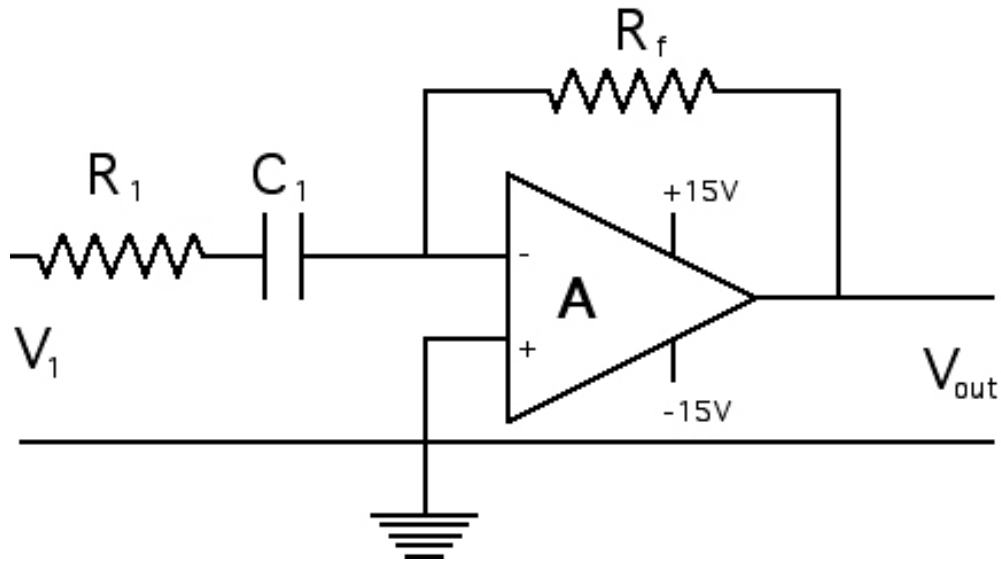

Figure 4.5. Highpass Op Amp Filter Circuit Design

The highpass op amp filter equation has a low-frequency cutoff point, f_L, where the gain has fallen to -3 dB. In other words, when $\mathbf{X_c} = \mathbf{R}$:

$$2\pi f_L = 1/ R_1 C_1$$

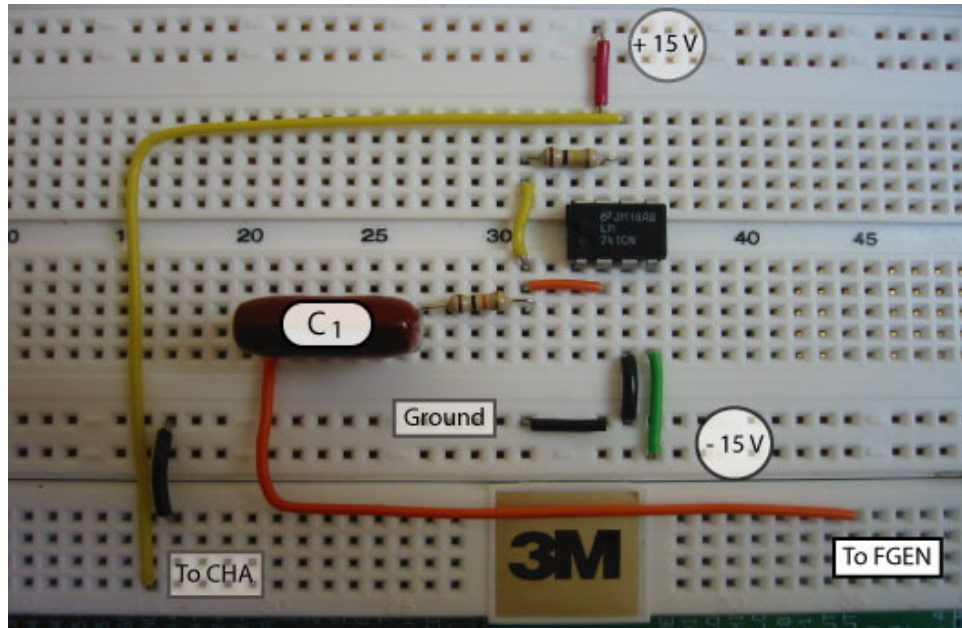Figure 4.6 shows this circuit on an NI ELVIS protoboard.

