THE GEORGE WASHINGTON UNIVERSITY

WASHINGTON, DC

SCHOOL OF ENGINEERING AND APPLIED SCIENCE

DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

ECE 2110: CIRCUIT THEORY LABORATORY

Experiment #11:

Final Project Preparation Lab 1 – Active Filter Design

EQUIPMENT

Lab Equipment	***Equipment Description***
(1) DC Power Supply	Keysight E36311A Triple Output DC Power Supply
(1) Function Generator	Agilent 33522A Function/Arbitrary Waveform Generator
(1) Digital Multimeter (DMM)	Agilent 34460A (DMM)
(1) Digital Oscilloscope	Keysight DSOX1024G Digital Oscilloscope
(1) Breadboard	Prototype Breadboard
(1) BNC T-Connector	One input to two output BNC connector
(1) Test Leads	Banana to Alligator Lead Set
(2) Test Leads	BNC to Banana Lead Set
(1) BNC Cable	BNC to BNC Cable

Table 1 – Equipment List

COMPONENTS

Type	***Value***	***Symbol Name***	***Multisim Part***	***Description***
Resistor	--- Ω	R	Basic/Resistor	Various Values
Capacitor	--- F	C	Basic/Capacitor	Various Values
Op-Amp	LM741	LM741	Basic/Analog/OpAmp/741	---
Power Amp	LM386	LM386	---	Audio Amplifier
Speaker	6Ω	---	---	18W Speaker

Table 2 – Component List

OBJECTIVES

- Understand the difference between active and passive filters
- Design and build a band-pass filter using active components
- Understand the limitations of the LM741
- Understand what an LM386 is and why it is necessary
- Build and measure a band-pass filter using LM741s and an LM386

Note: *At this point, the final project should be introduced by the GTA. Ideally, an introduction to the project will be given at the end of the last lab to prepare students for this prelab and lab. Students, please find the final project specifications document on the ECE 2110 lab website under the Projects section.*

INTRODUCTION

This lab will introduce you to the concept of **active filters** and explain how they differ from passive filters and why they are necessary. In Lab 10, you were introduced to **passive filters**. Passive filters consist of only passive components (inductors, capacitors, resistors). Because passive components cannot provide average power to a circuit, you cannot make a filter with a gain greater than 1 using only passive components. In many situations, you may wish to create a filter with a gain greater than 1. For this, you must incorporate an op-amp into the filter design.

Active 1st Order Low-Pass Filter

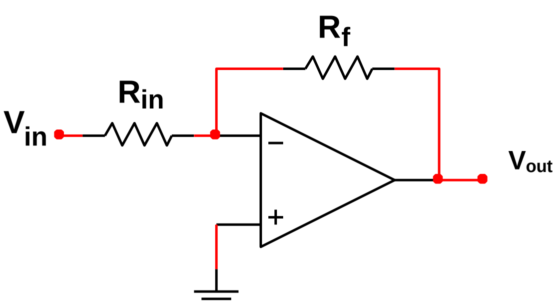


Figure 1 – Inverting Amplifier

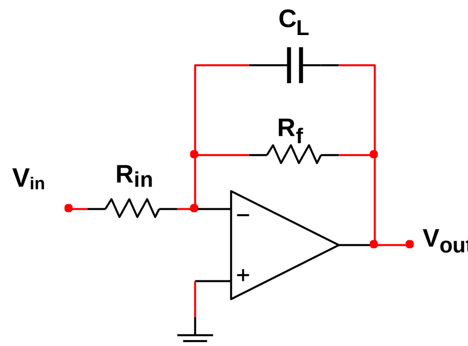


Figure 2 – Active 1st Order Low-Pass Filter

Figure 1 shows an inverting amplifier. From the lab on DC Operational Amplifiers, we know the gain of this amplifier is $\mathbf{V_{out}/V_{in} = -R_f/R_{in}}$. Instead of using just resistors, we can substitute impedances Z_f and Z_{in}, and the gain becomes $\mathbf{V_{out}/V_{in} = -Z_f/Z_{in}}$.

