Final Project: Active Filters, Audio Amplifiers, iPod Docking Station

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ECE 2110: Circuit Theory

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1. Introduction

The purpose of this final project was to integrate the knowledge students have been building since the first lecture of Circuit Theory. This project incorporates aspects of almost every single concept discussed in class and combines each element into a final design that must be implemented to filter and amplify an audio signal through two separate speakers. The final design had to consist of a bass section for lower tones and a treble section for higher tones. Each section needed to have its own volume control and LED bar that was used to visually show the volume levels in that branch of the circuit. The final project needed to handle a single audio input source from either an iPod or other source capable of connecting to a 3.5mm audio cable while also being able to hook up directly to the function generator for further testing of its filtering capabilities. This project was designed to not only test the students' abilities and knowledge of circuitry, but also how well they would be able to apply that knowledge to a real physical design and implement that design. In the end, it was important to not only build a functional docking station, but to also be able to fully understand how and why it worked.

2. Background Information

- **Filters** can be used to modify a signal to certain specifications, allowing only the desired frequencies through the circuit while blocking the unwanted frequencies.

$$V = I * R$$

Equation 2.1 – Ohm's Law Equation

$$p = I * V$$

Equation 2.2 – Power Equation

$$R_{equiv} = R_1 + R_2 + ... + R_n$$

Equation 2.3 – Equivalence Resistor Equation for Resistors in Series

$$R_{equiv} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + ... + \frac{1}{R_n}}$$

Equation 2.4 – Equivalence Resistor Equation for Resistors in Parallel

$$PE = \frac{|NV - MV|}{NV} * 100$$

Equation 2.5 – Percentage Error (PE) Equation, Nominal Value (NV), Measured Value (MV)

$$V_{R_x} = V_S\left(\frac{R_x}{R_1 + R_2 + ... + R_n}\right)$$

Equation 2.6 – Voltage Divider Equation with Resistors (R_1 through R_n) in Series for Voltage Drop (V) Across R_x

$$\omega_c = \frac{1}{R_f C_f}$$

Equation 2.7 – Cutoff Frequency Equation for Active Filter

$$T(\omega) = Gain = \frac{V_{out}}{V_{in}}$$

Equation 2.8 – Gain Equation, Also Known as the Transfer Function

3. Methods and Materials

Equipment:

- (1) Keithley Model 178 Digital Multimeter (DMM)
- (1) Agilent E3631A Triple Output DC Power Supplies
- (1) Agilent DSO1024A Digital Oscilloscope
- (1) Function Generator
- (3) Pairs of Banana to mini-grabber test leads
- (2) Pairs of Banana to Banana cables
- (2) Prototype Breadboards
- (1) Pair of Pliers
- (1) Wire Stripper and Cutter
- (1) iPod

Components:

- (14) LM741 Operational Amplifiers
- (2) LM386 Power Amplifiers
- (2) LED Bars
- (2) Speakers
- (1) 3.5mm Audio Input Jack
- (1) Male to Male 3.5mm Audio Cord
- (1) 120kΩ Resistor
- (5) 10kΩ Resistors
- (2) 32kΩ Resistors
- (2) 13kΩ Resistors
- (2) 16kΩ Resistors
- (2) 40kΩ Resistors
- (2) 10Ω Resistors
- (1) 1.5kΩ Resistor
- (1) 5kΩ Resistor
- (4) 1000pF Capacitors
- (2) 3.3μF Capacitors
- (4) 10μF Capacitors
- (2) 220μF Capacitors
- (2) 47nF Capacitors
- (2) 68nF Capacitors
- (1) 82nF Capacitor
- (1) 1kΩ Potentiometer
- (1) 50kΩ Potentiometer
- (1) Bundle of Wire

4. Experimental Procedures

4.1 Design Process:

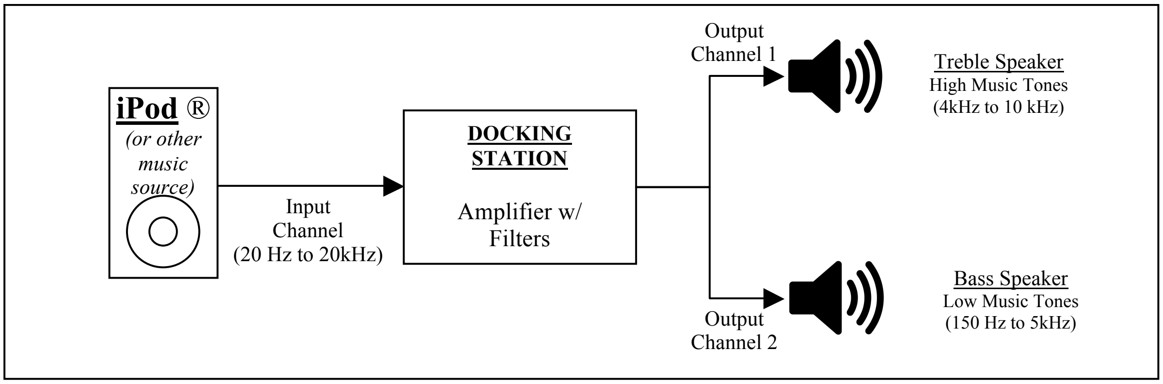

Figure 4.1.1 – High Level System Diagram

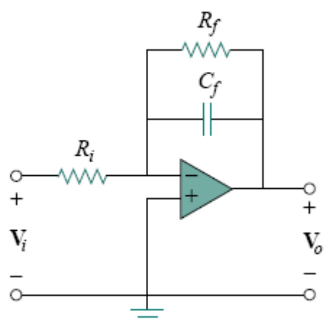

Figure 4.1.2 – Active 1st Order Low-Pass Filter

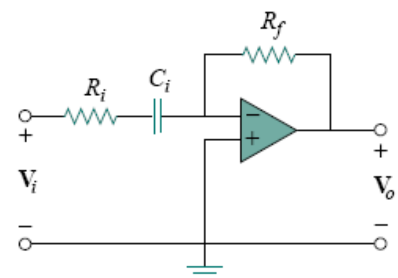

Figure 4.1.3 – Active 1st Order High-Pass Filter

4.2 Designing the Bass Section of the Docking Station:

Design Specifications:

- Gain = -1
- $\omega_{C_1} = 150Hz$
- $\omega_{C_2} = 5kHz$

$$Gain = -\frac{R_{f3}}{R_{i3}} = -\frac{10k\Omega}{10k\Omega} = -1$$

Design Procedure:

The student used known capacitor values that they had in their kit as the starting point for these calculations. With these values and the known desired cutoffs, they calculated the proper resistor values that would be necessary to match the desired specifications.

Low Pass Section:

$$R_{f1} = \frac{1}{\omega_{c2} C_1} = \frac{1}{(2\pi)(5kHz)(1000pF)} = 31{,}830\Omega \approx 31.8k\Omega$$

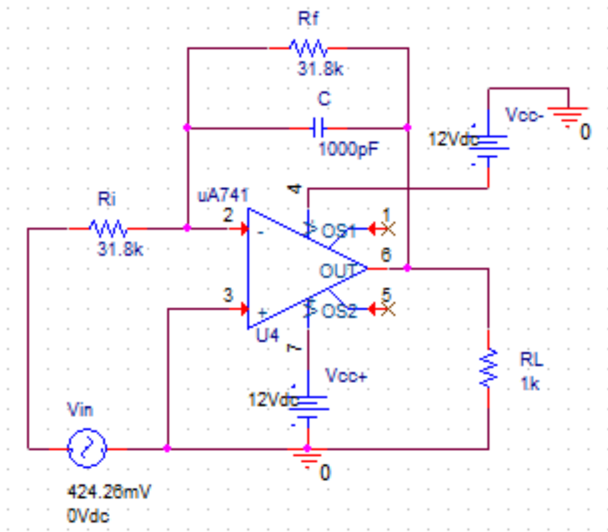

Figure 4.2.1 – Bass Low Pass Active Filter Design with 5kHz Cutoff

High Pass Section:

$$R_{f2} = \frac{1}{\omega_{c1} C_2} = \frac{1}{(2\pi)(150Hz)(0.082\mu F)} = 12{,}939\Omega \approx 12.9k\Omega$$