Figure 4.6. Highpass Op Amp Filter on NI ELVIS protoboard

2. Run a second Bode plot using the same scan parameters as in Exercise 4.3.

3. Observe that the low-frequency response is attenuated while the high-frequency response is similar to the basic op amp Bode plot.
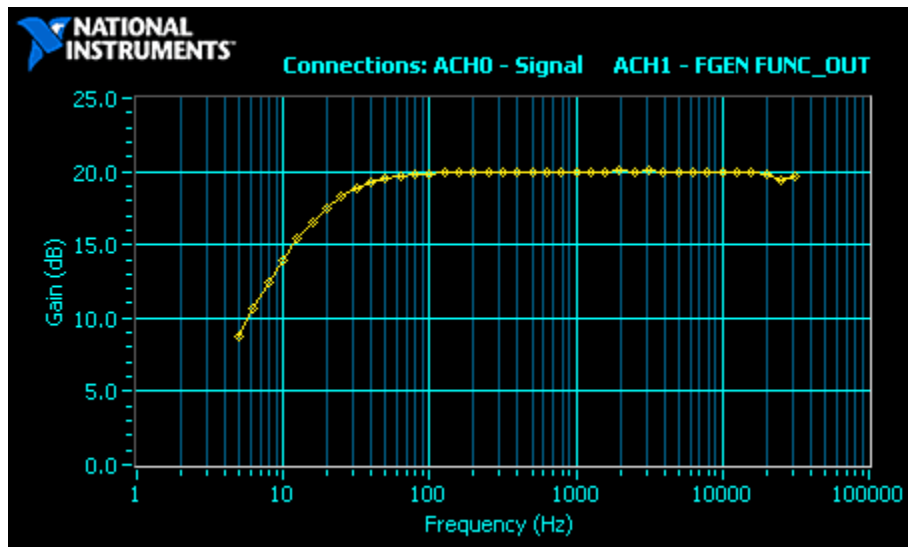

Figure 4.7. Bode Measurement of Highpass Op Amp circuit

4. Use the cursor function to find the low-frequency cutoff point, that is, the frequency at which the amplitude has fallen by -3 dB or the phase change is 45 degrees.

5. Compare your results with the following theoretical predication:

$$2\pi f_L = 1/ R_1 C_1$$

End of Exercise 4.4

Exercise 4.5: Lowpass Filter

The high-frequency roll-off in the op amp circuit is due to the internal capacitance of the 741 chip being in parallel with the feedback resistor, R_f. If you add an external capacitor, C_f, in parallel with the feedback resistor, R_f, you can reduce the upper frequency cutoff point. It turns out that you can predict this new cutoff point from the following equation:

$$2\pi f_U = 1/R_f\ C_f$$

Complete the following steps to perform an additional frequency measurement on the op amp circuit:

1. Short the input capacitor (do not remove it because you will use it in Exercise 4.6).

2. Add the feedback capacitor, C_f, (0.01 µf) in parallel with the 100 kΩ feedback resistor.
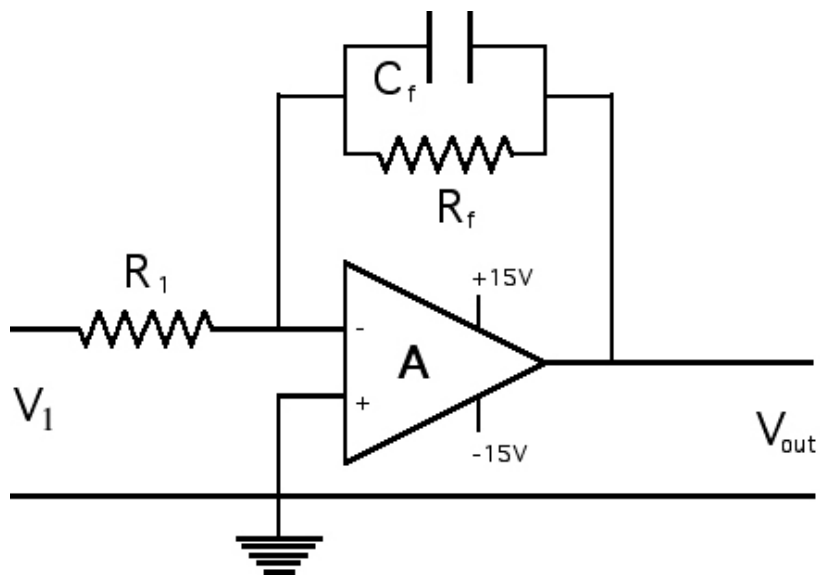

Figure 4.8. Lowpass Op Amp Filter Circuit Design

3. Run a third Bode plot using the same scan parameters.
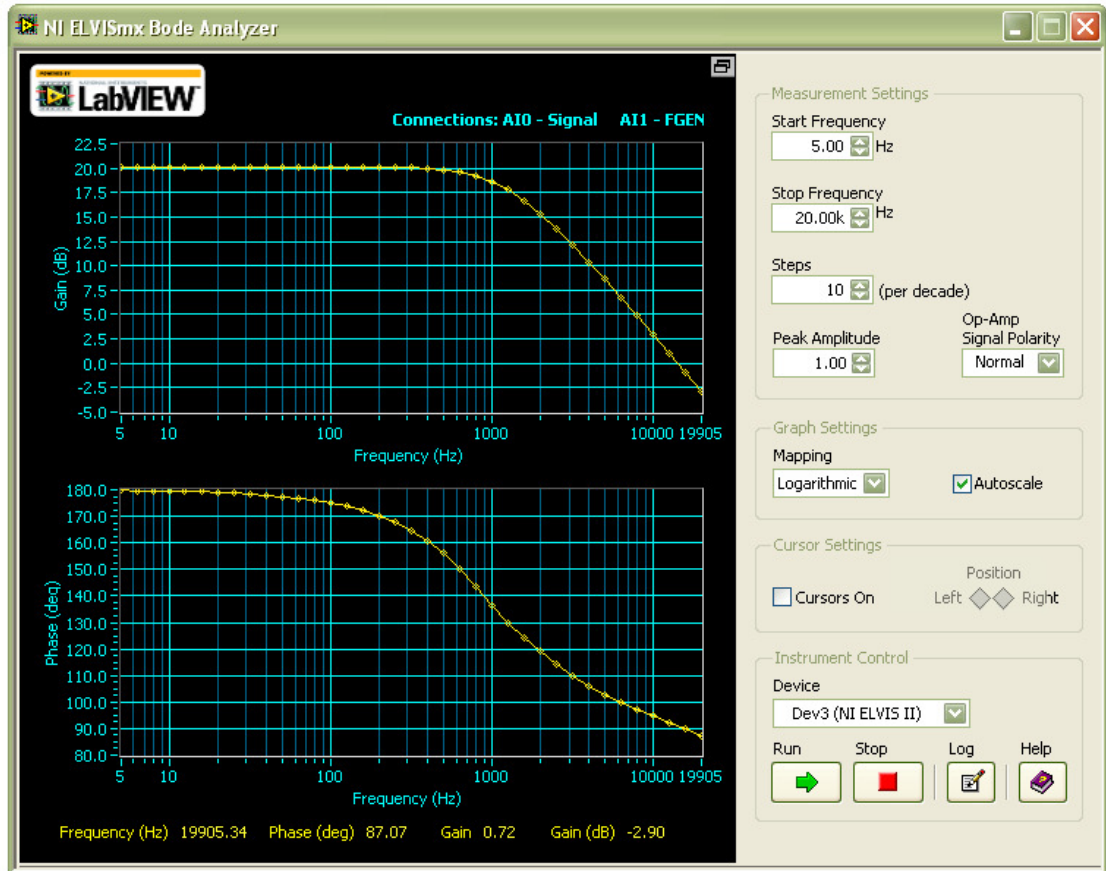
Figure 4.9. Bode Measurement of Lowpass Op Amp circuit