Figure 2 shows the same amplifier, now with a capacitor inserted in the feedback path. Z_{in} is still R_{in}, but Zf is the impedance of the resistor and capacitor in parallel, so $\mathbf{Z_f = Z_{Rf} \,||\, Z_{CL}}$: Substituting in the impedances as shown in **Figure 2**:

$$Z_f = R_f I \frac{1}{jwC_L} = \frac{\frac{R_f}{jwC_L}}{R_f + \frac{1}{jwC_L}} = \frac{R_f}{1 + jwR_fC_L}$$

Typically, for filters, the transfer function of interest is the voltage gain, defined as $\mathbf{T(\omega) = V_{out}/V_{in}}$. Since the voltage gain of the amplifier in **Figure 2** is $\mathbf{V_{out}/V_{in} = -Z_f/Z_{in}}$, the transfer function for the filter becomes:

$$T(w) = \frac{V_{out}}{V_{in}} = -\frac{Z_f}{Z_{in}} = -\frac{R_f}{R_{in}}\left(\frac{1}{1 + jwR_fC_L}\right)$$

What should be familiar is the expression in parentheses in the equation above, it is the transfer function for a low-pass filter. The expression outside of the brackets: $\mathbf{-R_f/R_{in}}$, means this low-pass filter has **gain**!

The **cutoff frequency** for this **low-pass filter** is:

$$w_e = \frac{1}{R_f C_L}$$

Note: *To* ***design*** *this filter, one chooses the appropriate resistors: R_f and R_{in} to* ***set the gain****, then determines C_L for the desired cutoff frequency (ω_C).*

Active 1st Order High-Pass Filter

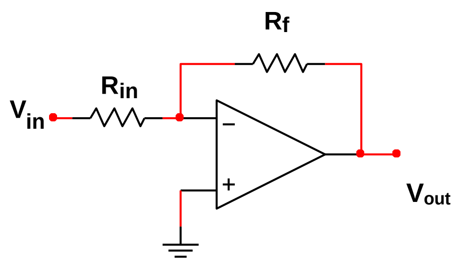


Figure 3 – Inverting Amplifier

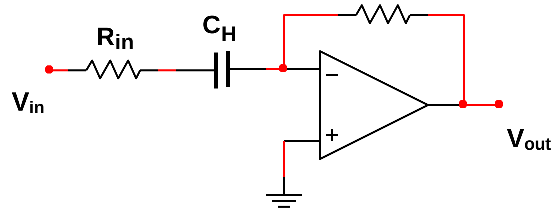


Figure 4 – Active 1st Order High-Pass Filter

Figure 4 shows how we can make the inverting amplifier into a high-pass filter by rearranging the capacitor to be in series with the input resistor. The transfer function then becomes:

$$T(w) = \frac{V_{out}}{V_{in}} = \frac{Z_f}{Z_{in}} = \frac{R_f}{R_{in} + \frac{1}{jwC_H}}$$

When the frequency is low (e.g. $\omega \rightarrow 0$), the transfer function approaches 0. As the frequency gets higher and higher (e.g $\omega \rightarrow \infty$), the transfer function becomes **$-R_f/R_{in}$**. This is the behavior of a high-pass filter. The **cutoff frequency** for this filter can be derived as:

$$w_e = \frac{1}{R_f C_H}$$

Creating an Active Band-Pass Filter by Cascading Filters

When two filters are chained together this is called ***cascading***. Passive filters can be cascaded together, as can active filters. As a simple example, we can cascade the **low-pass** and **high-pass** filters discussed above to create a **band-pass** filter as follows:

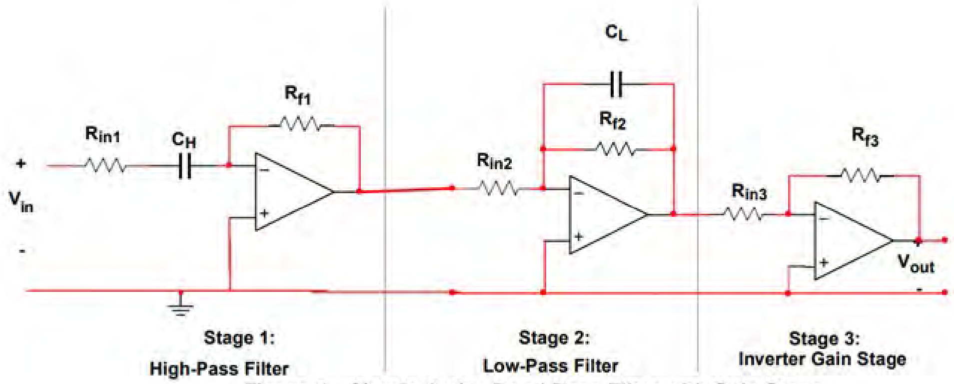


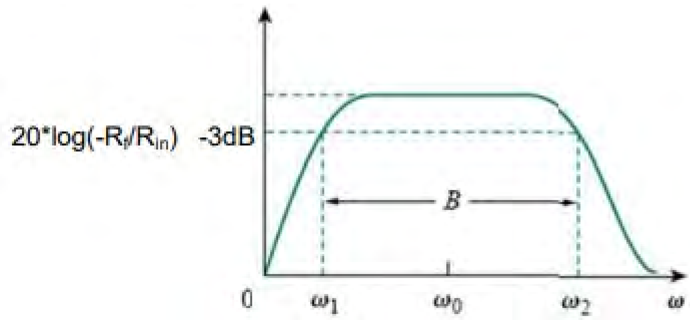
Figure 5 – Simple Active Band-Pass Filter with Gain Stage

What you should notice in **Figure 5** is the addition of a simple inverting amplifier shown as Stage 3. What is often done when cascading filters is to have the **final stage provide all of the gain** for the system. In this example, we set the gain of our active low-pass filter (Stage 1) to unity or 1. The next stage, the high-pass filter (Stage 2) also has a unity gain. Then, in the final stage, the inverting amplifier will set the gain for the system.

When amplifiers are cascaded, the gain of each stage is multiplied together to determine the overall gain. To determine the transfer function for the system in **Figure 5**, we multiply each individual transfer function for each stage:

$$T(w) = \frac{V_{out}}{V_{in}} = T_1(w) * T_2(w) * T_3(w) = -\frac{R_{f1}}{R_{in1}} \frac{1}{1 + jwR_{f1}C_L} * \left(\frac{R_{f2}}{R_{in2} + \frac{1}{jwC_H}} \right) * \frac{R_{f3}}{R_{in3}}$$

We see the overall gain for the system is set by the final stage (R_{f3}/R_{in3}).



The **low-pass** section, Stage 1, sets the upper cutoff frequency (**ω_1**). The **high-pass** section, Stage 2, sets the lower cutoff frequency (**ω_2**). The bandwidth of this band-pass filter is simply **ω_2-ω_1.**

$$w_2 = \frac{1}{R_{f1}e_L} \qquad w_1 = \frac{1}{R_{f2}e_H}$$

Note: *To design a band-pass filter using this configuration, first choose the desired gain and set R_{f3} and R_{in3}. Then, choose R_{f2} and R_{in2} to have unity gain. Similarly, R_{f1} and R_{in1} are chosen setting the gain of the first stage to 1 as well. Lastly, the cutoff frequencies are chosen and the values of the capacitors: C_L and C_H are solved for using the cutoff frequency equations.*