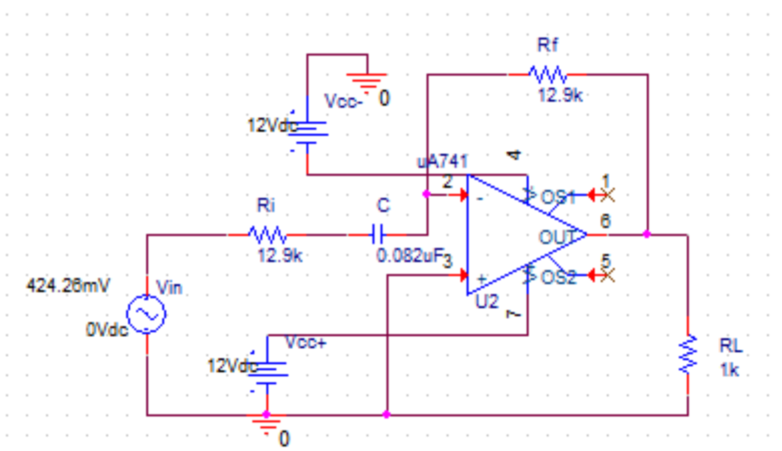

Figure 4.2.2 – Bass High Pass Active Filter Design with 150Hz Cutoff

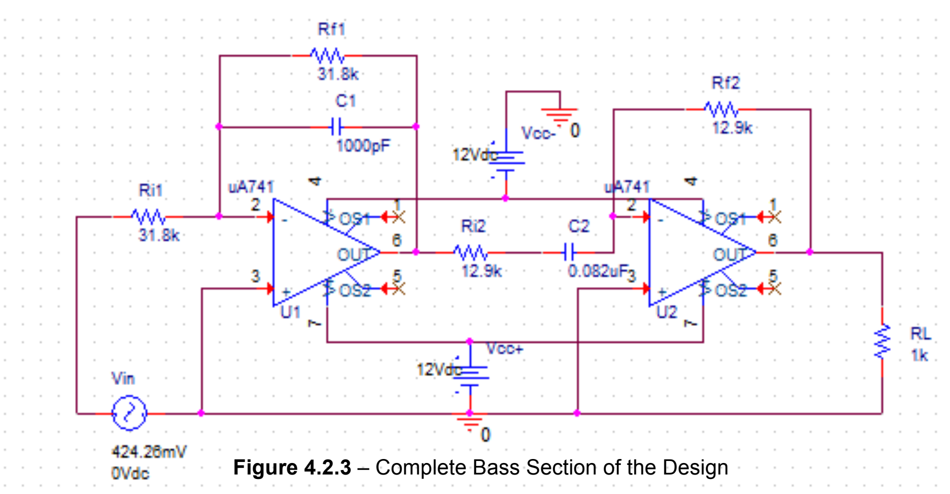

Figure 4.2.3 – Complete Bass Section of the Design

4.3 Designing the Treble Section of the Docking Station:

Design Specifications:

- Gain = -10
- $\omega_{C_1} = 4kHz$
- $\omega_{C_2} = 10kHz$

$$Gain = -\frac{R_{f3}}{R_{i3}} = -\frac{100k\Omega}{10k\Omega} = -10$$

Design Procedure:

The student used known capacitor values that they had in their kit as the starting point for these calculations. With these values and the known desired cutoffs, they calculated the proper resistor values that would be necessary to match the desired specifications.

Low Pass Section:

$$R_{f1} = \frac{1}{\omega_{c2}C_1} = \frac{1}{(2\pi)(10kHz)(1000pF)} = 15{,}915\Omega \approx 15.9k\Omega$$

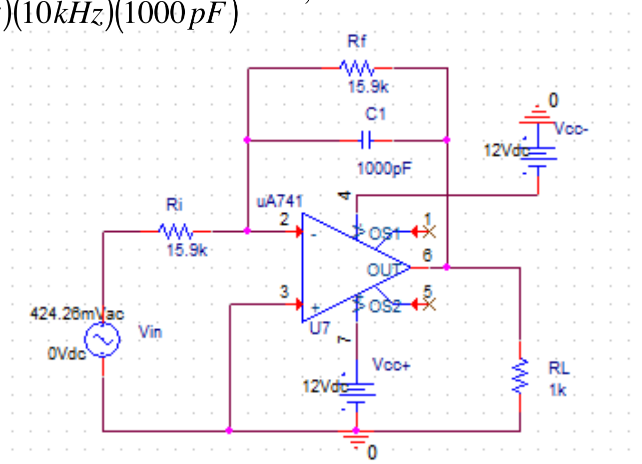

Figure 4.3.1 – Treble Low Pass Filter with 1kΩ Load and 10kHz Cutoff

High Pass Section:

$$R_{f2} = \frac{1}{\omega_{c1}C_2} = \frac{1}{(2\pi)(4kHz)(1000pF)} = 39{,}788\Omega \approx 40.0k\Omega$$

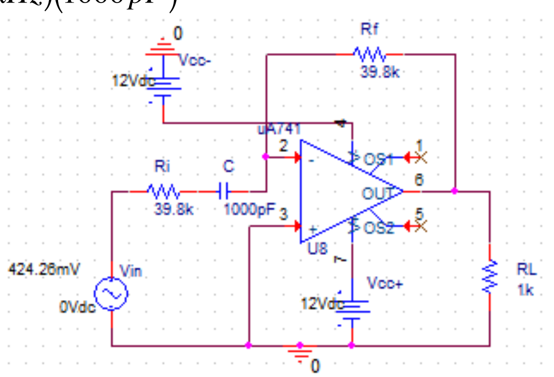

Figure 4.3.2 – Treble High Pass Filter with 1kΩ Load and 4kHz Cutoff

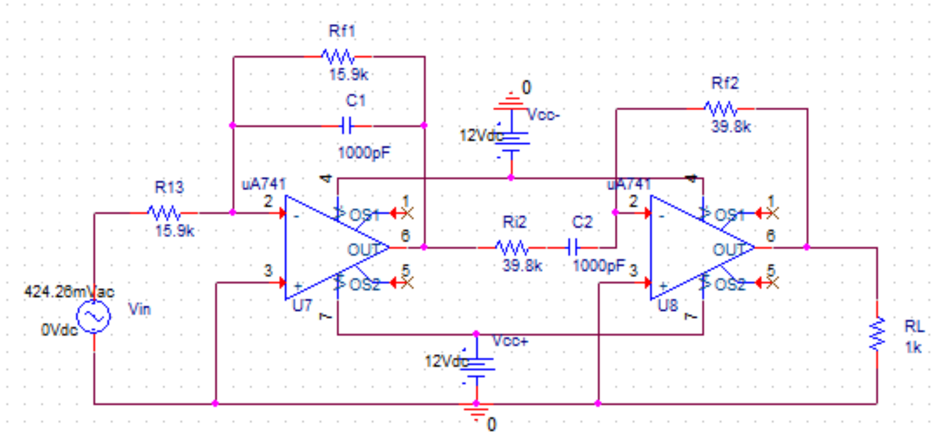

Figure 4.3.3 – Complete Treble Section of the Design

4.4 Designing the Amplification:

It became increasingly apparent in this project that the LM741 would not be capable of powering the speakers attached to the circuit. Therefore, it was necessary to implement the LM386 power amplifier to set the gain for each section of the docking station. Per the specifications sheet for the LM386, in particular the sample designs to set a specific gain, a resistor in series with a 10μF capacitor connected between pins 1 and 8 could be used to adjust the gain. In the case of the bass section, the resistor valued was adjusted to 5kΩ to give a gain between 20 and 50. The treble section amplifier included a resistor of 1.5kΩ to set the gain between 50 and 200. The output from the filters was attached directly to the input of the LM386, and the output of the LM386 passed through a potentiometer and on to the speaker.

4.5 Designing the Volume Control:

The concept of the volume control in this project was fairly simple. A single potentiometer was used between the power amplifier and the speaker to act like a voltage divider circuit. The greater the resistance of the potentiometer, the less voltage that would drop on the speaker and therefore the volume would decrease. A 1kΩ potentiometer was used in the bass section and a 50kΩ potentiometer was used in the treble section.

4.6 Designing the LED Bar Volume Display:

Design Specifications:

- Power Supply: 12 V_{DC} (±5%)
- Node Voltages (5 Total): 5 V_{DC}, 4 V_{DC}, 3 V_{DC}, 2 V_{DC}, 1 V_{DC} (±5%)

Calculations:

$\frac{7V}{12V} = 58.3\%$ < Meaning resistor #1 must be 66.6% of total resistance.

$\frac{70k\Omega}{120k\Omega} = 58.3\%$ < Resistor #1 can be 80kΩ

Other Resistors each get 1V drop across them, so they will all be equal to 10kΩ.

