Final Project - Formal Report

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Elizabeth Tu

Susan Zhao

TA: John Fischer

Instructor: Thomas Farmer

ESE 215 103

December 23, 2016

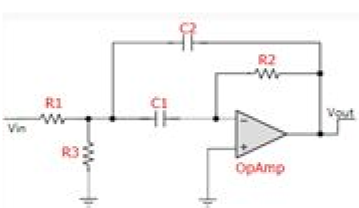
Final Project: Audio Docking Station

Introduction

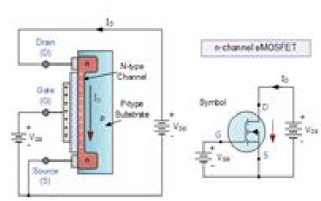
The purpose of this project was to create an audio docking station. This project consisted of three major components: a bass and treble filter, an amplifier, and a power supply. The power supply was constructed for the midterm project, where an AC input was converted to a +12 and -12DC output. Ideally, this power supply would power all the OpAmps in the filters and transistors in the amplifier component. The purpose of the treble and bass filter was to take an audio signal as the input, and separate it into “bass” or low frequency, and “treble” or high frequency signals. The amplifier acted as the component to intensify the signal enough to power the signal through the speakers provided. This project requires the initial design of the filter, amplifier, and power supply, a working simulation of each component and the components integrated, and finally testing and reiteration of the components adjusted for differences from the simulation.

Background

This project was broken into three main parts. This allowed for easier debugging and redesigning each step. The first step was to design and construct a bass and treble filter. The input was audio played on a laptop or phone, with voltages ranging from 0 to 300mVrms and frequencies ranging from 20Hz to 20kHz. The bass filter was designed to allow only music in the frequency range of 150 Hz to 350 Hz to pass, while the treble filter was designed to allow only music in the range of 8kHz to 10kHz pass. In this step, we used a Multiple Feedback Bandpass Filter (see left for general design) for both cases. The advantages in this design included the use of only one OpAmp -making it a first-order active bandpass filter, a resistor, R1, that could be replaced with a potentiometer and used to precisely control the gain of each filter, and a steep roll-off.



The amplifier used was a first-order, and used an n-channel MOSFET. As seen on the diagram to the right, the supply voltage is



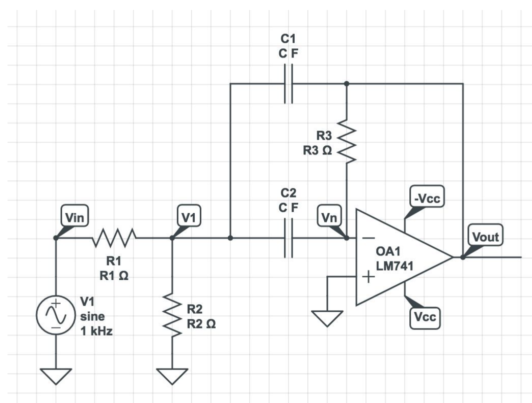
positive. The gate terminal is required to be biased, which we successfully accomplished by using a voltage divider. This enabled a constant, specific DC offset that allowed the MOSFET to operate as a linear amplifier. In both the filter and amplifier component, the +12 and -12 voltages were supplied by the power supply.

Part 1: Filter Component

The following hand calculations and simulations are shown in order to design filters that meet the requirement of 8kHz to 10kHz frequency range for treble and 150Hz to 350Hz frequency range for the bass. In order to design for these specifications, transfer functions were calculated, as well center and corner frequencies, bandwidth, Q, and roll off rate.

Hand Calculations:

Both filters were first order multiple feedback bandpass filters, each with components indexed as show in the schematic below. Capacitors are assumed to be the same value C for convenience.



Transfer Function:

$$\frac{V_{out}}{V_{in}} = \left(\frac{R_2}{R_1 + R_2}\right) * \frac{j\omega C R_3}{-\omega^2 \, C^2 \, R_3 \left(\frac{R_1 + R_2}{R_1 R_2}\right) + j\omega C \left[R_3 + \frac{2R_1R_2}{R_1 + R_2}\right] + 1}$$

Transfer Function Calculation:

$$\frac{V_1 - V_{in}}{R_1} + \frac{V_1}{R_2} + \frac{V_1}{Z_C} + \frac{V_1 - V_{out}}{Z_C} = 0$$

$$\frac{V_{out}}{R_3} + \frac{V_{out} - V_1}{Z_C} = 0$$

$$V_1 = V_{out}\left(\frac{1 + j\omega C R_3}{j\omega C R_3}\right)$$

$$V_1\left(\frac{R_1 + R_2 + j2\omega C R_1 R_2}{R_1 R_2}\right) - V_{out}\, j\omega C = \frac{V_{in}}{R_1}$$

$$V_{out}\left[\left(\frac{1 + j\omega C R_3}{j\omega C R_3}\right) * \left(\frac{R_1 + R_2}{R_1 R_2} + j2\omega C\right) + \frac{\omega^2 C^2 R_3}{j\omega C R_3}\right] = \frac{V_{in}}{R_1}$$

$$V_{out}\,\frac{\left[-\omega^2 C^2 R_3 + j\omega C\left(R_3 * \frac{R_1 + R_2}{R_1 R_2} + 2\right) + \frac{R_1 + R_2}{R_1 R_2}\right]}{j\omega C R_3} = \frac{V_{in}}{R_1}$$

$$\frac{V_{out}}{V_{in}} = \left(\frac{R_2}{R_1 + R_2}\right) * \frac{j\omega C R_3}{-\omega^2\, C^2\, R_3\left(\frac{R_1 + R_2}{R_1 R_2}\right) + j\omega C\left[R_3 + \frac{2R_1 R_2}{R_1 + R_2}\right] + 1}$$

Filter order:

The above bandpass filter is of first order. The transfer function can be separated into a constant, a zero at the origin with slope of 20 dB/decade and a quadratic pole with slope of -40 dB/decade. When these plots are superimposed, the zero at the origin and quadratic pole combine to a net slope of -20 dB/decade, making it first order.

Center Frequency Calculation:

Second term of quadratic pole:

$$-\omega^2\left(\frac{R_1 R_2}{R_1 + R_2}\right) C^2 R_3 = \frac{j^2 \omega^2}{\omega_c^2}$$

$$\omega_c = \frac{1}{\sqrt{C^2 R_3 (\frac{1}{R_1} + \frac{1}{R_2})}}$$

$$f_c = \frac{1}{2\pi} \frac{1}{\sqrt{C^2 R_3 (\frac{1}{R_1} + \frac{1}{R_2})}}$$

Treble Filter Center Frequency, where

$$R_1 = 8488\Omega, R_2 = 141\Omega, R_3 = 21221\Omega, C = 0.01uF$$
$$f_c = \frac{1}{2\pi}\frac{1}{\sqrt{(0.01uF)^2 * 21221 * (\frac{1}{8488} + \frac{1}{141})}} \approx 9kHz$$

Bass Filter Center Frequency, where

$$R_1 = 12732\Omega, R_2 = 1415\Omega, R_3 = 31831, C = 0.1uF$$
$$f_c = \frac{1}{2\pi}\frac{1}{\sqrt{(0.1uF)^2 * 31831 * (\frac{1}{12732} + \frac{1}{1415})}} \approx 250Hz$$

Q, Quality Factor Calculation:

$$Q = \frac{1}{2}\sqrt{\frac{R_3}{R_1 \parallel R_2}}$$

$$Q_{bass} = \frac{1}{2}\sqrt{\frac{31831}{\frac{12732 * 1415}{12732 + 1415}}} = 2.5$$

$$Q_{treble} = \frac{1}{2}\sqrt{\frac{21221}{\frac{8488 * 141}{8488 + 141}}} = 6.16667$$

Bandwidth Calculation:

$$B = \frac{\omega_0}{Q} = \frac{1}{\sqrt{C^2 R_3(\frac{1}{R_1} + \frac{1}{R_2})}} * \frac{1}{\frac{1}{2}\sqrt{\frac{R_3}{R_1 \parallel R_2}}} = \frac{2}{CR_3}$$

$$B_{treble} = \frac{2}{(0.01uF) * 21221} = 9424.6\ \frac{rad}{s} = 1500\ Hz$$

$$B_{bass} = \frac{2}{(0.1uF) * 31831} = 628.32\ \frac{rad}{s} = 100\ Hz$$

Corner Frequency Calculation:

$$\omega_{c1} = \omega_0 - \frac{B}{2}$$
$$\omega_{c2} = \omega_0 + \frac{B}{2}$$

Treble Corner Frequencies:

$$\omega_{c1\_treble} = 9000 - \frac{1500}{2} = 8250Hz = 8.25kHz$$

$$\omega_{c2\_treble} = 9000 + \frac{1500}{2} = 9750Hz = 9.75kHz$$

Bass Corner Frequencies:

$$\omega_{c1\_bass} = 250 - \frac{100}{2} = 200\ Hz$$

$$\omega_{c2\_bass} = 250 + \frac{100}{2} = 300\ Hz$$

Gain Selection:

The filters were designed to have roughly unity gain, as the outputs of each filter were then amplified in the next stage, an amplification sub-stage consisting of an inverting op amp with a potentiometer in place of Rf for gain control. In the actual circuit, 5k potentiometers were incorporated into R1 in order to achieve unity gain on the oscilloscope.