PRELAB

Part I – Active Band-Pass Filter Design

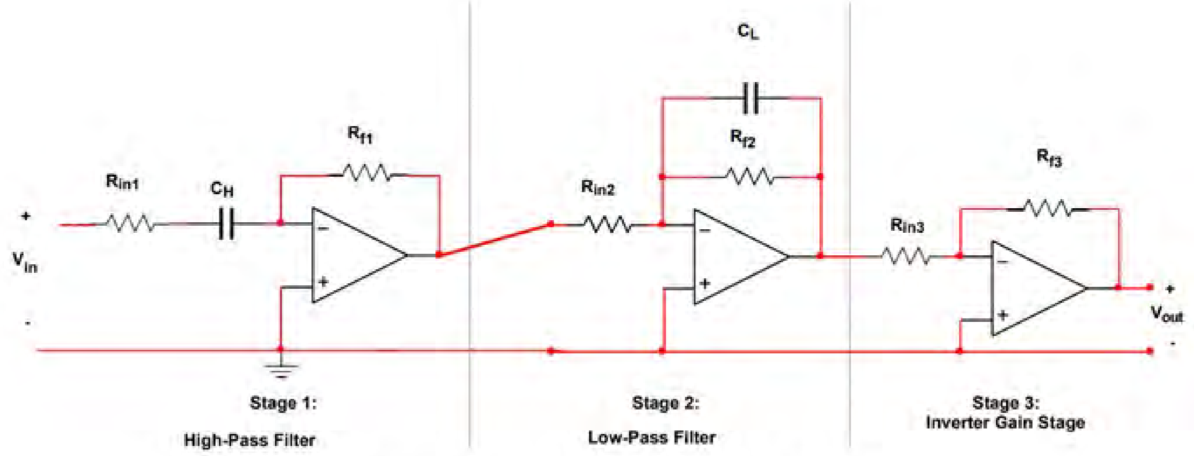


Figure P.1 – Active Band-Pass Filter with Gain Stage

1. Using the procedure discussed in the **Introduction**, **design** an **active band-pass filter** with a gain of -10, a lower cut-off frequency of **150Hz** and an upper cutoff frequency of **5kHz**. ***Be sure to show all work and mention any relevant assumptions or design decisions.***

   Note: *When choosing resistor values to set the gain for each stage, be certain to keep them very large in the high kΩ range.*

   - **ω_1 = 150Hz**
   - **ω_2 = 5kHz**
   - **Gain = -10**
2. **Save** this design as you will need to simulate it later in this prelab.

Part II – Active Low-Pass Filter Simulation

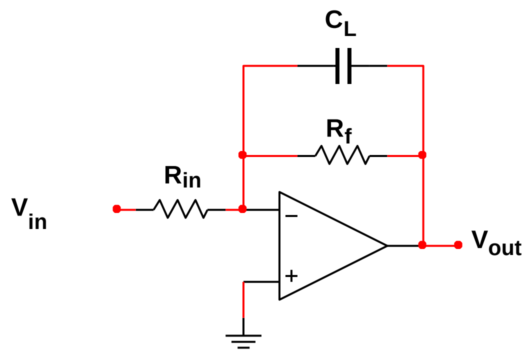


Figure P.2 – Active 1st Order Low-Pass Filter

1. **Simulate** the active low-pass filter section of the band-pass filter in **Multisim** using the LM741.
   - **DC Supply Voltage (V_{CC+} and V_{CC-}): ±12V**
   - **V_{in}: 300mV_{rms} sine wave**
   - **Load: 1kΩ**
2. **Run** an **AC Analysis** from **10Hz** to **6kHz**. **Measure V_{out}** (in RMS voltage) across the 1kΩ load at the following frequencies: 10Hz, 150Hz, 1kHz, 4kHz, 5kHz, 6kHz
3. **Using** the peak output voltage of V_{out}, **calculate** the **peak power dissipated** by the 1kΩ load resistor at each frequency.
4. **Calculate** the current drawn by the 1kΩ load resistor at the peak output power in each case.
5. **Record** these values in **Table P.2**.
6. **Plot** the **magnitude** and **phase** of V_{out}/V_{in} (in dB) versus frequency from 10Hz to 6kHz. 7. **Determine** the **-3dB frequency** from this plot.

Frequency	***V_{in} (rms)***	***V_{out} (rms)***	***Gain (V_{out}/V_{in})***	***P_{out} (peak)***	***I_{out} (peak)***
10Hz					
150Hz					
1kHz					
4kHz					
5kHz					
6kHz					
	-3dB Freq.				
Simulated					