This design process was used to design the original comparator circuit that would be used to implement the volume display. However, it became apparent after testing the circuit with these node voltages, the speakers would either need to be extremely loud to have something that was visually appealing, or there would not be much to see. For this reason, the first resistor in the voltage ladder was raised from 70kΩ all the way up to 120kΩ. This reduced the node voltages greatly and allowed for a much more visually appealing display when the music was being played.

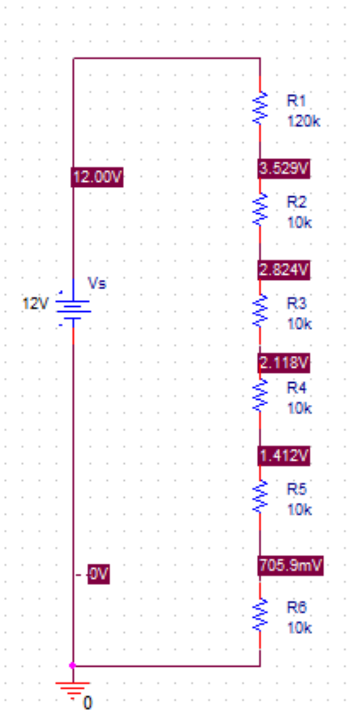

Figure 4.6.1 – Voltage Ladder Showing Node Voltages

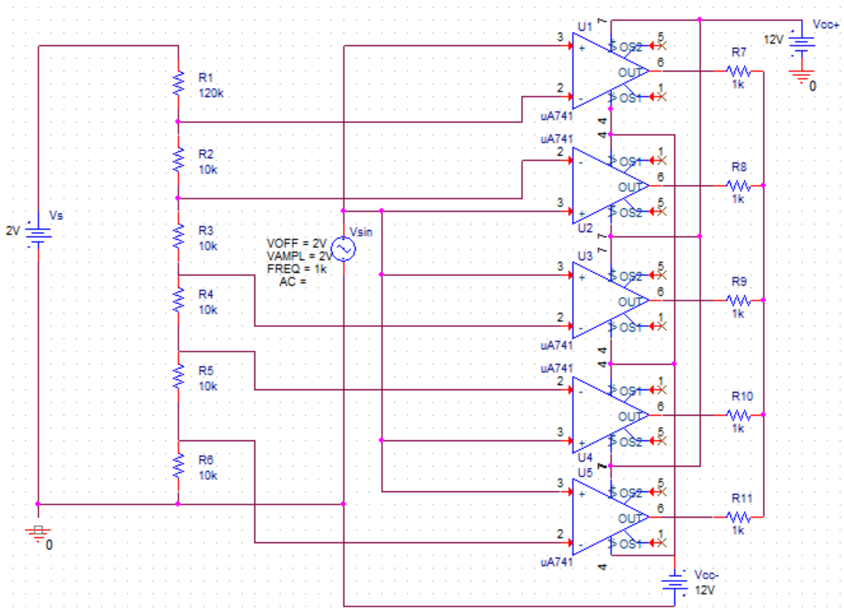

Figure 4.6.2 - LED Comparator Circuit Design

4.7 Putting It All Together:

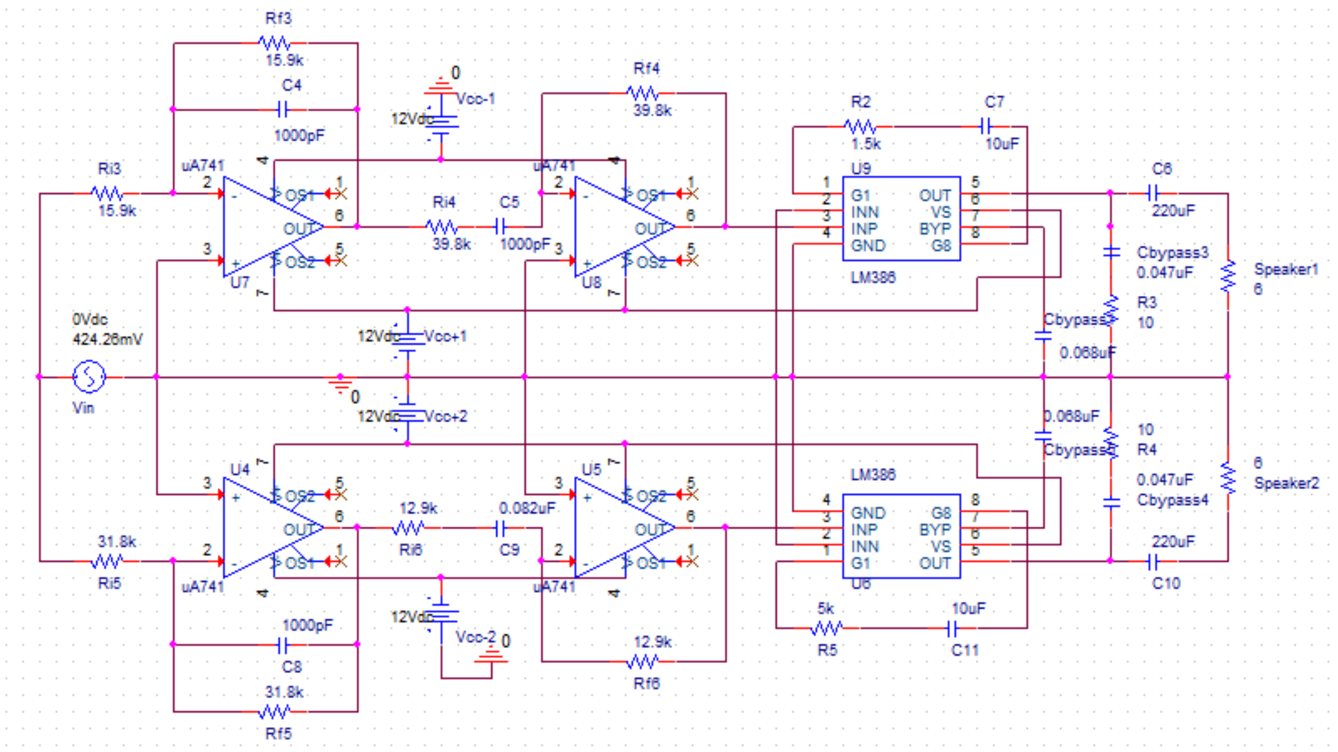

Figure 4.7.1 – Complete Circuit Design Showing Treble Section at Top, Bass Section at Bottom
(Does not include the two comparator circuits shown above in **Figure 4.6.2** and connected before each speaker)

5. Measurements and Results

*Sample Calculations can be found in **Section 9: Appendix**.

5.1 Results for **Section 4.2** Bass Design**:**

	V_{out} (RMS) (mV)			Gain (V_{out}/V_{in})		P_{out} Peak (mW)		I_{out} Peak (mA)	
Frequency	**Sim.**	**Meas.**	**% Error**	**Sim.**	**Meas.**	**Sim.**	**Meas.**	**Sim.**	**Meas.**
10Hz	424.254	422	0.53%	1.00	0.99	0.180	0.178	0.424	0.422
150Hz	424.061	420	0.96%	1.00	0.99	0.180	0.176	0.424	0.420
1kHz	415.945	410	1.43%	0.98	0.97	0.173	0.168	0.415	0.410
4kHz	330.659	310	6.25%	0.78	0.73	0.109	0.096	0.331	0.310
5kHz	299.664	300	0.11%	0.71	0.71	0.090	0.090	0.300	0.300
6kHz	271.529	280	3.12%	0.64	0.66	0.074	0.078	0.272	0.280
	Sim.	**Meas.**	**% Error**						
-3dB	5kHz	5kHz	0%						

Table 5.1.1 – Output Characteristic for Bass Low Pass Active Filter with 1kΩ Load and 5kHz Cutoff