Resistors R1 and R3 were related to the gain by the following equation:

$$R_1 = \frac{R_3}{2G}, G \approx 1$$

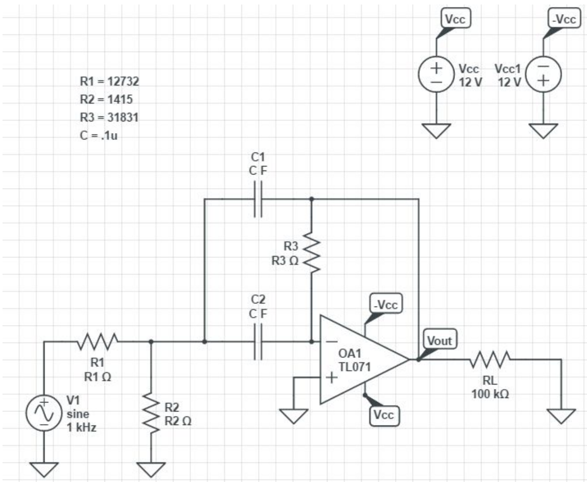
	TL071
Number of Channels (#)	1
Total Supply Voltage (Min) (+5V=5, +/-5V=10)	7
Total Supply Voltage (Max) (+5V=5, +/-5V=10)	36
GBW (Typ) (MHz)	3
Slew Rate (Typ) (V/us)	13
Rail-to-Rail	In to V+
Vos (Offset Voltage @ 25C) (Max) (mV)	6
Iq per channel (Typ) (mA)	1.4
Vn at 1kHz (Typ) (nV/rtHz)	18

Bass Filter

TL071 OpAmp: Low-Noise JFET-Input General-Purpose OpAmp, originally an LM741 OpAmp was used in this filter -but afterwards it was replaced with a TL071 to reduce the noise-induced static being emitted from the speaker

Resistors: 12.7kΩ, 1.4kΩ, 31.8kΩ

Capacitors: 0.1uF (2)

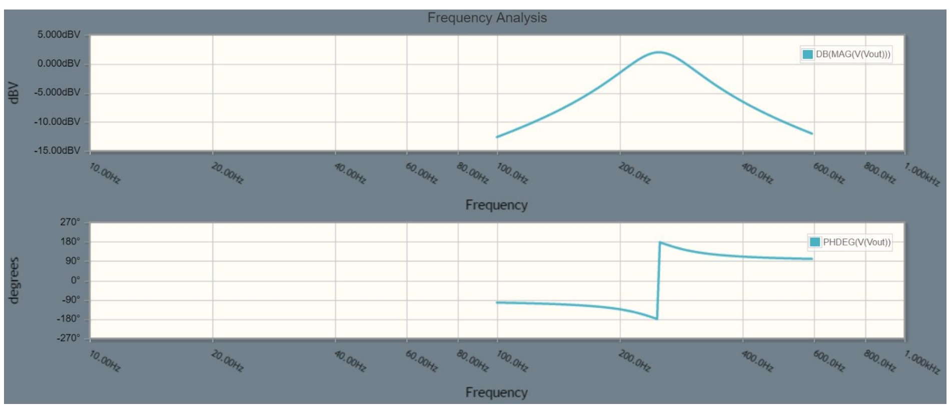


Roll-off rate:

@1kHz: -17.55dB, 10kHz: -38.01dB

-38.01 - (-17.55) = -20.46

-20.46dB/decade



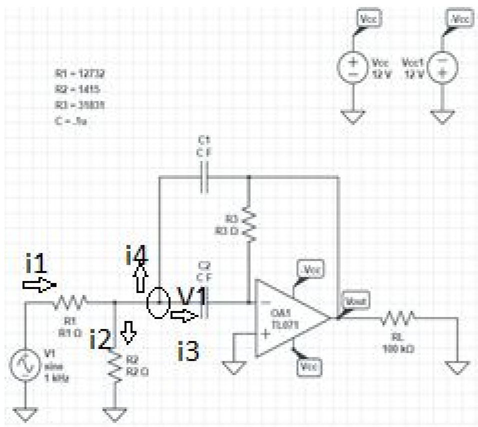
Input/Output Impedance:

Resistors: Z = R, Z = 12.7kΩ, 1.4kΩ, 31.8kΩ

Capacitor: Z = 1/jωC, ω = 2πf = 2π(250Hz) = 1570.8rad/sec

1/j(0.1uF)(1570.8rad/sec) = 6.37kΩ

Calculation of input impedance of Bass Filter



$Z_{in} = V_{in} / i_1$

$V_{in} = i_1R_1 + V_1$

$i_1 = i_2 + i_3 + i_4$

$i_1 = V_1/R_1 + V_1/C_2 + V_1\text{-}V_{out}/C_1$

let V_{in} = 1V, $1 - i_1R_1 = V_1$

$i_{in} = 7.85(10^{-5})$ A

$Z_{in} = 1V / i_{in} = 12.7k\Omega$

Calculation of Output Impedance

$Z_{out} = R_L(V - V_L) / V_L$

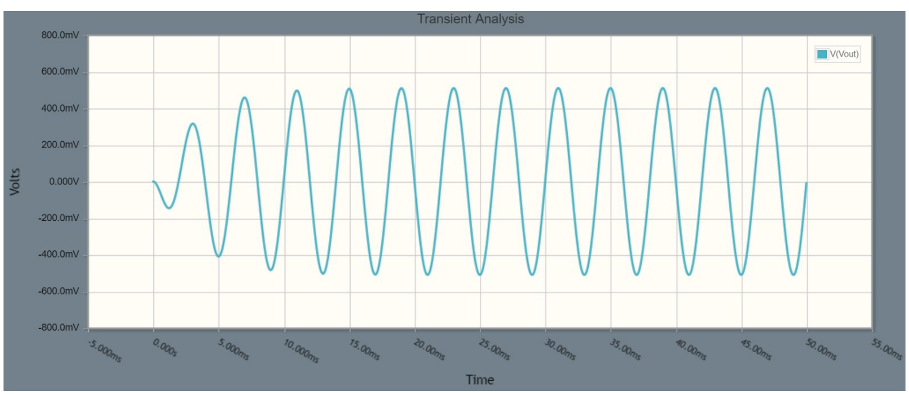
Let $R_L = 1k\Omega$, $V_1 = 1V$

$V = V_1R_3 / C_2$

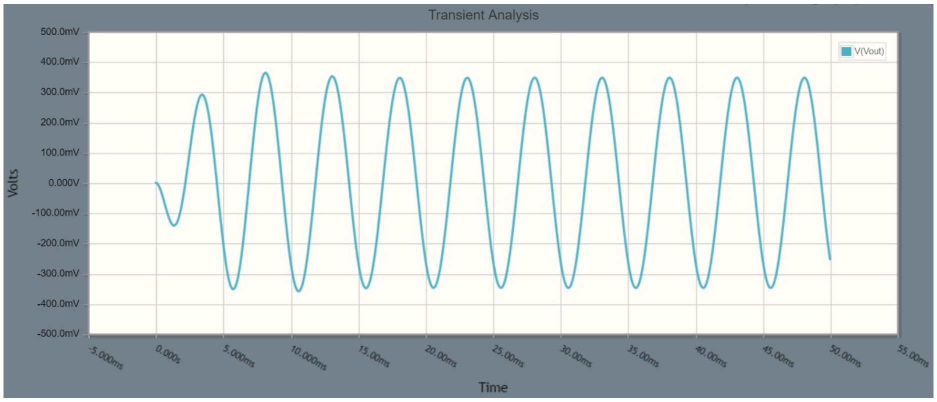
$V_L = V_1R_3R_L / C_2$

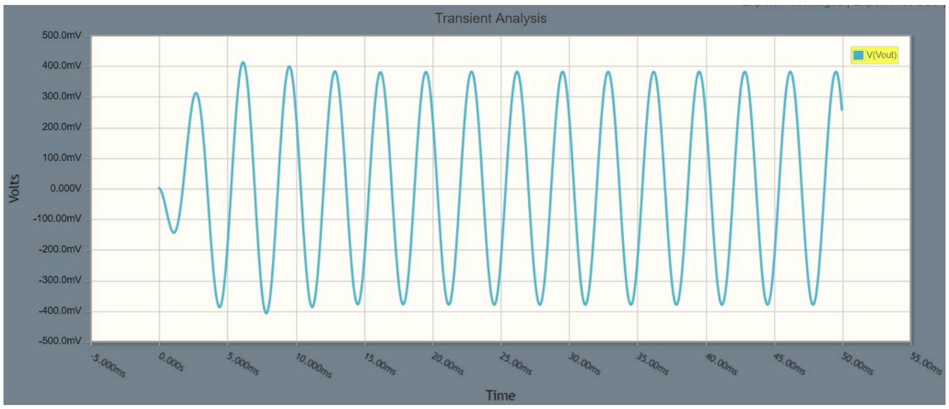
$Z_{out} = 999\Omega$

Time-domain simulation @250Hz



Time-domain simulations @ 200Hz and 300Hz (cutoff frequencies)