Table P.2 – Low-Pass Filter Simulation Data

Part III – Active High-Pass Filter Simulation

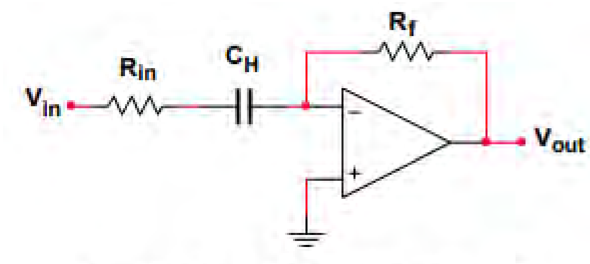


Figure P.3 – Active 1st Order High-Pass Filter

1. **Simulate** the active high-pass filter section of the band-pass filter in **Multisim** using the LM741.
   - **DC Supply Voltage (V_{CC+} and V_{CC-}): ±12V**
   - **V_{in}: 300mV_{rms} sine wave**
   - **Load: 1kΩ**
2. **Run** an **AC Analysis** from **10Hz** to **6kHz**. **Measure V_{out}** (in RMS voltage) across the 1kΩ load at the following frequencies: 10Hz, 150Hz, 1kHz, 4kHz, 5kHz, 6kHz
3. **Using** the peak output voltage of V_{out}, **calculate** the **peak power dissipated** by the 1kΩ load resistor at each frequency.
4. **Calculate** the current drawn by the 1kΩ load resistor at the peak output power in each case.
5. **Record** these values in **Table P.3**.
6. **Plot** the **magnitude** and **phase** of V_{out}/V_{in} (in dB) versus frequency from 10Hz to 6kHz. 7. **Determine** the **-3dB frequency** from this plot.

Frequency	***V_{in} (rms)***	***V_{out} (rms)***	***Gain (V_{out}/V_{in})***	***P_{out} (peak)***	***I_{out} (peak)***
10Hz					
150Hz					
1kHz					
4kHz					
5kHz					
6kHz					
	-3dB Freq.				
Simulated					

Table P.3 – High-Pass Filter Simulation Data

Part IV – Active Band-Pass Filter Simulation

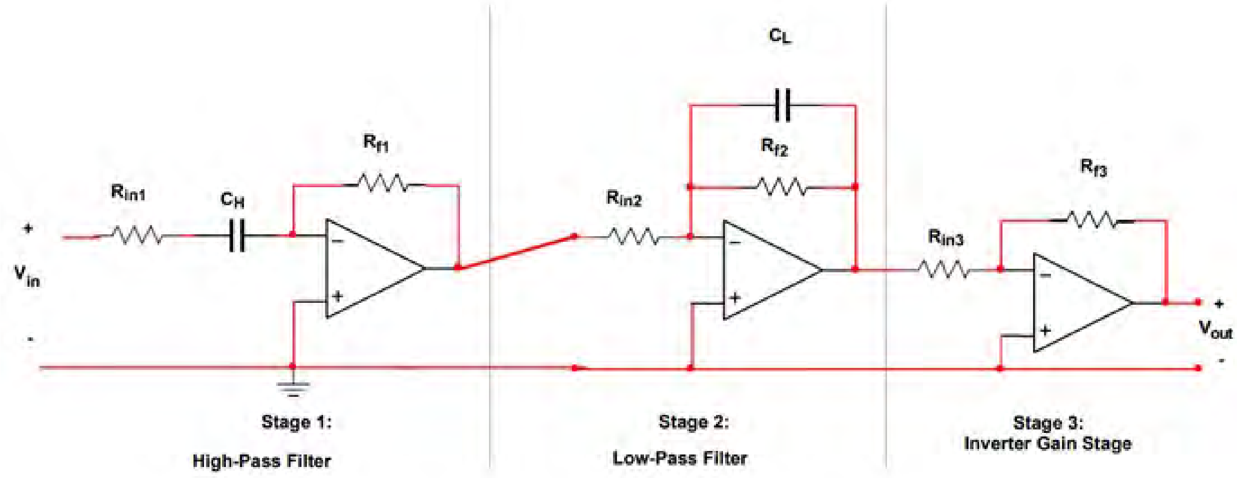


Figure P.4 – Active Band-Pass Filter with Gain Stage

1. **Simulate** the cascaded active band-pass filter, including the inverter gain stage, in **Multisim** using the LM741.
   - **DC Supply Voltage (V_{CC+} and V_{CC-}): ±12V**
   - **V_{in}: 300mV_{rms} sine wave**
   - **Load: 1kΩ**
2. **Run** an **AC Analysis** from **10Hz** to **6kHz**. **Measure V_{out}** (in RMS voltage) across the 1kΩ load at the following frequencies: 10Hz, 150Hz, 1kHz, 4kHz, 5kHz, 6kHz
3. **Using** the peak output voltage of V_{out}, **calculate** the **peak power dissipated** by the 1kΩ load resistor at each frequency.
4. **Calculate** the current drawn by the 1kΩ load resistor at the peak output power in each case.
5. **Record** these values in **Table P.4**.
6. **Plot** the **magnitude** and **phase** of V_{out}/V_{in} (in dB) versus frequency from 10Hz to 6kHz.
7. **Determine** both the lower and upper **-3dB frequencies** from this plot.