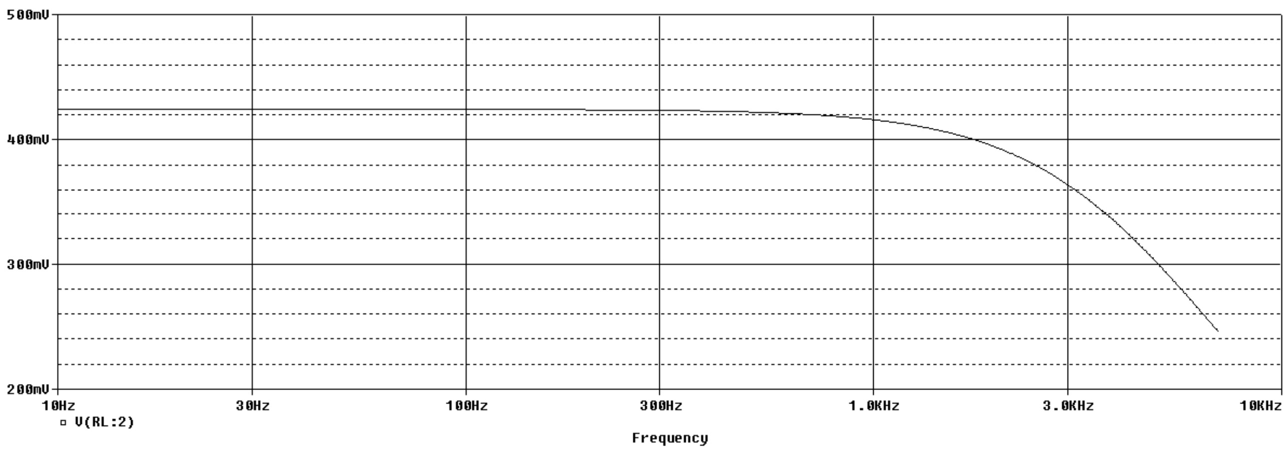

Figure 5.1.1 – PSPICE Curve Showing Voltage Magnitude Across 1kΩ Load for Bass Low Pass Filter

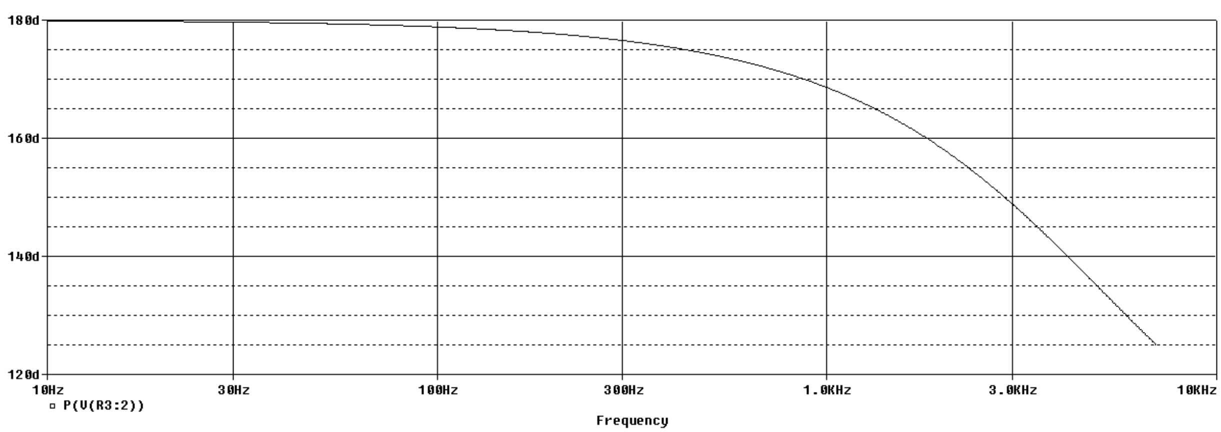

Figure 5.1.2 – PSPICE Curve Showing Voltage Phase Across 1kΩ Load for Bass Low Pass Filter

	V_{out} (RMS) (mV)			Gain (V_{out}/V_{in})		P_{out} Peak (mW)		I_{out} Peak (mA)	
Frequency	**Sim.**	**Meas.**	**% Error**	**Sim.**	**Meas.**	**Sim.**	**Meas.**	**Sim.**	**Meas.**
10Hz	28.136	30	6.62%	0.07	0.07	0.001	0.001	0.028	0.030
150Hz	300.00	300	0%	0.71	0.71	0.090	0.090	0.300	0.300
1kHz	419.598	415	1.10%	0.99	0.98	0.176	0.172	0.420	0.415
4kHz	424.018	420	0.95%	1.00	0.99	0.180	0.176	0.424	0.420
5kHz	424.119	422	0.50%	1.00	0.99	0.180	0.178	0.424	0.422
6kHz	424.173	424	0.04%	1.00	1.00	0.180	0.180	0.424	0.424
	Sim.	**Meas.**	**% Error**						
-3dB	150Hz	150Hz	0%						

Table 5.1.2 – Output Characteristic for Bass High Pass Active Filter with 1kΩ Load and 150Hz Cutoff

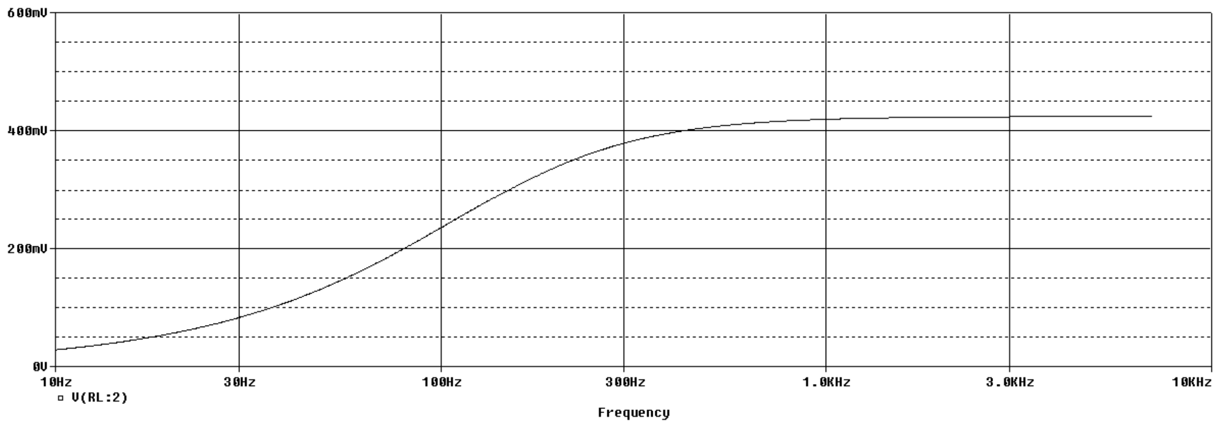

Figure 5.1.3 – PSPICE Curve Showing Voltage Magnitude Across 1kΩ Load for Bass High Pass Filter

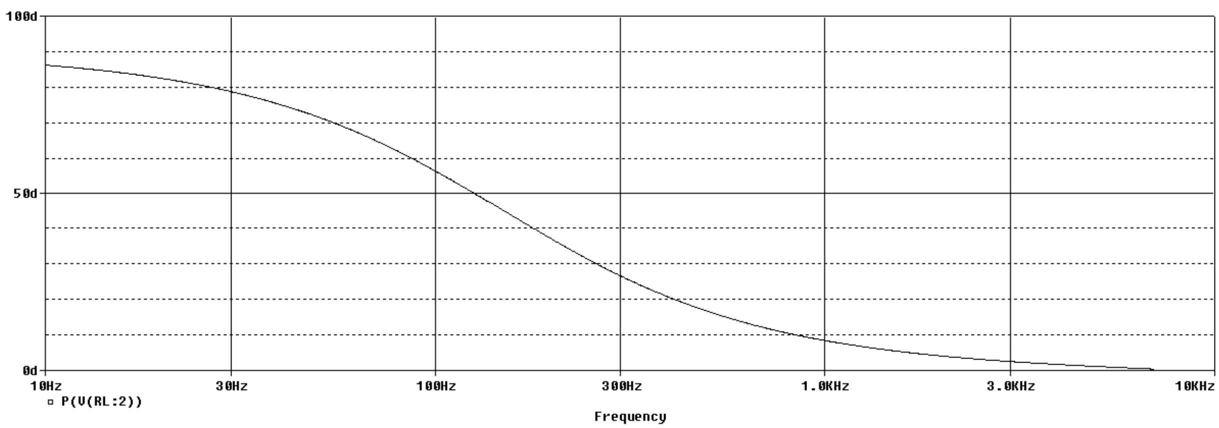

Figure 5.1.4 – PSPICE Curve Showing Voltage Phase Across 1kΩ Load for Bass High Pass Filter

	V_{out} (RMS) (mV)			Gain (V_{out}/V_{in})		P_{out} Peak (mW)		I_{out} Peak (mA)	
Frequency	**Sim.**	**Meas.**	**% Error**	**Sim.**	**Meas.**	**Sim.**	**Meas.**	**Sim.**	**Meas.**
10Hz	28.135	30	6.63%	0.07	0.07	0.001	0.001	0.028	0.030
150Hz	300.00	300	0%	0.71	0.71	0.090	0.090	0.300	0.300
1kHz	411.379	415	0.88%	0.97	0.98	0.169	0.172	0.411	0.415
4kHz	331.166	320	3.37%	0.78	0.75	0.110	0.102	0.331	0.320
5kHz	299.140	300	0.29%	0.71	0.71	0.090	0.090	0.299	0.300
6kHz	271.013	280	3.32%	0.64	0.66	0.073	0.078	0.271	0.280
	Sim.	**Meas.**	**% Error**						
-3dB	150Hz, 5kHz	150Hz, 5kHz	0%						