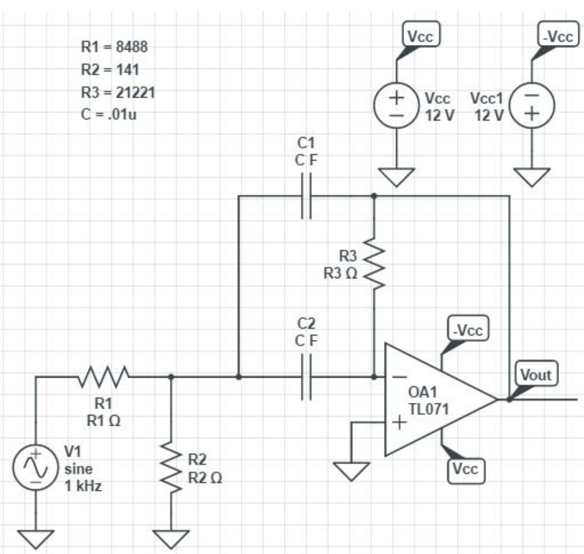


Treble Filter

TL071 OpAmp: Low-Noise JFET-Input General-Purpose OpAmp

Resistors: 8.49kΩ, 141Ω, 21.2kΩ

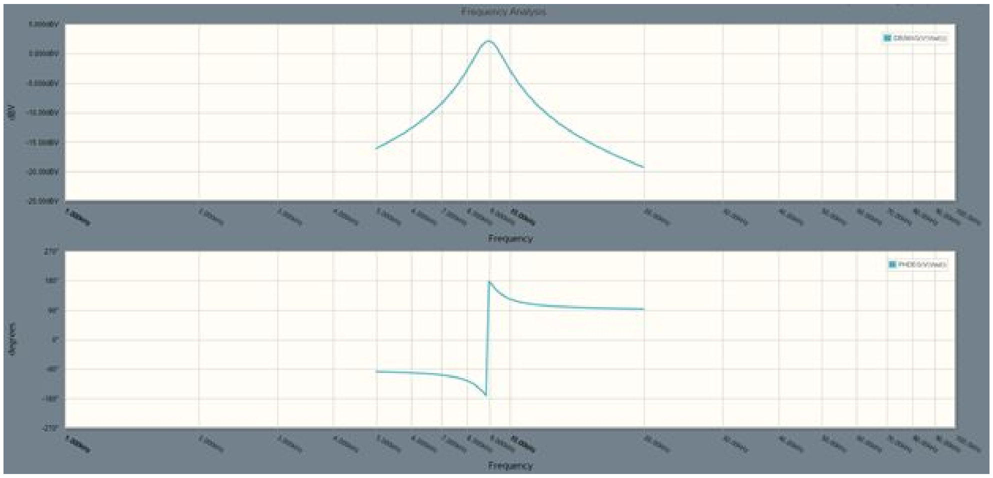
Capacitor: 0.01uF (2)



Roll-off Rate:
@ 15kHz: -14.5dB, 150kHz, -37.25dB

-37.25 - (-14.5) = -22.75

-22.75dB/decade



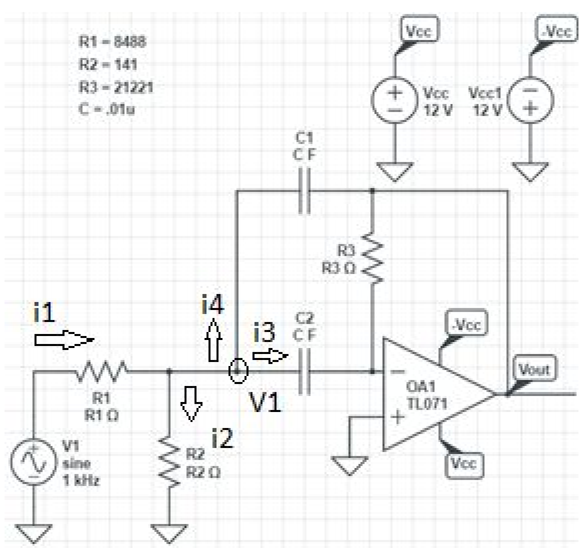
Input/Output Impedance:

Resistors: Z = R, Z = 8.49kΩ, 141Ω, 21.2kΩ

Capacitor: Z = 1/jωC, ω = 2πf = 2π(9kHz) = 56548.7rad/sec

1/j(0.01uF)(56548.7rad/sec) = 6.37kΩ

Calculation of input impedance of Treble Filter



$Z_{in} = V_{in} / i_1$

$V_{in} = i_1R_1 + V_1$

$i_1 = i_2 + i_3 + i_4$

$i_1 = V_1/R_1 + V_1/C_2 + V_1\text{-}V_{out}/C_1$

let V_{in} = 1V, $1 - i_1R_1 = V_1$

$i_{in} = 1.18(10^{-4})$ A

$Z_{in} = 1V / i_{in} = 8.49k\Omega$

Calculate Output Impedance

$Z_{out} = R_L(V - V_L) / V_L$

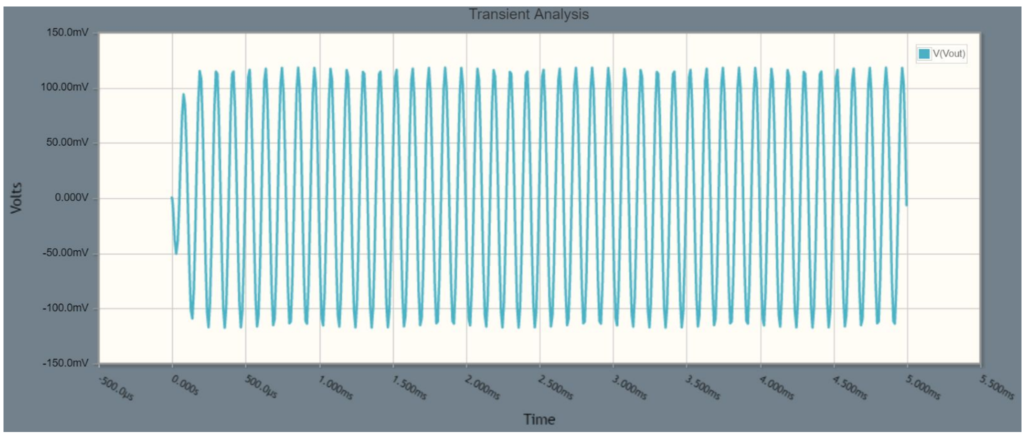
Let $R_L = 1k\Omega$, $V_1 = 1V$

$V = V_1R_3 / C_2$

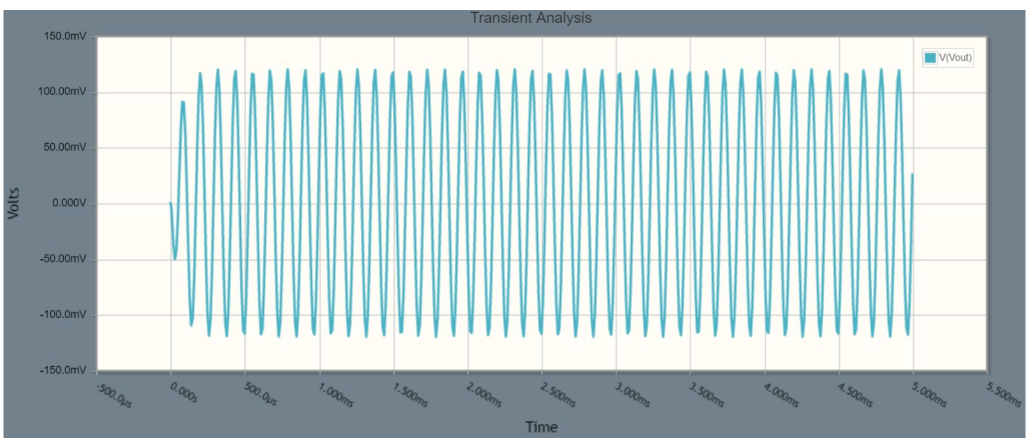
$V_L = V_1R_3R_L / C_2$

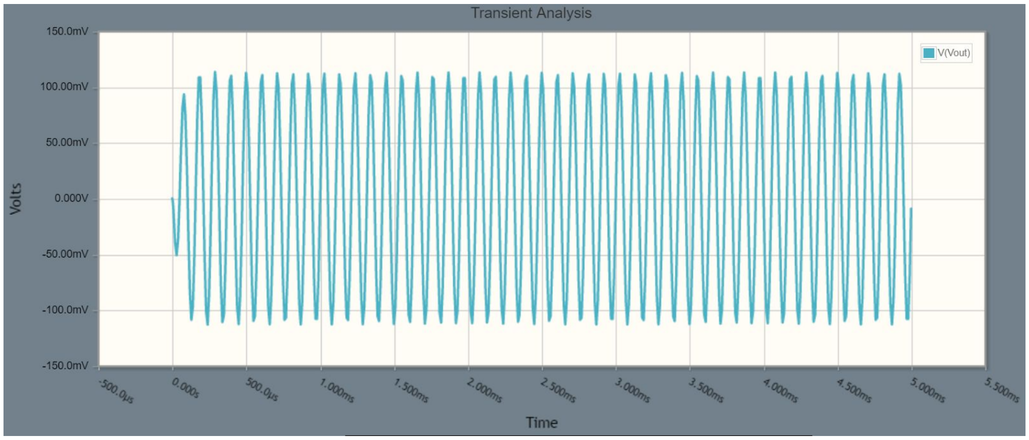
$Z_{out} = 1k\Omega$

Time-domain simulation @9kHz



Time-domain simulation @8.5kHz, 9.5kHz





Expected DC power requirements:

Voltage: 12V and -12V to power the TL071 OpAmps

Current: 1.4mA x (2 OpAmps) = 2.8mA

Power: 6V x (2.8mA) = 16.8mW

We expect the OpAmps to draw the greatest amount of current in this stage, and there requires about 6V to power the TL071.

<u>Experimental Setup</u>:

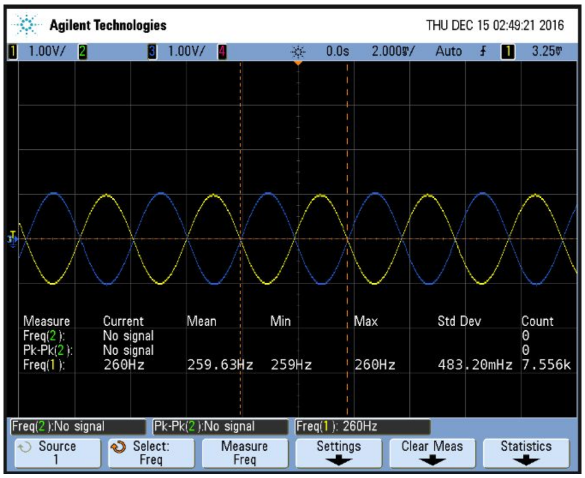
The above schematic was built using physical components. Resistors were found and put in parallel to get the sum closest to the value given in the schematics above. Two separate filters were built on separate breadboards for testing.