Frequency	***V_{in} (rms)***	***V_{out} (rms)***	***Gain (V_{out}/V_{in})***	***P_{out} (peak)***	***I_{out} (peak)***
10Hz					
150Hz					
1kHz					
4kHz					
5kHz					
6kHz					
	Lower -3dB	***Upper -3dB***			
Simulated					

Table P.4 – Band-Pass Filter Simulation Data

LAB

Part I – Active Low-Pass Filter

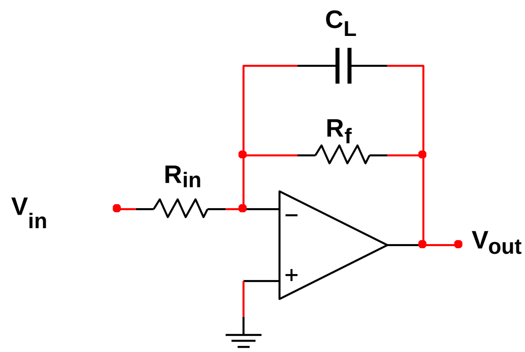


Figure 1.1 – Active 1st Order Low-Pass Filter

1. **Build** the active low-pass filter section on a breadboard. ***Show the GTA your setup before applying power.***
   - **DC Supply Voltage (V_{CC+} and V_{CC-}): ±12V**
   - **V_{in}: 300mV_{rms} sine wave**
   - **Load: 1kΩ**
2. **Measure V_{out}** using the DMM (RMS voltage) across the 1kΩ load at the following frequencies: 10Hz, 150Hz, 1kHz, 4kHz, 5kHz, 6kHz
3. **Using** the peak output voltage of V_{out}, **calculate** the **peak power dissipated** by the 1kΩ load resistor at each frequency.
4. **Calculate** the current drawn by the 1kΩ load resistor at the peak output power in each case.
5. **Record** these values in **Table 1.1**.
6. **Adjust** the **frequency** of the function generator until you find the **exact -3dB frequency** of the filter, where $V_{out} = \frac{1}{\sqrt{2}} * (\max V_{out})$.

Frequency	***V_{in} (rms)***		***V_{out} (rms)***		***Gain (V_{out}/V_{in})***		***P_{out} (peak)***		***I_{out} (peak)***	
	Sim.	***Meas.***	***Sim.***	***Meas.***	***Sim.***	***Meas.***	***Sim.***	***Meas.***	***Sim.***	***Meas.***
10Hz										
150Hz										
1kHz										
4kHz										
5kHz										
6kHz										
	-3dB Freq.									
Simulated										
Measured										
Error										

Table 1.1 – Low-Pass Filter Output Characteristics with 1kΩ Load

Part II – Active High-Pass Filter

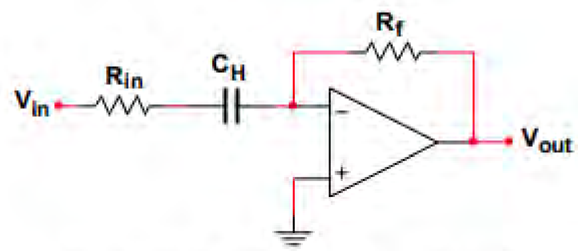


Figure 2.1 – Active 1st Order High-Pass Filter

1. **Build** the active high-pass filter section on a breadboard. ***Show the GTA your setup before applying power.***
   - **DC Supply Voltage (V_{CC+} and V_{CC-}): ±12V**
   - **V_{in}: 300mV_{rms} sine wave**
   - **Load: 1kΩ**
2. **Measure V_{out}** using the DMM (RMS voltage) across the 1kΩ load at the following frequencies: 10Hz, 150Hz, 1kHz, 4kHz, 5kHz, 6kHz
3. **Using** the peak output voltage of V_{out}, **calculate** the **peak power dissipated** by the 1kΩ load resistor at each frequency.
4. **Calculate** the current drawn by the 1kΩ load resistor at the peak output power in each case.
5. **Record** these values in **Table 2.1**.
6. **Adjust** the **frequency** of the function generator until you find the **exact -3dB frequency** of the filter, where $V_{out} = \frac{1}{\sqrt{2}} * (\max V_{out})$.