Table 5.1.3 – Output Characteristic for Complete Bass Band Pass Active Filter with 1kΩ Load

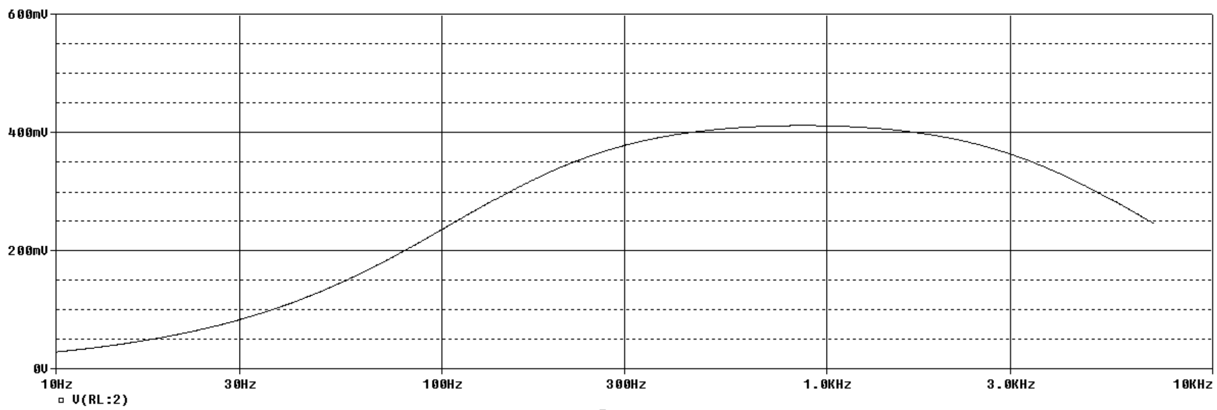

Figure 5.1.5 – PSPICE Curve Showing Voltage Magnitude Across 1kΩ Load for Entire Bass Section

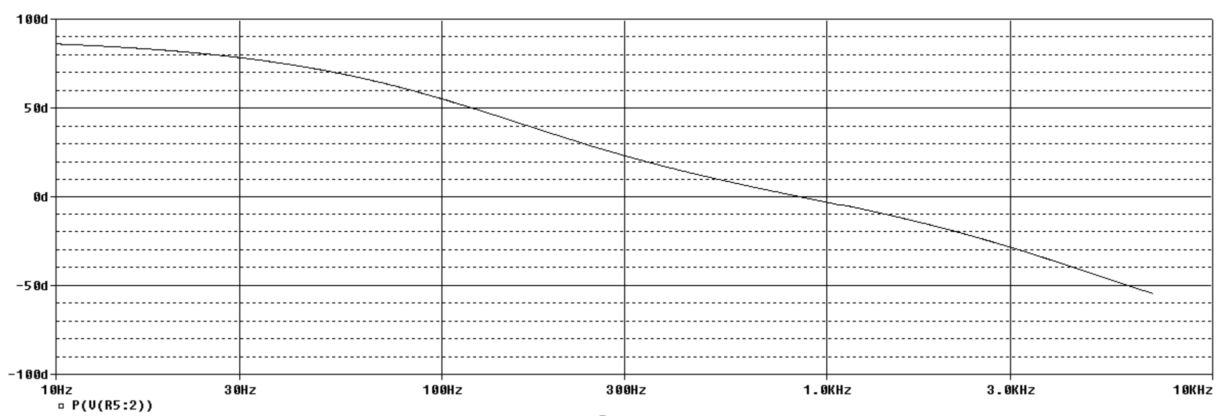

Figure 5.1.6 – PSPICE Curve Showing Voltage Phase Across 1kΩ Load for Entire Bass Section

Band Pass Active Filter Results:

Max Voltage Out at 1kHz of 411.639mV.

$$i = \frac{V_{out}}{R_L} = \frac{411.639mV}{8\Omega} = 51.5mA$$

The LM741 can only deliver a max current of ~25mA and therefore cannot handle the amount of current needed in this application. The 8Ω load would draw over double that amount of current. Therefore, the LM386 must be used in place of the LM741 as a power amplifier.

	V_{out} (RMS) (mV)			Gain (V_{out}/V_{in})		P_{out} Peak (mW)		I_{out} Peak (mA)	
Frequency	**Sim.**	**Meas.**	**% Error**	**Sim.**	**Meas.**	**Sim.**	**Meas.**	**Sim.**	**Meas.**
10Hz	28.133	30	6.63%	0.07	0.07	0.990	0.113	3.52	3.75
150Hz	300.00	300	0%	0.71	0.71	11.3	11.3	37.5	37.5
1kHz	411.639	415	0.82%	0.97	0.98	21.2	21.5	51.5	51.9
4kHz	330.901	320	3.30%	0.78	0.75	13.7	12.8	41.4	40.0
5kHz	299.098	300	0.30%	0.71	0.71	11.2	11.3	37.4	37.5
6kHz	270.268	280	3.60%	0.64	0.66	9.14	9.80	33.8	35
	Sim.		**Meas.**		**% Error**				
-3dB	150Hz, 5kHz		150Hz, 5kHz		0%				

Table 5.1.4 – Output Characteristic for Complete Bass Band Pass Active Filter with 8Ω Load

*LM386 Amplification set between +20 and +50

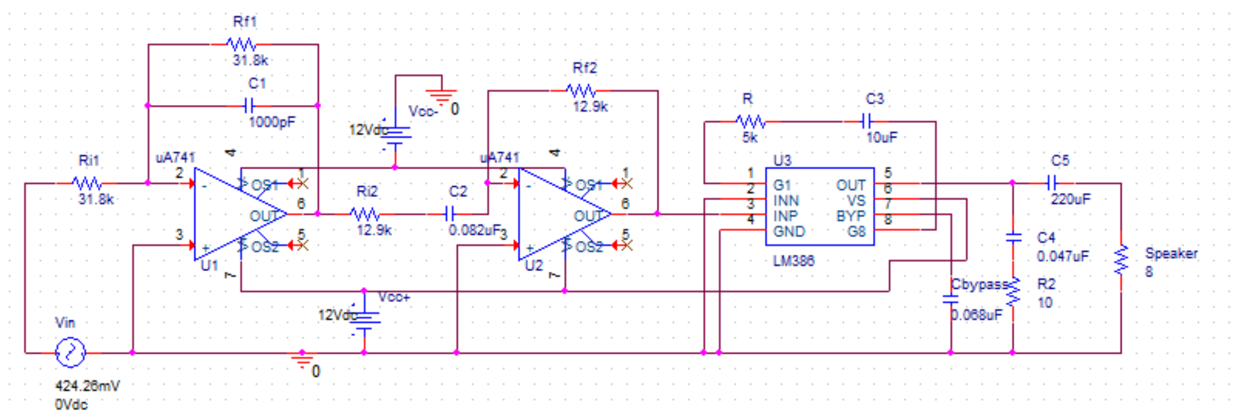

Figure 10 – Bass Band Pass Active Filter Design with Amplification for 8Ω Load

	V_{out} (RMS) (V)	Gain (V_{out}/V_{in})	P_{out} Peak (mW)	I_{out} Peak (mA)
Frequency	**Meas.**	**Meas.**	**Meas.**	**Meas.**
10Hz	0.077697	0.18	0.113	3.75
150Hz	6.4986	15.3	11.3	37.5
1kHz	10.350	24.4	21.5	51.9
4kHz	8.3505	19.7	12.8	40.0
5kHz	7.5484	17.8	11.3	37.5
6kHz	6.8422	16.1	9.80	35
	Meas.			
-3dB	150Hz, 5kHz			

Table 5.1.5 – Output Characteristic for Complete Bass Band Pass Active Filter with 8Ω Load and Amplification

5.2 Results for **Section 4.3** Treble Design:

*Extensive tables showing measurements and results have been omitted from this section in favor of presenting the data in the form of PSPICE plots. The tables of data would turn out to be very similar in their effect as those presented in the previous section regarding the Bass section of the design. The results simply confirm the PSPICE results.