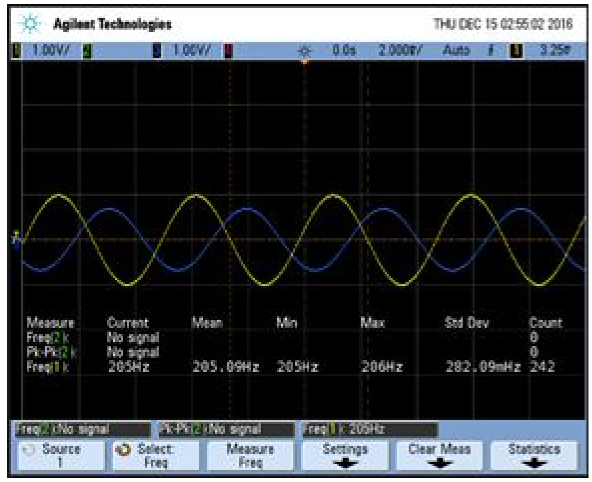
<u>Experimental Procedure</u>:

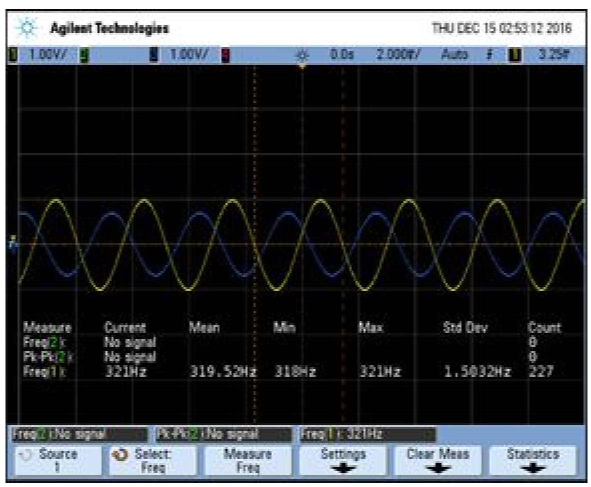
The OpAmp was initially powered using the tabletop power supply. The input was a generated sine wave with target frequencies, and the output was probed and displayed on the oscilloscope. The sine wave was set up with a frequency of 250Hz for the bass filter and 9kHz for the treble and an amplitude of 300Vrms. We probed the output, comparing it to the input sine wave. We swept the frequency, noting that the gain was one at our center frequency, and 0.707 at the corner frequencies. This was repeated for both filters, and several adjustments in resistor values were made to adjust for gain. As an initial test, we connected the rails to the 12V and -12V output of the power supply of the midterm.

<u>Experimental Results</u>:

Bass Filter Results

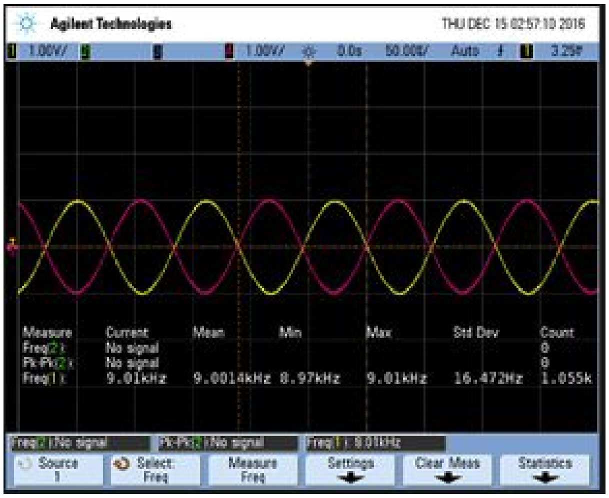


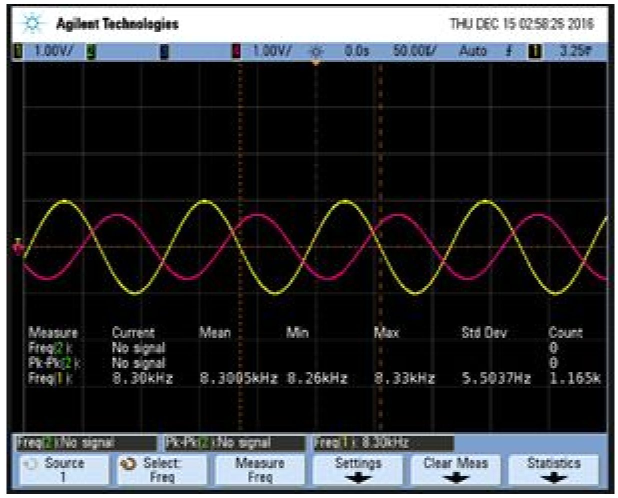


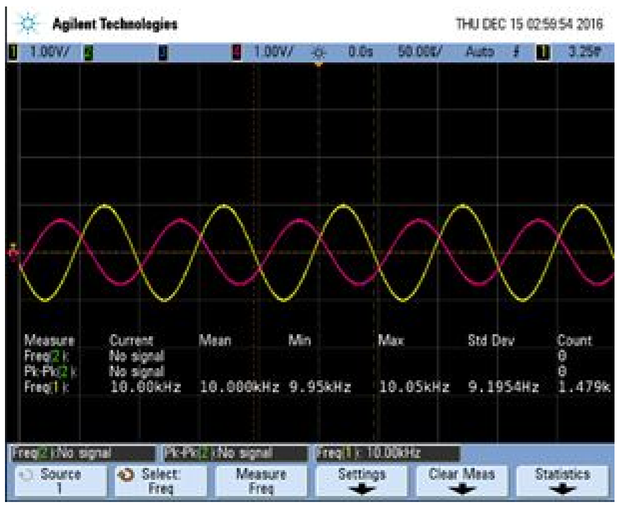


From these oscilloscope readings, it can be noted that we successfully created a bandpass filter with a gain of one at the target center frequency, 250Hz. The peaks of both the output and the input waves align, and this was accomplished mostly due to the use of a potentiometer in place of resistor R1. As for the corner frequencies, there was only a discrepancy of around 10-20 Hz, and 0.707 times the original amplitude (-3dB) was achieved at frequencies of 205Hz and 321 Hz.

Treble Filter Results







Similarly to the bass results, we were successful in creating a filter with a gain of one at the designated center frequency. In this case, the center frequency was 9kHz. We swept the frequencies, and verified that the largest gain was at 9kHz. Our corner frequencies were analyzed to be 8.30kHz, and 10kHz. Likewise to the bass filter, the use of a potentiometer allowed us to alter the resistance (and impedance) and change the gain until it reached a value of one. As for the combined power supply and filter circuit, the potentiometer was adjusted to have the same gain. Overall, the power supply successfully powered the opamp and in turn both filters as a whole.

<u>Error Analysis</u>:

There was approximately a 8-20% difference in the corner frequencies in the bass filter, and 0-4% difference in the corner frequencies in the treble filter. This difference was slightly greater than expected, since the simulation originally provided a shorter bandwidth. This can be attributed to the difference in resistor values, the parasitic resistance of the capacitors, and the effectiveness of the opamp. The resistor values were not equal to those in the simulation, due to the values provided in the lab that had to be but in series to attain the value we wanted.

Conclusion:

This filter stage, being the first main component, was crucial to the success of the audio docking station as a whole. Initially, we had constructed a second-order bandpass filter using a lowpass filter cascaded with a highpass filter. However, when performing simulations, we discovered that both the gain was low (-4 to -10dB) and the bandwidth was extremely large. We decided to switch to multiple feedback filters, and successfully generated a bode plot centered at 250Hz with a bandwidth of 100Hz for the bass filter, and a bode plot centered at 9kHz with a bandwidth of 1kHz. These were both first-order filters, with a roll-off rate of -20dB/decade. This may have been a source of error due to the softer, less-steep roll-off rate as opposed to a second-order filter. This initial stage went through many redesign efforts and debugging, although it was relatively easy to do so due to the division of components of this project.

Part 2: Amplifier Component

The following calculations are shown in order to calculate the necessary voltage bias for the transistor in order to deliver the specification of 1/4W of power to the 8Ω load. The amplifier used a single BS170 MOSFET transistor.

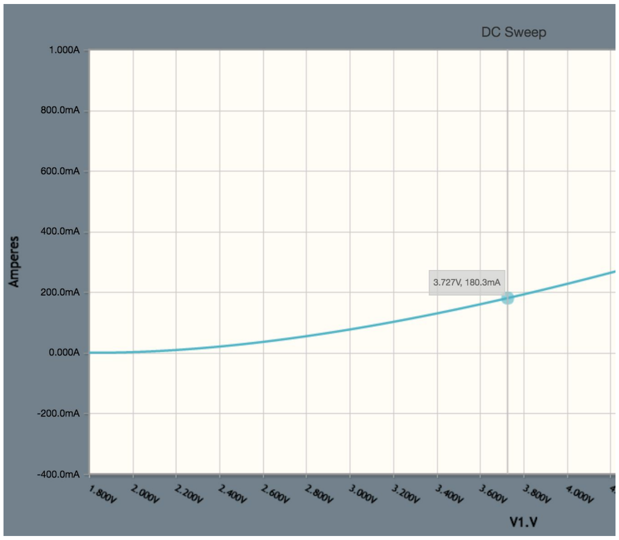
Transistor bias:

$$P = 0.25W, R_{load} = 8\Omega$$

$$P = \frac{v^2}{R};\ 0.25 = \frac{v^2}{8}; V_{peak} = 1.41V$$

$$i = \frac{v}{R} = \frac{1.41}{8}; i_{peak} = 180mA$$

In order to deliver 0.25W of power to the load, the peak voltage must be 1.41V and the peak current must be 180mA. Based on the I_{DS} vs V_{DS} simulation plot of the BS170 below, the transistor must receive 3.7V in order for the current from drain to source to be 180mA.