Frequency	***V_{in} (rms)***		***V_{out} (rms)***		***Gain (V_{out}/V_{in})***		***P_{out} (peak)***		***I_{out} (peak)***	
	Sim.	***Meas.***	***Sim.***	***Meas.***	***Sim.***	***Meas.***	***Sim.***	***Meas.***	***Sim.***	***Meas.***
10Hz										
150Hz										
1kHz										
4kHz										
5kHz										
6kHz										
	-3dB Freq.									
Simulated										
Measured										
Error										

Table 2.1 – High-Pass Filter Output Characteristics with 1kΩ Load

Part III – Active Band-Pass Filter

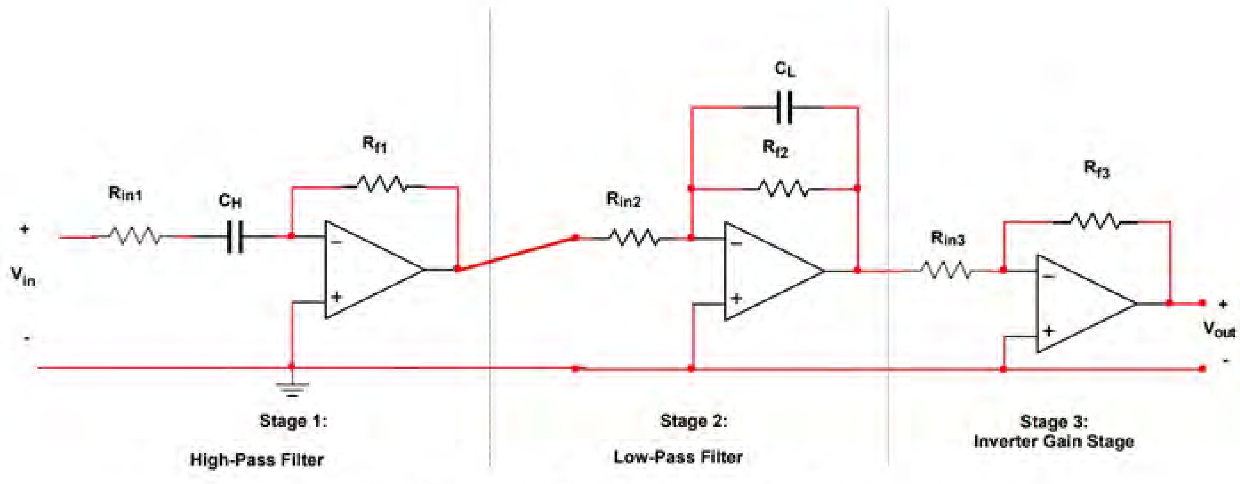


Figure 3.1 – Active Band-Pass Filter with Gain Stage

7. **Build** the active low-pass filter section on a breadboard. ***Show the GTA your setup before applying power.***
   - **DC Supply Voltage (V_{CC+} and V_{CC-}): ±12V**
   - **V_{in}: 300mV_{rms} sine wave**
   - **Load: 1kΩ**
8. **Measure V_{out}** using the DMM (RMS voltage) across the 1kΩ load at the following frequencies: 10Hz, 150Hz, 1kHz, 4kHz, 5kHz, 6kHz
9. **Using** the peak output voltage of V_{out}, **calculate** the **peak power dissipated** by the 1kΩ load resistor at each frequency.
10. **Calculate** the current drawn by the 1kΩ load resistor at the peak output power in each case.
11. **Record** these values in **Table 3.1**.
12. **Adjust** the **frequency** of the function generator until you find the **exact -3dB frequencies** (upper and lower) of the filter, where $V_{out} = \frac{1}{\sqrt{2}} * (\max V_{out})$.

Frequency	***V_{in} (rms)***		***V_{out} (rms)***		***Gain (V_{out}/V_{in})***		***P_{out} (peak)***		***I_{out} (peak)***	
	Sim.	***Meas.***	***Sim.***	***Meas.***	***Sim.***	***Meas.***	***Sim.***	***Meas.***	***Sim.***	***Meas.***
10Hz										
150Hz										
1kHz										
4kHz										
5kHz										
6kHz										
	Lower -3dB		***Upper -3dB***							
Simulated										
Measured										
Error										

Table 3.1 – Band-Pass Filter Output Characteristics with 1kΩ Load

Part IV – Active Band-Pass Filter with Small Load

1. For the band-pass filter you have simulated and measured, **calculate** the amount of current a 6Ω load would draw at the **highest value** of $\mathbf{V_{out}}$ you recorded in **Table 3.1**.
   a. **What** is the value in **mA**? Include this in your lab write-up
   b. **Can** the LM741 op-amp provide this much current to a **6Ω load**?
      i. **Download** the LM741 specification sheet from the lab website. ii. **Look** for the electrical parameter: "**Output Short Circuit Current**"
      iii. **Is** this value **more** or **less** than the amount of current a 6Ω load would draw?
   c. **Replace** the 1kΩ load in your **Multisim** simulation with a **6Ω load**.
      i. **Run** an **AC Analysis** from **10Hz** to **6kHz**. **Measure** $\mathbf{V_{out}}$ (in RMS voltage) across the 6Ω load at the following frequencies: 10Hz, 150Hz, 1kHz, 4kHz, 5kHz, 6kHz
      ii. **What** do you notice about your results?
2. From Step 1 you should realize that the **LM741 cannot support a small load** like 6Ω.
   a. We **need an amplifier** for the 3rd stage of our band-pass filter that can provide enough current to our 6Ω load.
   b. For this, we will replace Stage 3 of our amplifier with a power amplifier called the **LM386**.
      i. The **LM386 is not an op-amp**. It is a self-contained amplifier that can provide a great deal of current to **small loads**. ii. **Download** the LM386 specification sheet from the lab website.
3. On page 5 of the LM386 specification sheet a sample configuration is shown.
   a. **Replace** the **3rd stage** of your amplifier with this sample configuration.
   b. Instead of a 6Ω load, use the **speaker** provided in your kit.
4. **Measure** $\mathbf{V_{out}}$ using the DMM (RMS voltage) across the speaker at the following frequencies: 10Hz, 150Hz, 1kHz, 4kHz, 5kHz, 6kHz
5. **Using** the peak output voltage of V_{out}, **calculate** the **peak power dissipated** by the speaker at each frequency.
6. **Calculate** the current drawn by the speaker at the peak output power in each case.
7. **Record** these values in **Table 4.1**.
8. **Adjust** the **frequency** of the function generator until you find the **exact -3dB frequencies** (upper and lower) of the filter, where $V_{out} = \frac{1}{\sqrt{2}} * (\max V_{out})$.

Frequency	***V_{in} (rms)***		***V_{out} (rms)***		***Gain (V_{out}/V_{in})***		***P_{out} (peak)***		***I_{out} (peak)***	
	Sim.	***Meas.***	***Sim.***	***Meas.***	***Sim.***	***Meas.***	***Sim.***	***Meas.***	***Sim.***	***Meas.***
10Hz										
150Hz										
1kHz										
4kHz										
5kHz										
6kHz										
	Lower -3dB		***Upper -3dB***							
Simulated										
Measured										
Error										

Table 4.1 – Band-Pass Filter Output Characteristics with 6Ω Load

POST-LAB ANALYSIS

Be certain to include:

1. Your **calculations** for how you designed the band-pass filter.
2. The **Multisim schematic** for the band-pass filter.
3. The **Multisim output** showing V_{out}/V_{in} (in dB) versus frequency for the low-pass filter, high-pass filter, and finally the band-pass filter.

Answer the following questions and provide some discussion on the following:

1. **Why** was the LM741 incapable of driving a 6Ω load?
2. **Why** is the LM386 capable of driving the 6Ω load?
3. **Why** did we use the speaker instead of a 6Ω resistor in Part IV?

REFERENCES

[1] Thomas, Roland E., Albert J. Rosa, and Gregory J. Toussaint. *The Analysis and Design of Linear Circuits*. 7th ed. Hoboken, NJ: Wiley, 2012.