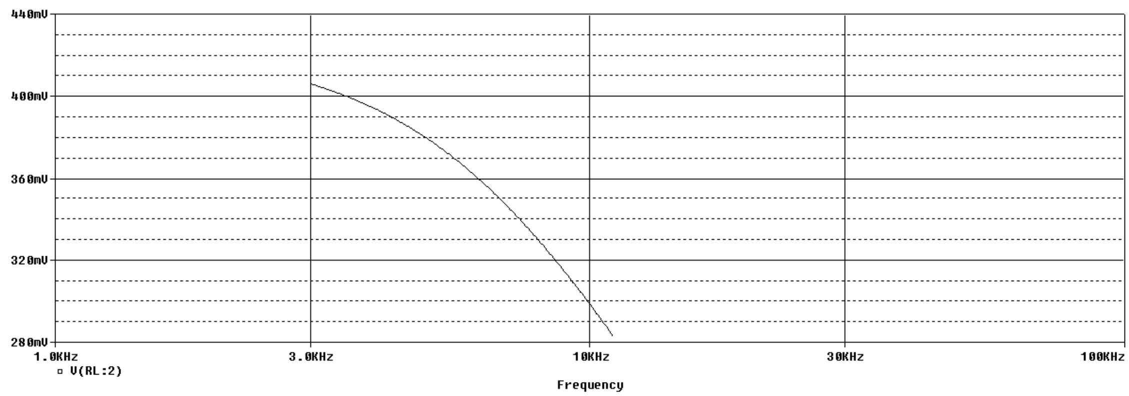

Figure 5.2.1 – Treble Low Pass Filter Voltage Magnitude

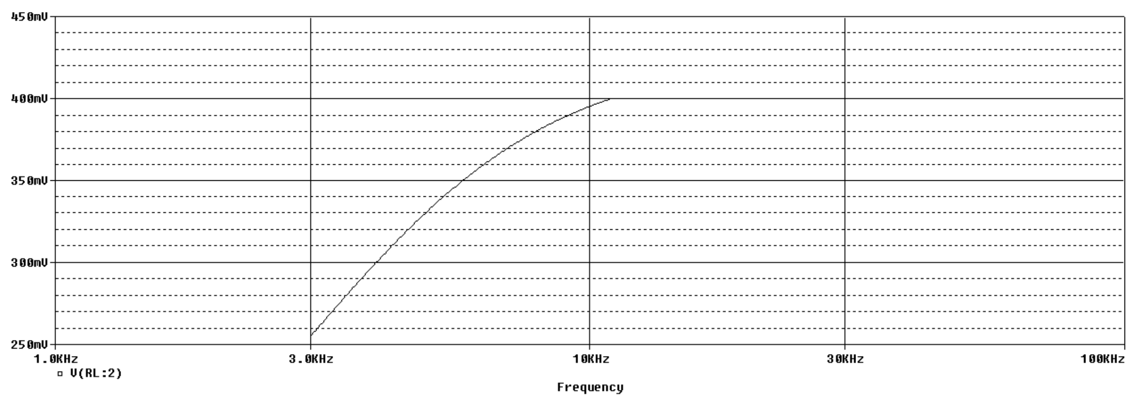

Figure 5.2.2 – Treble High Pass Filter Voltage Magnitude

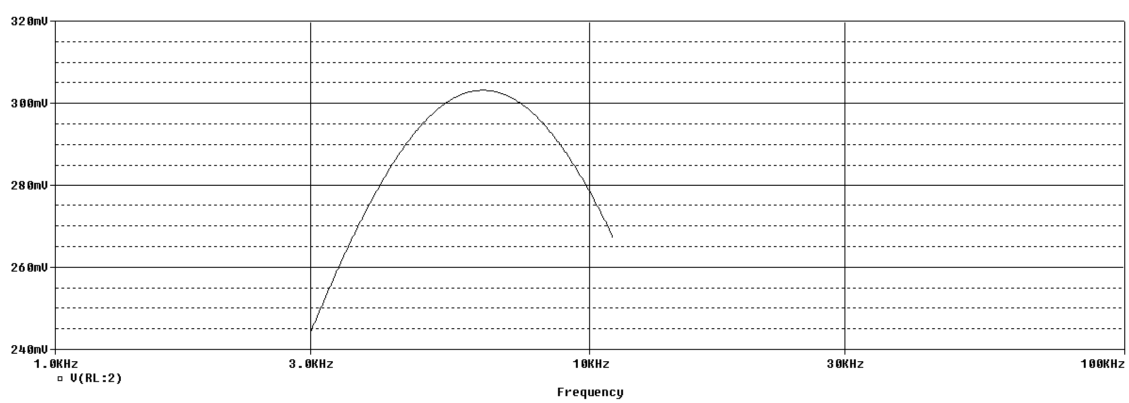

Figure 5.2.3 – Treble Band Pass Filter Voltage Magnitude (Cutoff frequencies are 4kHz and 10kHz)

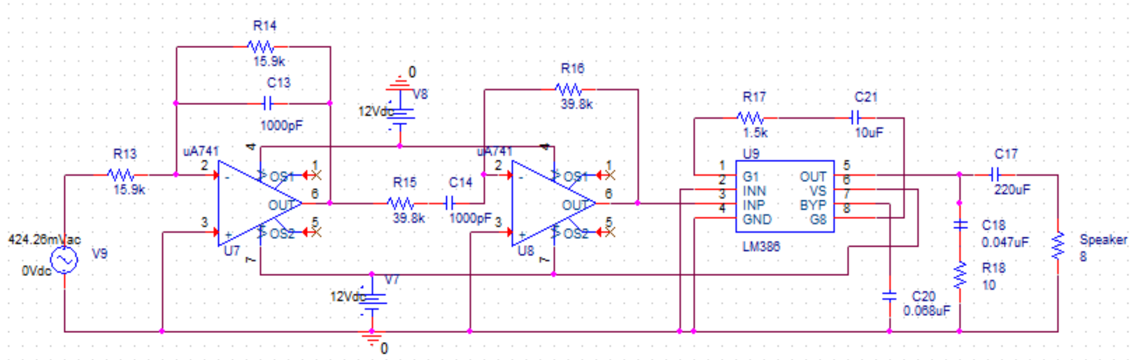

Figure 5.2.4 – Treble Band Pass Filter with 8Ω Load and Amplification

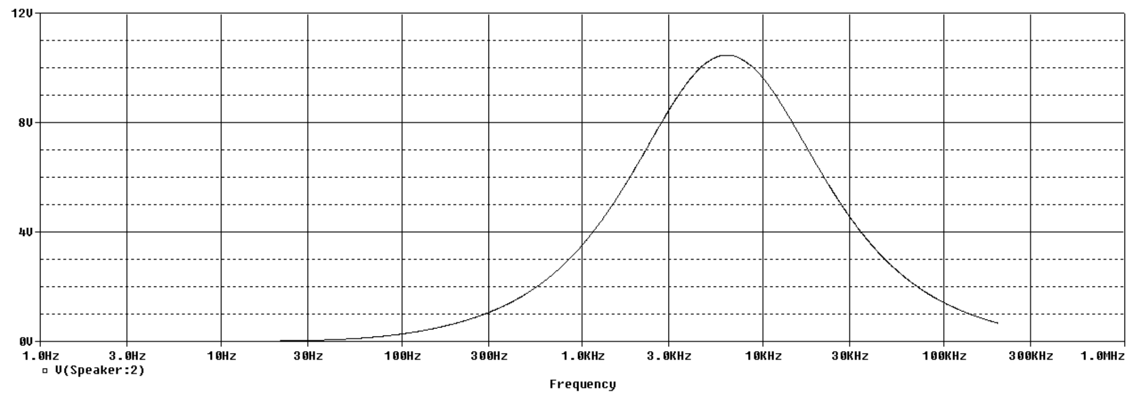

Figure 5.2.5 – Treble Band Pass Filter with Amplification Showing Voltage Magnitude

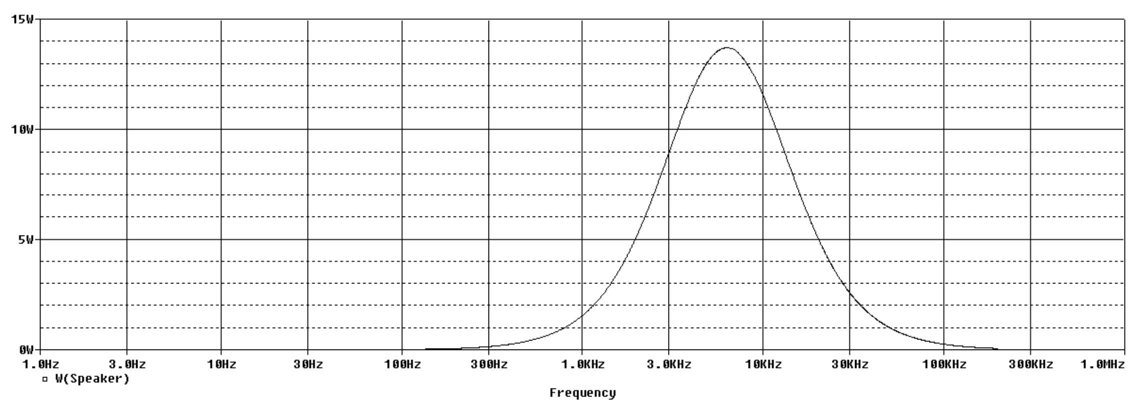

Figure 5.2.6 – Treble Band Pass Filter with Amplification Showing Power Magnitude

5.3 Results for **Section 4.6** Comparator Circuit for LED Bar Volume Display:

*These results show the original comparator circuit design from Lab Report 12, which was tweaked to work for the specifications needed in this final project. For example, a fifth node voltage was added by adding in another resistor and the node voltages were all brought down. In the end, the results seen from the PSPICE output would be nearly identical, with an extra line.