Figure 4.9 shows that the high-frequency response is attenuated much more than the basic op amp response.

4. Use the cursor function to find the high-frequency cutoff point, that is, the frequency at which the amplitude has fallen by -3 dB or the phase change is 45 degrees.

5. Compare your results with the following theoretical prediction:

$$2\pi f_U = 1/ R_f C_f$$

Note: the 90-degree phase change from the very low-frequency range to the upper-frequency range. This is as expected for a single-pole RC filter stage.

End of Exercise 4.5

Exercise 4.6: Bandpass Filter

If you allow both an input capacitor and a feedback capacitor in the op amp circuit, the response curve has both a low-cutoff frequency, f_L, and a high-cutoff frequency, f_U. The frequency range $(f_U - f_L)$ is called the bandwidth. For example, a good stereo amplifier has a bandwidth of at least 20,000 Hz.

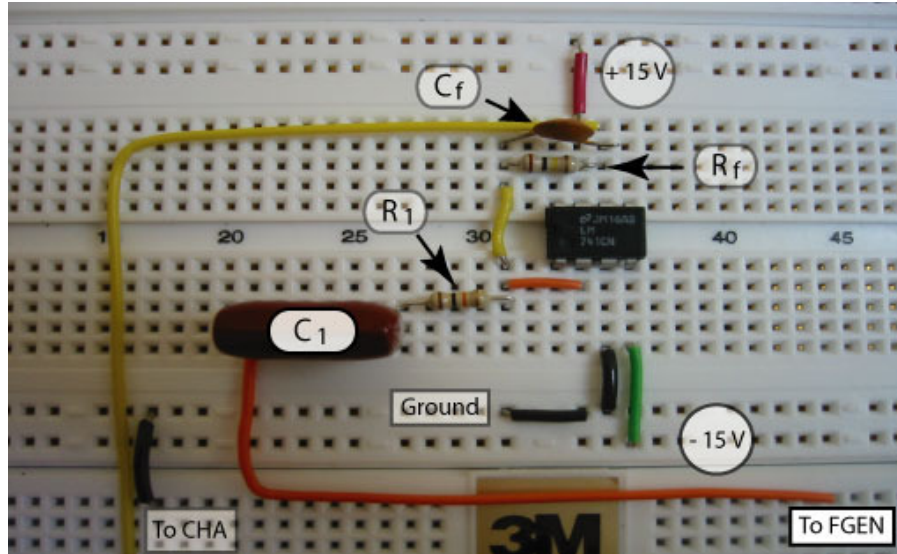Figure 4.10 shows a bandpass filter on an NI ELVIS II protoboard.

Figure 4.10. Bandpass Op Amp circuit on NI ELVIS protoboard
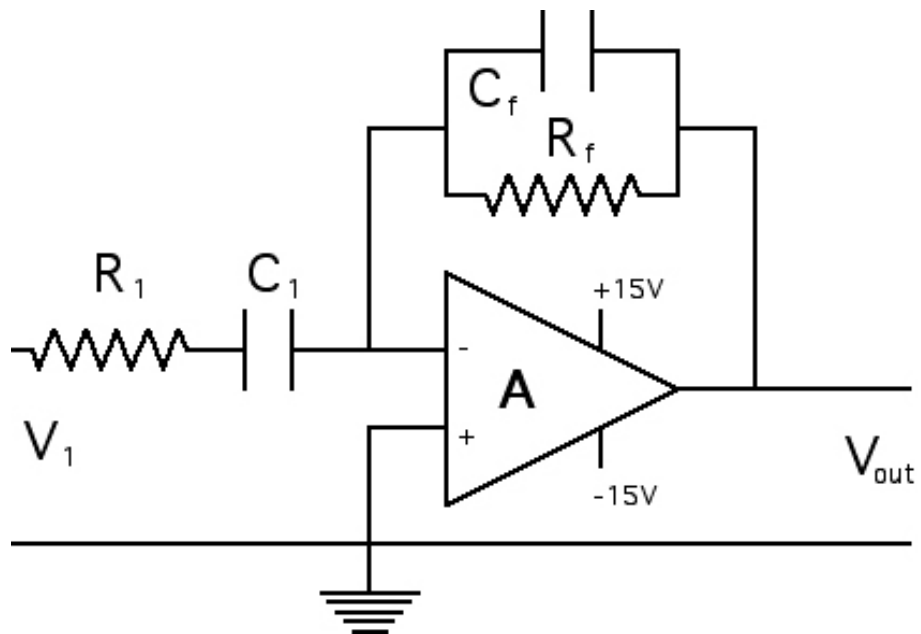
1. Remove the short on C_1.

Figure 4.11. Bandpass Op Amp Filter Circuit Design

2. Run a fourth Bode plot using the same scan parameters.

Figure 4.12. Bode Measurement of Bandpass Op Amp circuit

Using the cursors, draw a line between the -3 dB points. All frequencies with an amplitude above this line are contained within the frequency pass band.

How does this bandwidth measurement agree with the theoretical prediction of $(f_U - f_L)$?

End of Exercise 4.6

For Further Study

The generalized op amp transfer curve is given by the following phasor equation

$$\mathbf{V_{out}} = (\mathbf{Z_f}/\mathbf{Z_1})\mathbf{V_{in}}$$

where the impedance values for the four circuits are:

Op Amp	Z_f	Z_1	Gain
Basic	R_f	R_1	R_f/R_1
Highpass	R_f	$R_1 + X_{C1}$	$R_f/(R_1 + X_{C1})$
Lowpass	$R_f + X_{Cf}$	R_1	$(R_f + X_{Cf})/R_1$

| | Bandpass | $R_f + X_{Cf}$ | $R_1 + X_{C1}$ | $(R_f + X_{Cf})/(R_1 + X_{C1})$ |

Table 4.0. Impedance Values for the FourOp Amp Circuits

At any frequency, you can use the impedance analyzer (Imped) to measure the impedances Z_f and Z_1. A LabVIEW program can calculate the ratio of two complex numbers. The magnitude of the ratio $|Z_f/Z_1|$ is the gain.

Note: You could also use the impedance analyzer to find the frequencies where R_1 equals X_{C1} and R_f equals X_{Cf} to verify that the lower- and upper-frequency cutoff points from the Bode plot are equal to these frequencies.

Multisim Challenge: Design a Second-Order Lowpass Filter

In Exercise 4.5, you built a lowpass filter with a single capacitor in the feedback loop. At high frequencies beyond the cutoff point, the gain falls off linearly with a slope of 6 dB/octave. Some applications require a sharper roll-off. You can accomplish this using a filter design with two or more capacitors in the filter design.