This means the voltage bias must follow:

$$3.7 - v_{in} = 3.7 - 300v_{rms} = 3.3V$$

According to the BS170 spec sheet, the gate threshold voltage must be 2.1V, which the 3.3V bias satisfies.

A voltage divider was used to take the 12V power supply and provide roughly 3.3V to the transistor. Resistor values are large, in the mega ohm range, so as to prevent unnecessary flow of current.

Due to the nature of the single stage amplifier, R_D in this case is simply the load.

Resistor Values:

Given 12V power supply and assuming Rb, the top resistor, is 10MΩ:

$$12 * \frac{R_a}{R_a + 10} = 3.3V, R_a = 3.8M\Omega$$

Peak Power:

$$P_{max} = V_{max} * I_{max} = (1.41V) * (180mA) = 0.254W$$

Coupling Capacitor:

A 100uF capacitor was added to the gate of the transistor in order to couple the voltage divider bias at AC. This coupling capacitor looks like an open at DC, blocking current from entering at DC and allowing the correct voltage bias to the transistor. However, at AC, the capacitor passes both the DC offset and the input signal to the transistor.

Expected DC Power Requirements:

Power Supply: 12V, taking 3.3V from voltage divider

Current: 180mA * 2 amplifiers = 360mA total

Total Power= (1.414 peak voltage) * (180mA peak current) = 0.25W to each speaker

Amplifier Simulation:

A BS170 n-channel MOSFET was selected, a small signal mosfet rated for a maximum drain current of 500mA and 60V from drain to source, with the following ratings:

BS170G

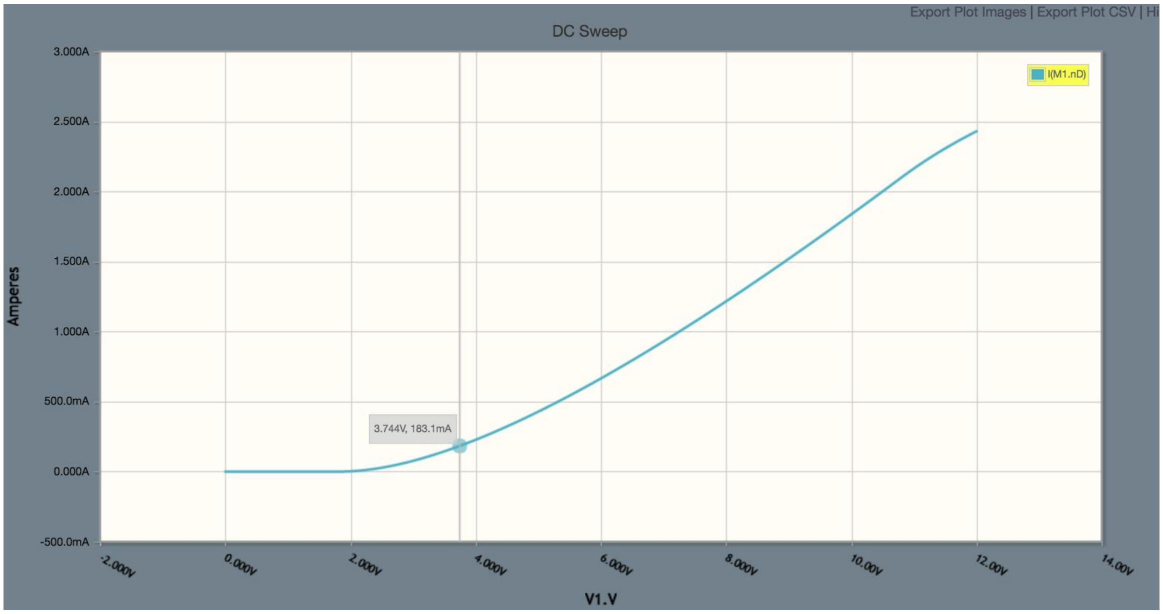
ELECTRICAL CHARACTERISTICS (T_A = 25°C unless otherwise noted)

Characteristic	Symbol	Min	Typ	Max	Unit
OFF CHARACTERISTICS					
Gate Reverse Current (V_{GS} = 15 Vdc, V_{DS} = 0)	I_{GSS}	–	0.01	10	nAdc
Drain–Source Breakdown Voltage (V_{GS} = 0, I_D = 100 μAdc)	$V_{(BR)DSS}$	60	90	–	Vdc
ON CHARACTERISTICS (Note 1)					
Gate Threshold Voltage (V_{DS} = V_{GS}, I_D = 1.0 mAdc)	$V_{GS(Th)}$	0.8	2.0	3.0	Vdc
Static Drain–Source On Resistance (V_{GS} = 10 Vdc, I_D = 200 mAdc)	$r_{DS(on)}$	–	1.8	5.0	Ω
Drain Cutoff Current (V_{DS} = 25 Vdc, V_{GS} = 0 Vdc)	$I_{D(off)}$	–	–	0.5	μA
Forward Transconductance (V_{DS} = 10 Vdc, I_D = 250 mAdc)	g_{fs}	–	200	–	mmhos
SMALL–SIGNAL CHARACTERISTICS					
Input Capacitance (V_{DS} = 10 Vdc, V_{GS} = 0, f = 1.0 MHz)	C_{iss}	–	–	60	pF
SWITCHING CHARACTERISTICS					
Turn–On Time (I_D = 0.2 Adc) See Figure 1	t_{on}	–	4.0	10	ns
Turn–Off Time (I_D = 0.2 Adc) See Figure 1	t_{off}	–	4.0	10	ns

1. Pulse Test: Pulse Width ≤ 300 μs, Duty Cycle ≤ 2.0%.

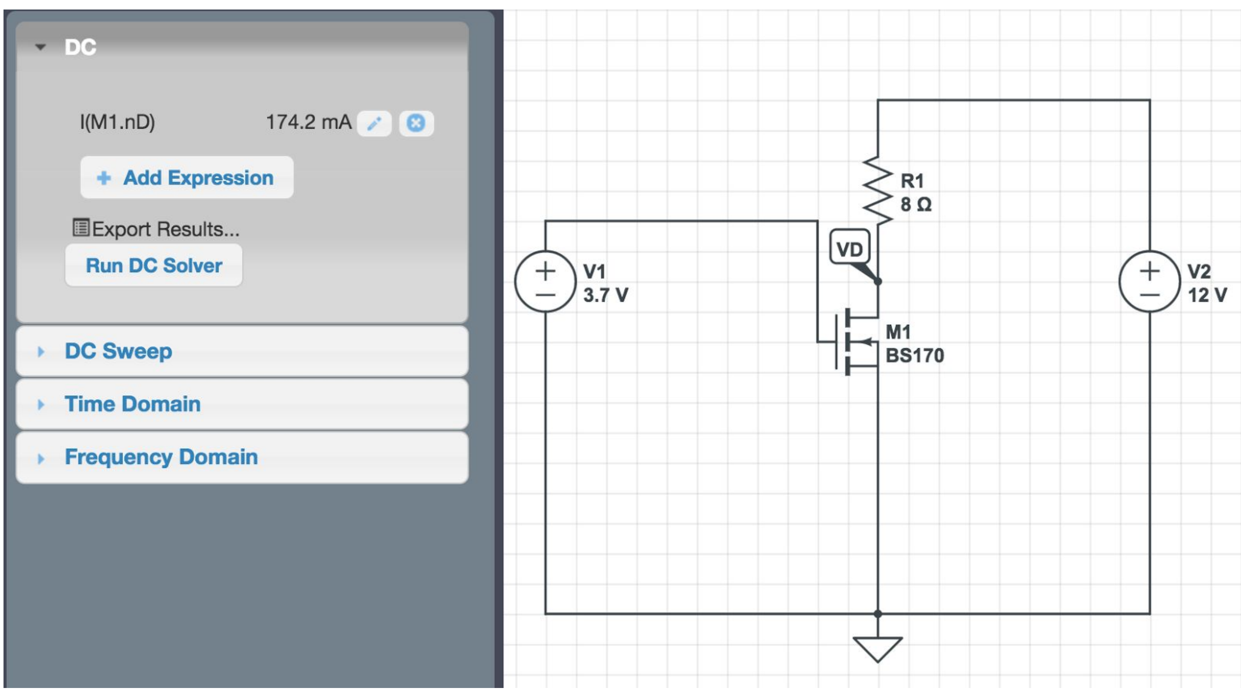
I_D vs. V_{GS} curve of BS170 transistor:

Threshold Voltage = 2.1V, 180mA at 3.7V

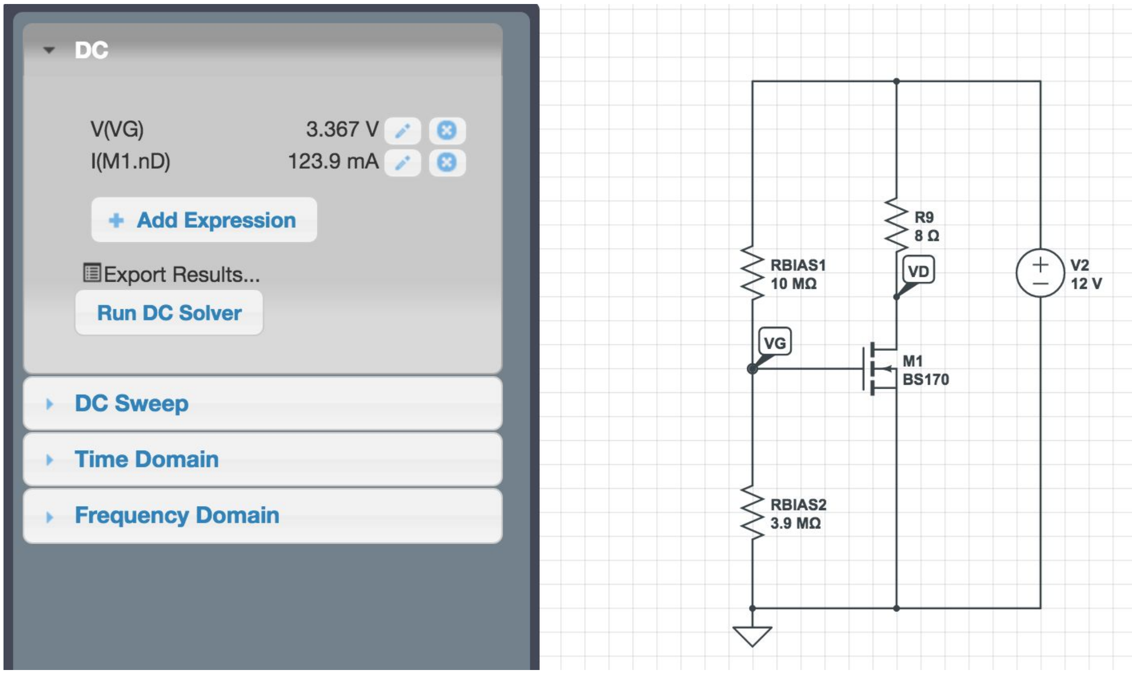


DC Simulation of BS170 at 3.7V:

(peak voltage including bias at maximum voltage of input signal)

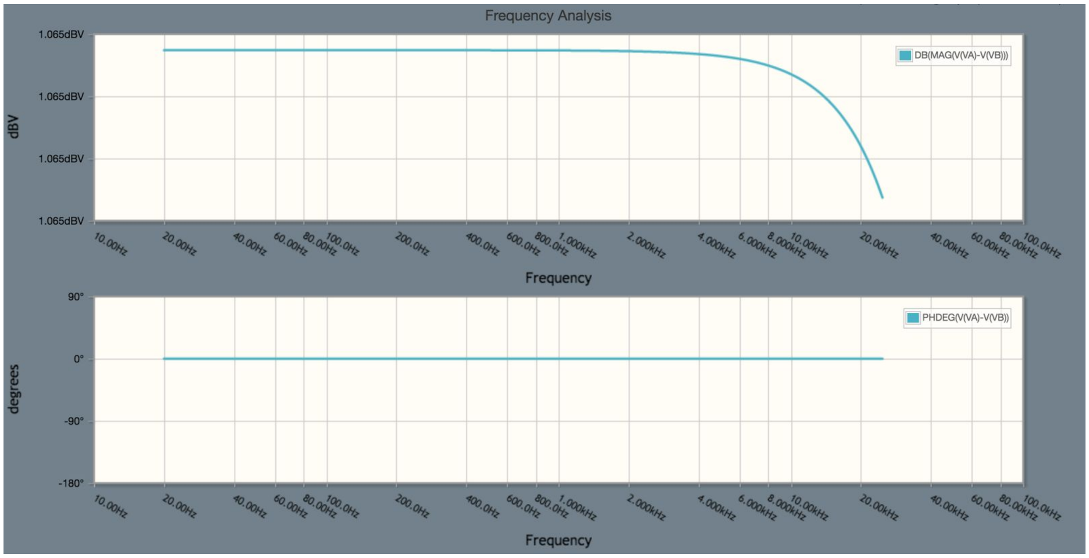


DC Simulation of BS170 with Bias Resistors:



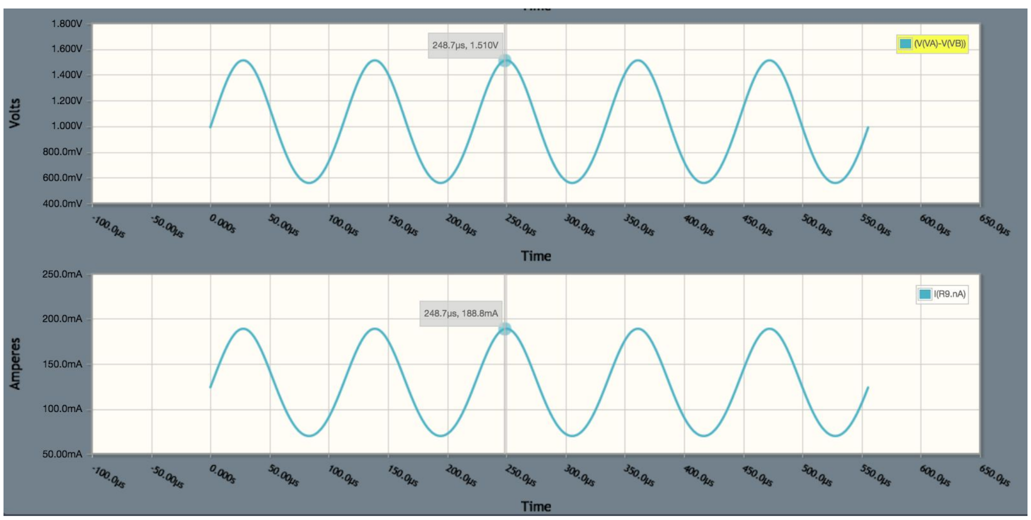
With the bias resistors and without the input signal at DC, the voltage at the gate is the expected 3.3V, yielding a current less than 180mA. Only when the ac input signal is at its maximum, adding an additional 0.424V, will the total voltage at the gate equal 3.7V and the current through the load be 180mA.

Bode Plot of voltage across the load, from 20Hz to 25kHz:

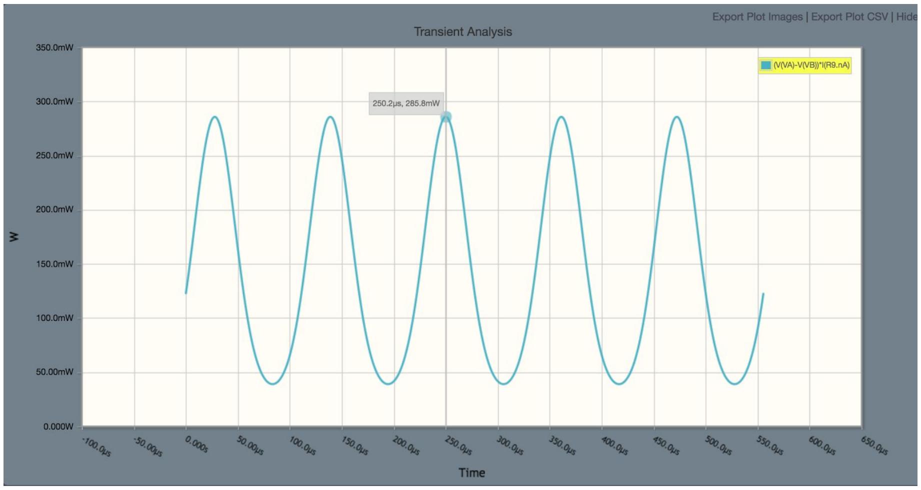


Time Domain Simulation, centered at 9000Hz:

Showing maximum voltage and current received by load: V=1.510V, I=188.8mA



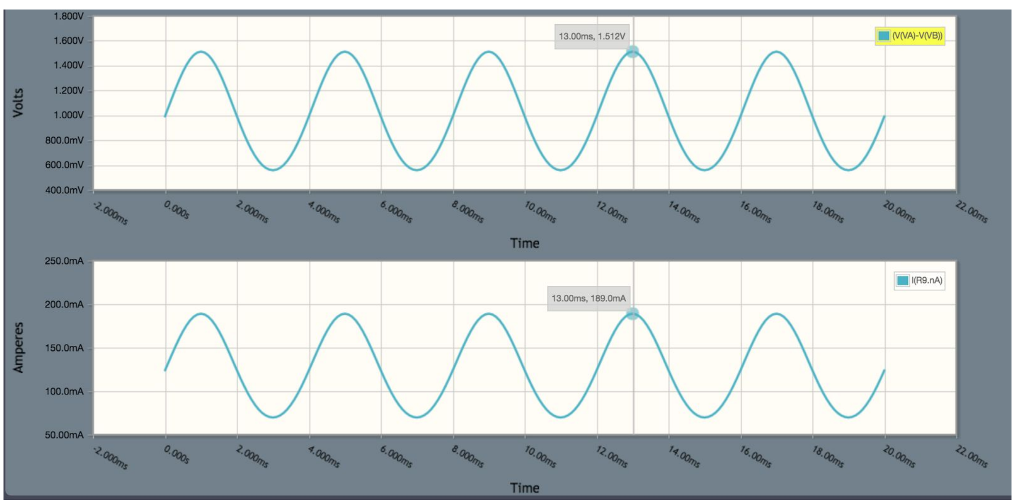
Showing maximum power received by load: $P_{max} = 0.285W \approx 0.25W$



Time Domain Simulation, centered at 250Hz:

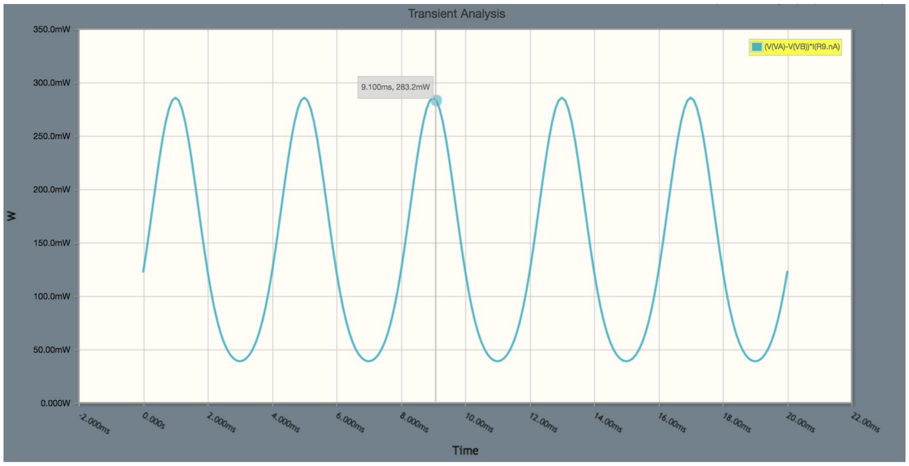
Showing maximum voltage and current through load:

V=1.512V, I=189mA



Showing maximum power received by load:

$P_{max} = 0.283W \approx 0.25W$



Experimental Setup:

The amplifier was attached to the output of both filters and powered using the Agilent E3631A Triple Output DC Power Supply, powering the amplifier and +Vcc terminal of the op amps in the filter with a 12V rail. The filter-amplifier output was then connected to the 8 ohm speaker using an audio cord. Power was measured by reading the voltage provided by the power supply as well as the current provided and multiplying the two values.

Experimental Procedure:

With the filter's output cascaded into the amplifier, the output of the amplifier was connected to the 8 ohm load. Music from a laptop served as the input into the filter. With the circuit powered we recorded the voltage drop read by the power supply from 12V as well as the current pulled from the power supply displayed on the screen. Multiplying these two values provides the max power delivered to the speaker.

Experimental Results:

With one output connected, the power supply dropped from from 12V to 10.40V and the current pulled varied from 140mA to 160mA. This yields 1.6V across the load.

Voltage across Load	Min Current to Load	Max Current to Load	Power Delivered
1.6V	140mA	160mA	224-256mW

With both filters connected, the voltage dropped to an expected 8.86V and the current drawn doubled to roughly 340mA.

Error Analysis:

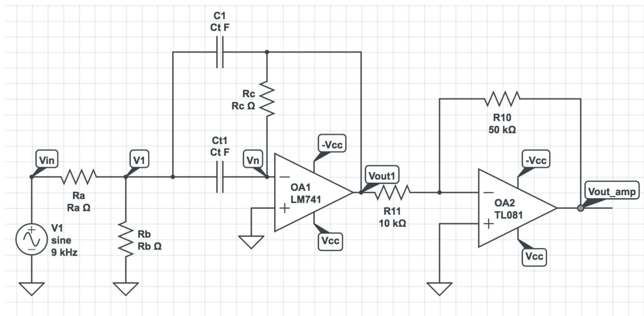
The maximum voltage through, current drawn, and power delivered to the speakers matched closely the expected results. The voltage across the load varied from the expected 1.4-1.5V, because the power supply was varying due to the ac music input and was not a constant 300mV RMS. Other voltage, and thus current differences, can come from additional resistance through the audio cables.

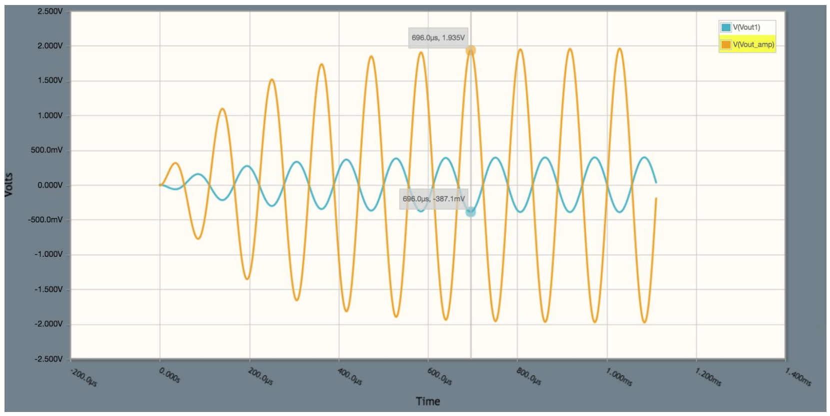
Conclusion:

The above results were consistent when we installed the same experimental setup and measured power various instances. Initially, we used a resistor value of 3MΩ that did not deliver enough voltage to the gate of the transistor to provide maximum power. This was due to a misunderstanding in the derivation of the bias of the voltage divider, which we thought was simply the ratio of resistor B to resistor A. However, replacing the incorrect value with a 3.9MΩ resistor allowed for an audible output and the expected current drawn. This stage of the project was relatively easy to debug, as changing the value of the second resistor changes the transistor bias. An improved version of the amplifier could have included an additional buffer transistor to negate any potential effects of the load resistance on the current drawn.

Part 3: Final Integration

The final circuit integrates the filter subcomponent, a voltage amplifier substage, and the transistor amplifier stage. The voltage amplifier was included in order to provide some voltage gain before the transistor stage, using an inverting op amp and a 50k potentiometer.





Hand Calculations:

Total current power supply can deliver:

At 12V, I_{SC} = 79.28mA, according midterm simulation.

This value is noticeably less than the required 180mA per speaker. In order to avoid this problem, we tested our filter plus amplifier from the bench power. We did conduct a trial run off of the midterm power supply, but as expected, the sound quality was poor as both speakers pulled too much current and therefore reduced the voltage supplied.

Total current required by filters:

2.8 mA for 2 op-amps

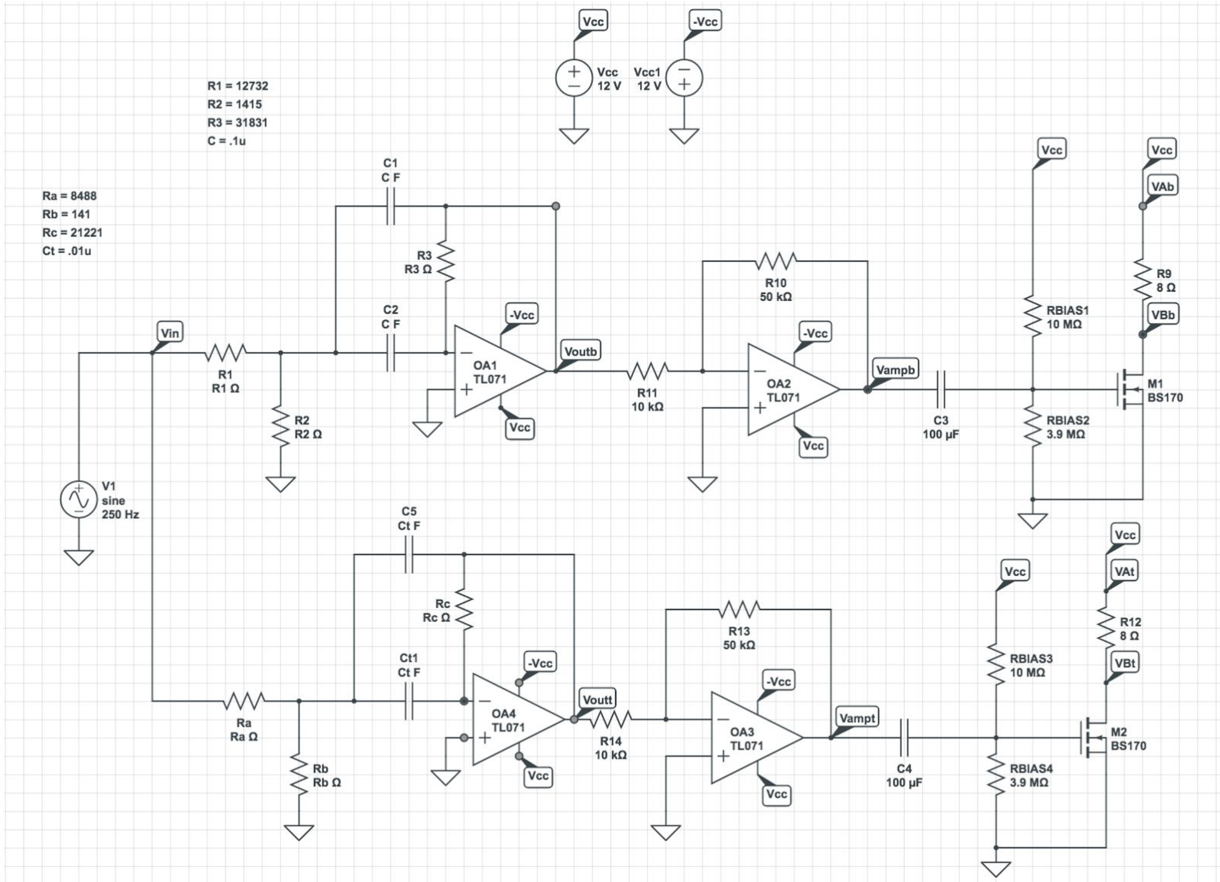
Total current required by amplifiers:

2*180mA= 360 mA in order to satisfy 0.25W power for two 8ohm loads

Total current required = 362.8mA, satisfied using bench power supply

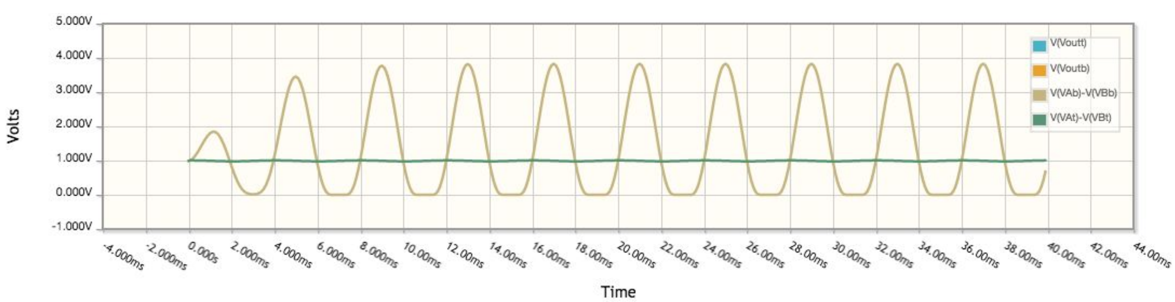
Simulations:

Final schematic:

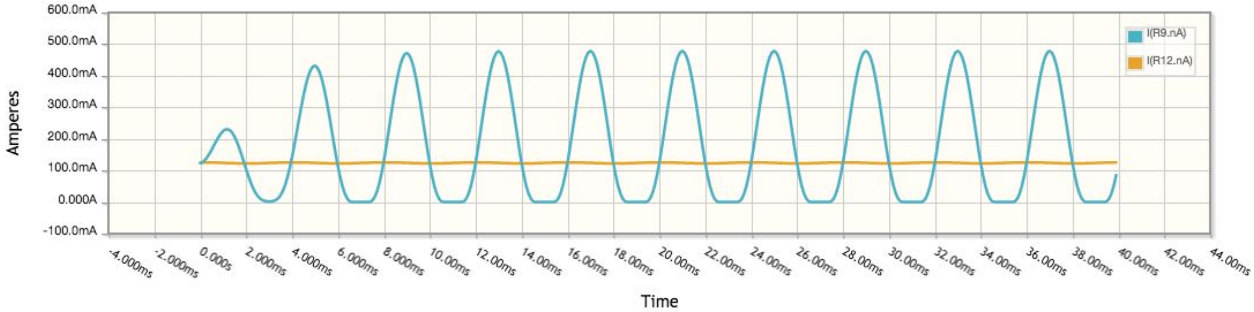


Output at 250Hz:

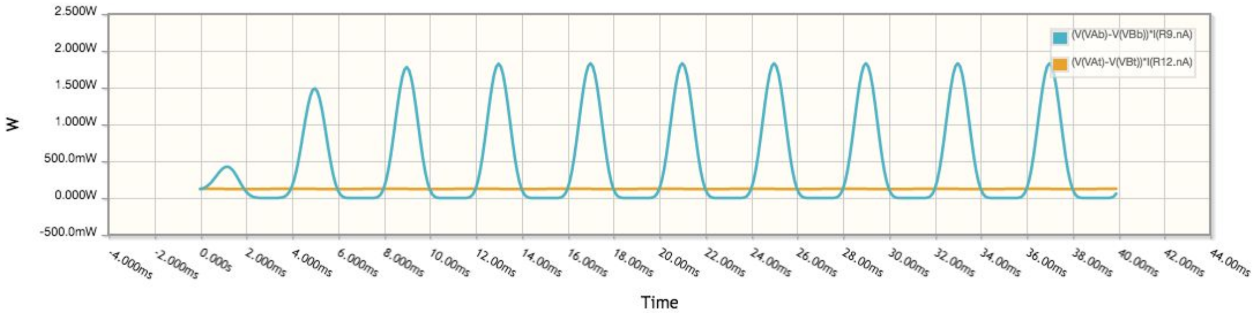
Voltage:



Current:

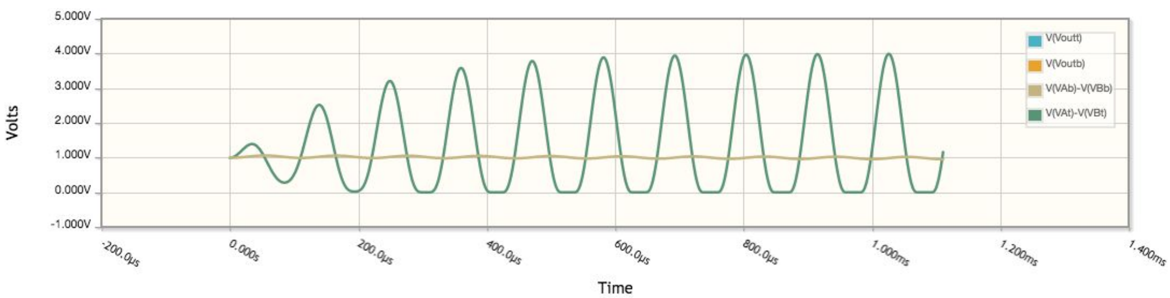


Power:

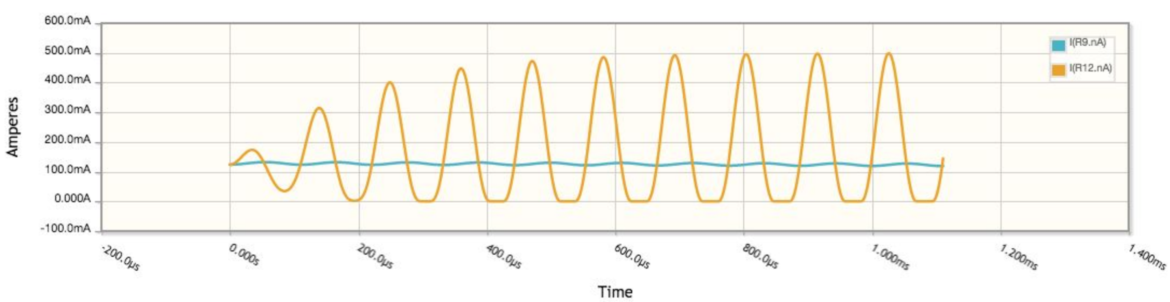


Output at 9000Hz:

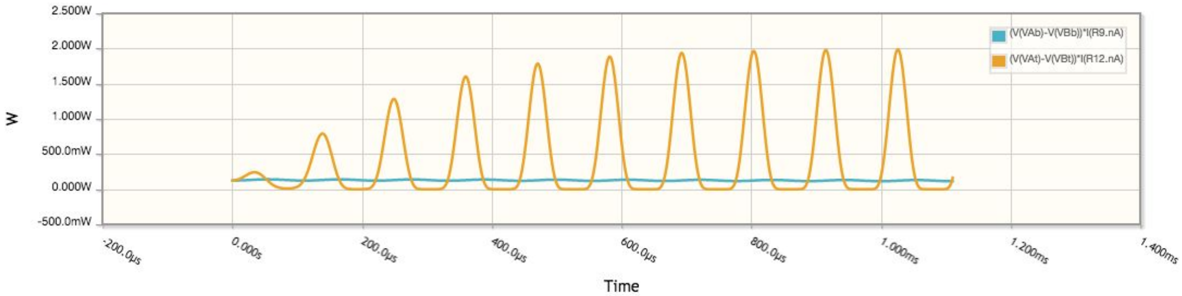
Voltage:



Current:



Power:



Experimental Setup:

With all the individual components built, it was a fairly smooth transition into combining them all into the final, complete system. For our initial test, we connected 12V, -12V and ground to the power supply, Agilent U8002A. Both the filters and the two amplifiers were powered by the power supply and connected to a common ground. The input wires, connected to a laptop, was connected to the treble and bass, and the output of the treble and bass were connected their respective amplifiers. Due to the nature of the amplifier, a greater input voltage was required. To solve this, we connected the output from the filters to an inverting opamp with a large gain, providing an output with a much greater voltage. The final output from the amplifier was connected to the speakers.

Another test included using the midterm power supply. This replaced the rail inputs that were connected to the Agilent U8002A power suppl. A major concern regarded the current drawn by the circuit. Unlike the first power supply, the audio docking system generated an unclear sound on the speakers. This was due to the large amount of current drawn, reducing the amount of voltage on the rails.

Experimental Procedure:

The outputs of the amplified treble and bass frequencies were connected to the oscilloscope, as well as the input from the laptop playing music. The frequency response was verified by analyzing the outputs compared to the frequency readings of the original song displayed on the oscilloscope. Since the overall circuit was connected to the power supply, we were able to see how much current was being drawn from the constant voltage supply.

We also conducted subjective analysis, listening to the output of the music on the speakers and evaluating the sound quality. In the first stages of testing, we experienced a lot of noise that translated to static on the speakers. This was a grounding problem, which incited us to rebuild our circuit to become more compact and all share a common ground rail. We exchanged the LM741 in favor of the low-noise TL071. These changes minimized the amount of static heard from the speakers.

Experimental Results:

After testing both filters plus amplifiers on the speaker, each filter pulled about 160 mA of current and prompted a voltage drop of 1.6 V across the speaker's load. Qualitatively, the sound of each individual filter with the other unplugged was noticeably better than the quality of both bass and treble connected, as the two loads pulled around 300 mA total. This caused the 12V power supply to output only 8.8 V. The additional noise problem was addressed, as indicated in the procedure, by consolidating the circuit's ground and grounding directly to the bench power supply instead of the rail on the breadboard.

Error Analysis:

There were many unexpected changes to power consumption once all the components were connected. The most prominent change came from the current drawn by the amplifier. This was partially alleviated by the high current limit we set on the Agilent 30V power supply. However, due to this current and power consumption, the transistor often overheated and required replacement. Subjectively, the music emitted from the speakers was not of the highest quality. This error was mostly attributed to the amplifier, since we had previously tested the filters with the pre-constructed amplifier already available to us. The questionable reliability of the amplifier is partially due to the biasing of the transistor. There were only several M□ resistor values available at the lab, reducing our available choices when performing the DC bias.

Conclusion:

The complete system was successful in playing both the treble and bass frequencies on the speakers. While this was far from the perfect system, we were able to calculate, design and built each component to the design specifications. Combining the power supply, filter, and amplifier made it difficult to pinpoint the sources of error, providing us with the important lesson of testing each component individually and thoroughly to minimize any problems. One action we wished we had taken was to test the amplifier with the oscilloscope input. In this lab, we decided to immediately connect the music to the filter and amplifier and adjust according to the sound quality from the speakers. If we had tested with the scope, it would have provided us with more accurate data to utilize in adjusting values in the amplifier. Other ways to improve this system would have been to consider filters of different topologies, including Butterworth and Sallen-key, increase the order of the filters, and build a two stage amplifier with a buffer so the impedance of the load would not affect the current through it.