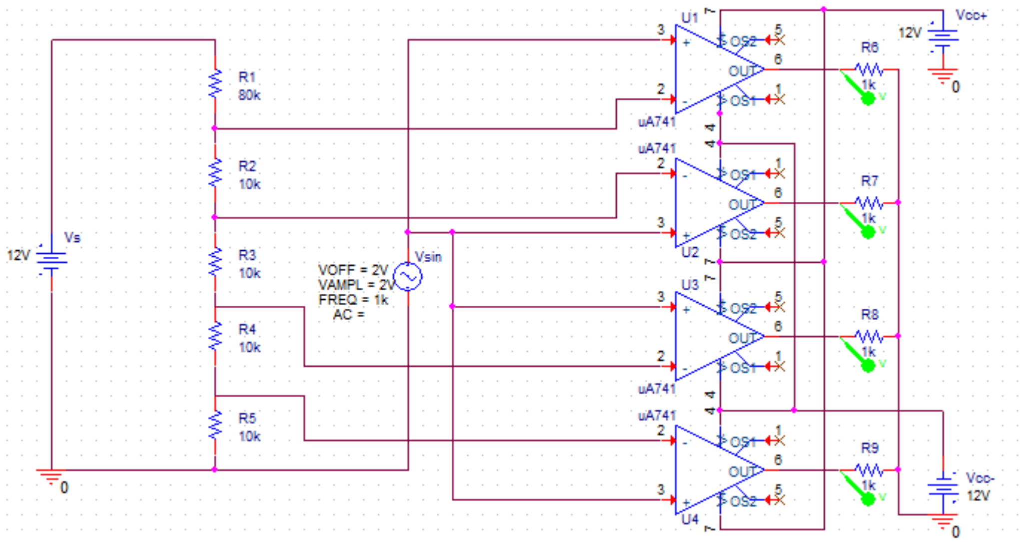

Figure 5.3.1 – Original Voltage Ladder Comparator Design

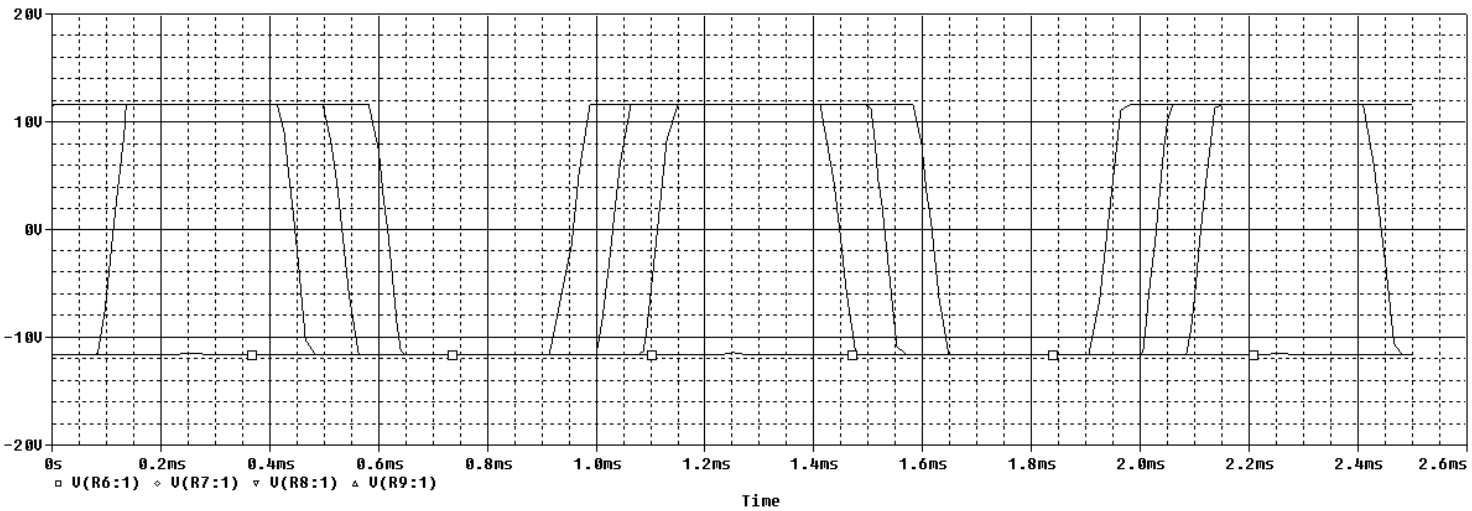

Figure 5.3.2 – Voltage Ladder Comparator Results Showing Different V_{out} Values Jumping from +12V to -12V

***It is important to see here that all four outputs are plotted on the same graph in these results. It is difficult to differentiate which is which, however there is one obvious result to be noted. The line at the bottom of the results, the constant -12V output is the output from the top comparator, which is comparing the sine voltage source and the 4V reference. Because the sine source has a max of 4V, it never rises above the 4V reference mark and therefore never changes from the -12V output. In the remaining three curves, it is fairly obvious that the voltages are periodically switching from roughly +12V to -12V. The values are not quite exactly 12V because there is some loss in the LM741 and there is the slightest delay as the comparator switches between the +12V and -12V.