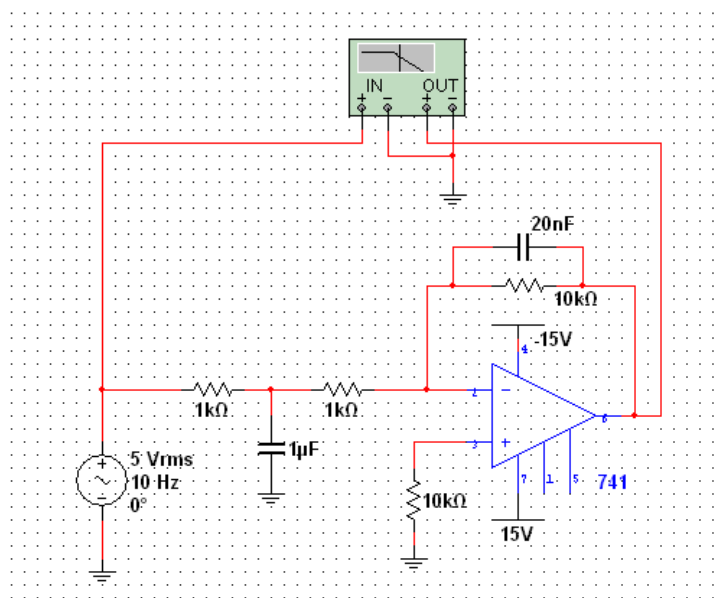1. Design a second-order lowpass filter with a -3 dB cutoff point, f_c, at 1000 Hz.

Figure 4.13. Multisim solution of a Second-order Op Amp Filter

This filter has two cutoff points

$$f_{c1} = (R_1 \| R_2)/(2\pi C_1) \quad \text{and} \quad f_{c2} = (2\pi R_3 C_2)^{-1}$$

In the special case when $f_{c1} = f_{c2} = f_c$, the gain expression for this filter becomes

$$|G| = \frac{-R_3/(R_1+R_2)}{1+(f/f_c)^2}$$

2. Pick resistors and capacitors to satisfy the special case requirement that

$$f_{c1} = f_{c2} = 1000 \text{ Hz}$$

3. Launch the Multisim program Two Pole Active Filter.

4. Double-click on the Bode analyzer icon to open a results window.
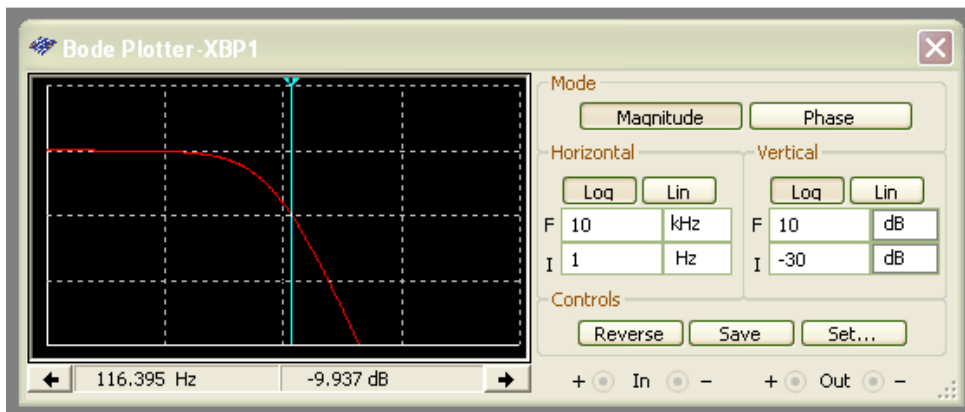
5. Run this program and view the Bode plot.

Figure 4.14. Frequency Response of a Second-order Op Amp Filter

6. From the graph of the gain, estimate the slope of the roll-off curve (should be 40 dB/decade).

7. Modify this program with your component values.

8. Compare the slope of the roll-off curve with the previous result in Exercise 4.5 for a single-pole lowpass filter.

9. If you have the time and components, try building a real two-pole circuit on the NI ELVIS II protoboard.

How well does the Bode plot of the theoretical design match your real circuit? Refer to the Lab 3 Multisim Challenge to recall how to overlay in Excel a theoretical design curve with a measured real curve.