5.4 Results for **Section 4.7** Entire Design Together:

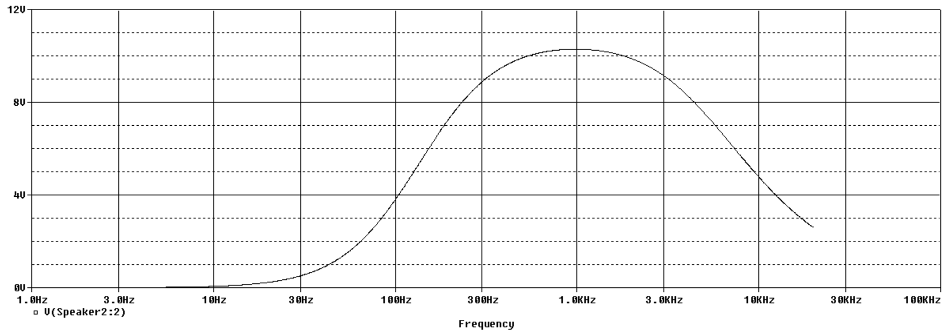

Figure 5.4.1 – Final Bass Section Voltage Output Across Speaker

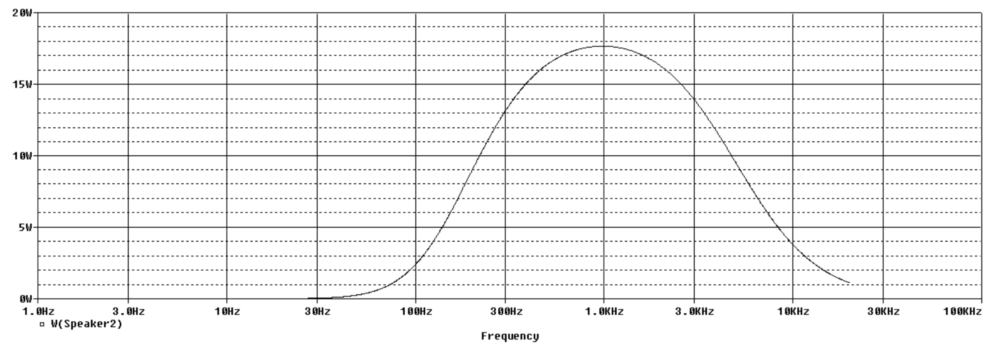

Figure 5.4.2 – Final Bass Power Dissipated by Speaker

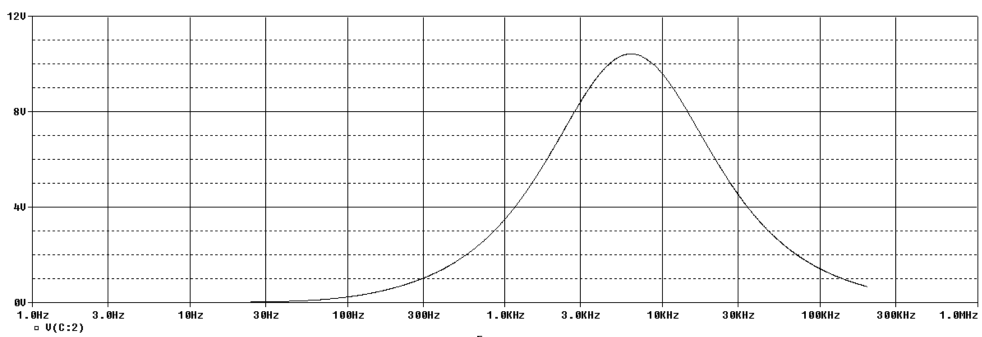

Figure 5.4.3– Final Treble Section Voltage Output Across Speaker

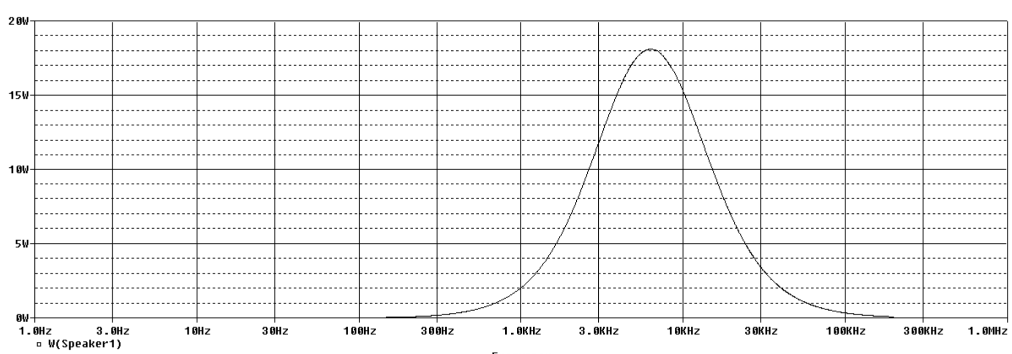

Figure 5.4.4 – Final Bass Power Dissipated by Speaker

6. Analysis and Discussion

Discussion from Lab 11 Memo:

In presenting the data, it is also important to understand the data and interpret it. One of the most important methods in analyzing data is observing any error found between the simulated results and the measured results from the lab. In these particular experiments, the most important error is that which was found in the output voltage. This error is so crucial to determining the accuracy of the experiment because the rest of the data in the tables presented through this memorandum are derivatives of the original V_{out} measurements. The gain, current, and power are all found using the output voltage, therefore the most important error to be noted and observed is only the error found in the output voltage. When looking at the errors collected throughout this lab, they are all relatively small, meaning the lab results accurately and precisely confirm the simulated results. The slight error is most likely due to the tolerances of the resistors and capacitors used in the lab and the less precise measuring ability of the oscilloscope. It cannot output very many significant figures and can sometimes change its reading based on the scale set for the measurements.

It is also necessary to quickly explain the reasoning behind the choice of the LM386 over the LM741. According to the specifications sheet of the LM741, the Output Short Circuit Current is only 25mA, not nearly enough for the power necessary to power the 8Ω speaker. The LM386, on the other hand, is designed to be a power amplifier and is capable of outputting much more current and therefore more power. For this reason, it is smart to choose the LM386 as the power amplifier so that the speaker can be properly powered.

In the final part of this lab, it is also important to realize that the 8Ω load connected to the circuit is a speaker and not a resistor. The tiny resistors that are available in the lab are not capable of handling the current and power of the circuit in this application. If a simple resistor were placed in the circuit as the load, it would simply fry up and start to burn. The speaker on the other hand is capable of handling much more power and can be safely placed into the circuit as the load for this application. In the final result, the LM386 was configured so that the amplification would fall somewhere between +20 and +50. At +50, the max power would have fallen above the 20W capacity of the speaker, so to be safe, the LM386 setup was adjusted so that the max power would fall just below 20W.

General Project Discussion:

The results of this project are fairly straightforward. The project consisted of designing, building, and implementing almost all of the knowledge that the students have gained this entire semester in Circuit Theory. The basis of the project rested in the knowledge of filters, which is a very specific form of a voltage divider using an AC circuit with capacitors and inductors to be able to isolate certain bands of frequencies, allowing desired frequencies to pass through and filtering out unwanted frequencies. One important note is that this circuit will not simply rid the audio signal of the unwanted frequencies, but it will reduce their volume, making the desired frequencies the most prevalently heard.

Another important thing to mention here would be some of the challenges that were faced throughout this project. The single most difficult challenge was figuring out where to place decoupling capacitors and how big to make them in order to properly remove the noise from the circuit. In the original design, there was a lot of random noise coming from the power supply because it was not perfect DC voltage, but had AC voltage as well. In the end, it was necessary to connect a small capacitor from both the positive and negative power supply directly to ground. This sent the AC noise straight to ground and only allowed the DC voltage to power the op-amps. This cut out almost all of the noise that was remaining in the circuit and made for a much clearer, crisp sound through the speaker. Another thing to mention would be the pure time it took to be able to design and build the circuit. Granted, a much simpler design could have taken less time, but in order to have the wiring neat and understandable, it took a lot of time organizing and mentally laying out the design to decide what would work best.

7. Conclusion

In conclusion, this project required a ton of work and a lot of effort to be able to design and build such a complete and functional device such as this iPod docking station. While it may have been difficult, it really helped to expand students' technical knowledge of the concepts that they have been learning all semester and broadened their view on the applications of their skills to a device that is very useful in common applications today. While the project was in the end a success, a few things could have been done to make it even better. One main thing that could be done to improve this design would be to use second order filters instead of first order ones. Another improvement would be using better knobs for the volume control that had finer control than the simple potentiometers. One more possible enhancement would be to use ten total comparators from ten node voltages to light each individual LED bar. This would add increased sensitivity in terms of the lights being on or off as each LED would operate separately rather than two at a time as it is in this final design. Overall, this project successfully challenged students to strive for their own best and to produce a final design that was not only functional, but also understood by the student in terms of how it worked. It is one thing to build a working product, but it is another entirely to fully understand that product, how it works, and why it works. This project surely pushed students to fully grasp the concepts of circuit theory in order to design and build the best docking station possible.

8. References

[1] GWU SEAS ECE Department, "Final Project Specs," The ECE 2110 Course Website, Fall 2011. <http://www.seas.gwu.edu/~ece11/fall11/FinalProjectSpecs.pdf>

[2] GWU SEAS ECE Department, "Lab 11," The ECE 2110 Course Website, Fall 2011. <http://www.seas.gwu.edu/~ece11/fall11/lab11.pdf>

[3] GWU SEAS ECE Department, "Lab 12," The ECE 2110 Course Website, Fall 2011. <http://www.seas.gwu.edu/~ece11/fall11/lab12.pdf>

[4] Thomas, Roland E., Rosa, Albert, J., "The Analysis and Design of Linear Circuits, 6th Edition," Wiley, 2009.

9. Appendix

<u>9.1 Sample Calculations</u>:

Sample Percent Error Calculation for 10Hz Frequency in **Table 5.1.1:**

$$PE = \frac{|NV - MV|}{NV} * 100 = \frac{|424.254mV - 422mV|}{424.254mV} * 100 = 0.53\%$$

Sample Gain Calculation for 5kHz Frequency in **Table 5.1.1:**

$$T(\omega) = Gain = \frac{V_{out}}{V_{in}} = \frac{300mV}{424.254mV} = 0.707$$

Sample I_0 Peak Calculation for 5kHz Frequency in **Table 5.1.1:**

$$I_0 Peak = \frac{V_{out}}{R} = \frac{300mV}{1k\Omega} = 0.300mA$$

Sample P_{out} Calculation for 5kHz Frequency in **Table 5.1.1:**

$$P_{out} = V_{out} I_0 = (300mV)(0.300mA) = 0.090mW$$

9.2 Picture of Final Project: