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ESE 215 – 001 (Circuits Laboratory)
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Final Project

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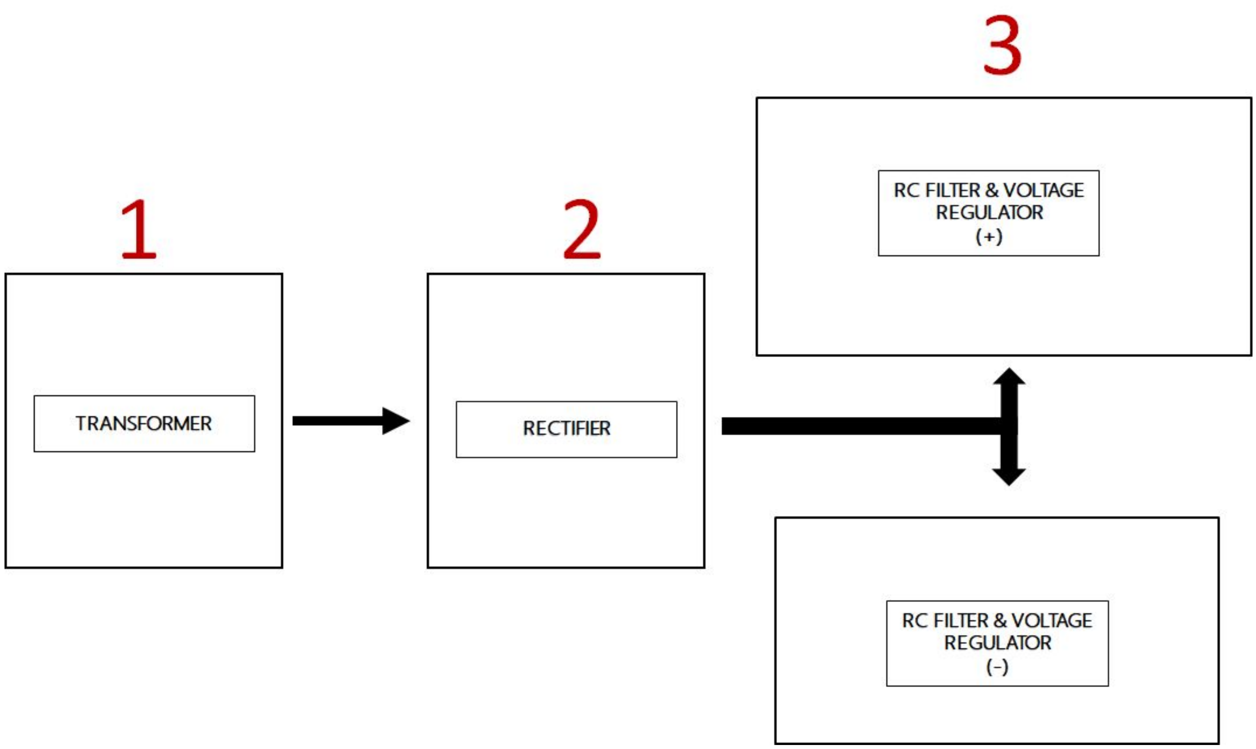
PART I – Power Supply

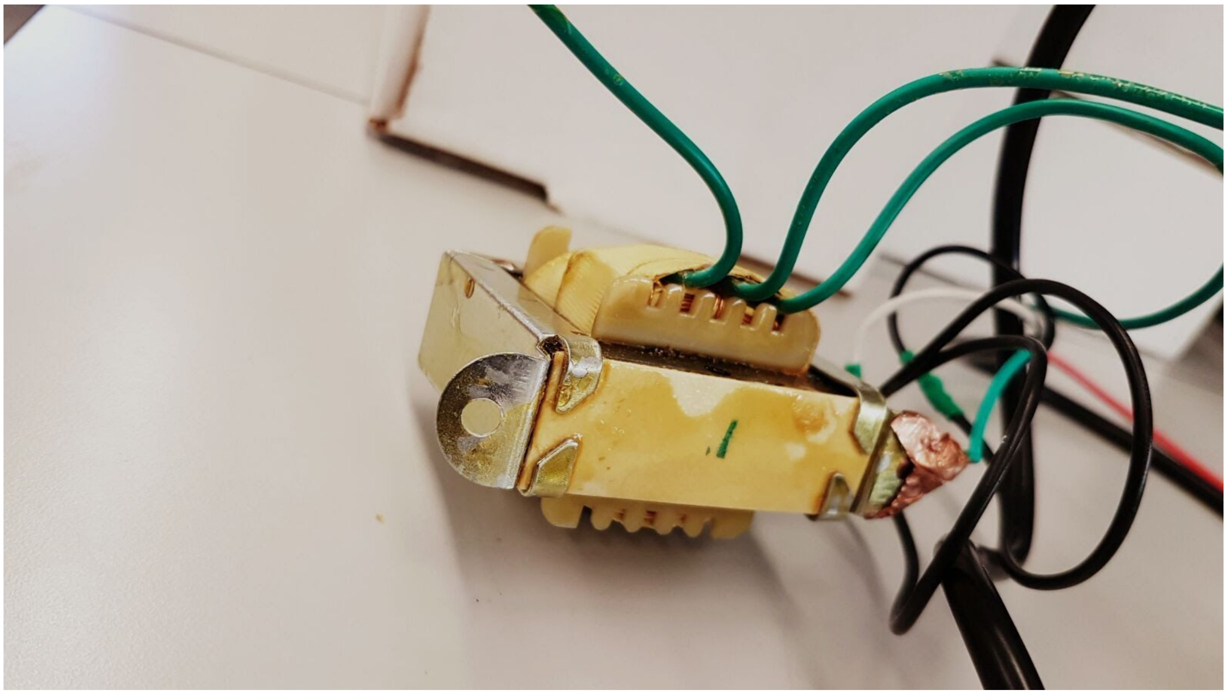
Introduction

We began this project by working on the power supply. The purpose of the power supply was to power the Operational Amplifiers used in our bass and treble filters. Our goal was to convert 120V AC(Alternating Current) to 15V DC(Direct Current). The electricity from the wall is AC because it is more effective to supply to households across long distances. This is because it is easier to step it up or down depending on the need of a resistor (household appliance). We started from scratch by first calculating by hand the values for the resistors and capacitors we were going to use. The power supply consisted of 3 stages.



Stage 1:

The first stage was to use a step down transformer to step down the 120 V rms (root mean square) from the wall to 15V.



The transformer pictured above (Hammond / 166K18) is the transformer we used in our simulations and subsequently in the final project. We used a center-tapped transformer because it can be used to generate a positive and a “negative” AC voltage. This is advantageous because we can then convert these signals to positive and negative DC voltages which can be used for +VCC and -VCC on the operational amplifiers respectively.

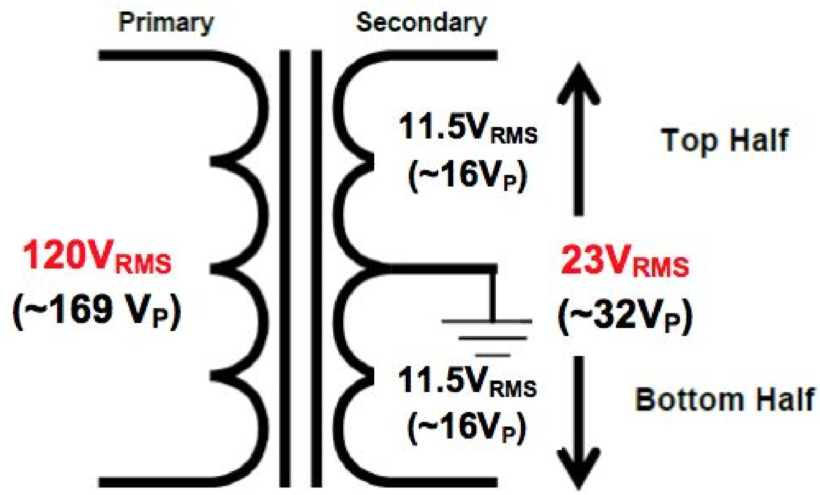
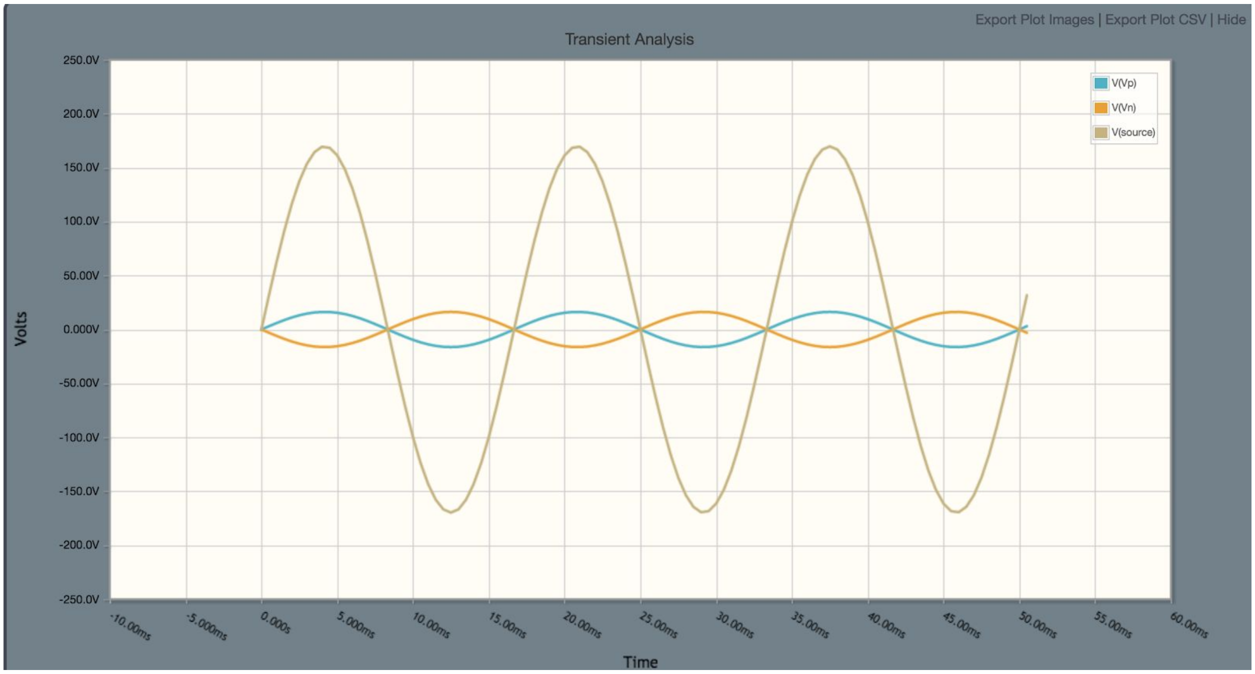


Figure 1 – Center Tapped Transformer Schematic

Since the voltage from the wall was 120V rms(169.70V peak) and we wanted to step it down to 11.5V rms (16.26 V peak), we used the typical transformer equation

$$\frac{Vp}{Vs} = \frac{Np}{Ns}$$

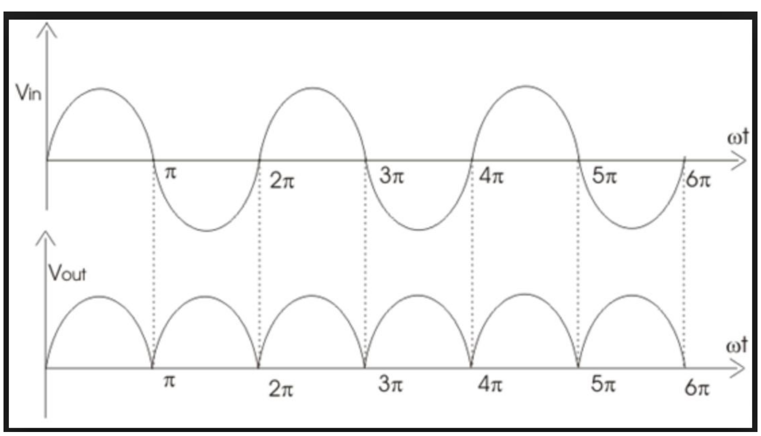
to check whether the number of turns we needed corresponded with what was calibrated on the transformer. If the ratio is greater than 1 it means that it is a step-up transformer which was what we were looking for. The ratio for the number of turns ended up being 5.22: 1 which was exactly what we needed for the voltage ratio (shown above).



The above figure shows the result of our simulation on the transformer

Stage 2:

After the transformer successfully stepped down the voltage, the next stage involved converting the AC signal to DC. This was done by using diodes as a rectifier such that the current only flows in one direction. We used a bridge rectifier (full wave rectification) set-up to isolate the alternating sinusoid to only alternate in one either direction (either positive or negative)



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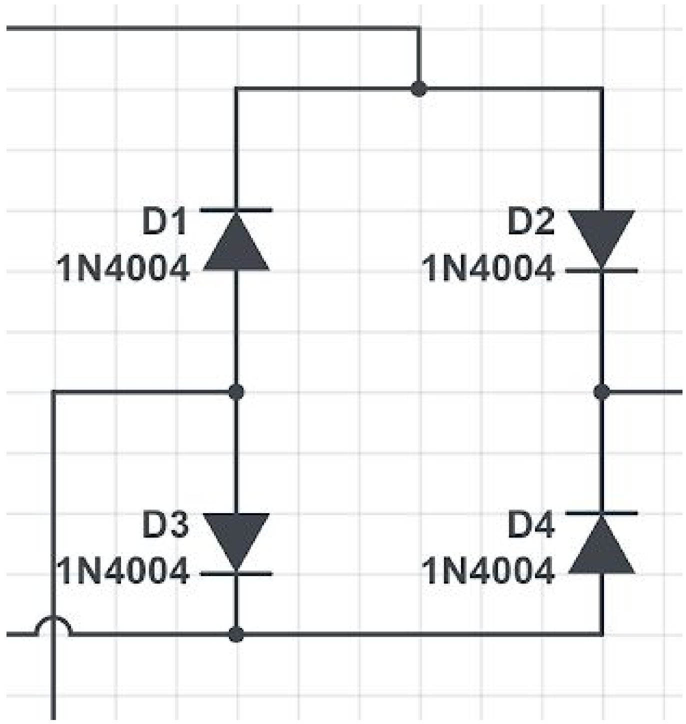
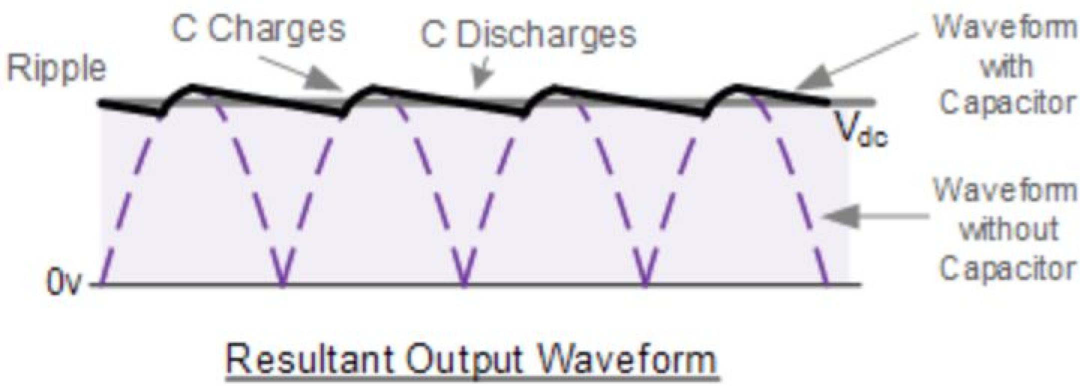
The diagram above is an example of the signal obtained from rectification with a diode. When any current flows through the diode from anode to cathode, there is a constant voltage drop across the diode. The diode we used was a 1N4004, which has a voltage drop of 0.93V. The stepped down voltage output from the transformer was 16.26V, but due to the 0.93 V voltage drop across the diode, the final calculated output voltage was $16.26 \times 0.93 = 15.12$ V, which was the range we were looking for.



The figure above shows a bridge rectification setup with four diodes. At either the positive or negative cycle of the input source, only 2 diodes would be conducting in the forward direction, whilst the other two diodes are reverse biased. In the case of the diagram above, diode D2 and D3 are conducting when the input is positive and D4 and D1 conduct when the input is negative. We wanted to have both positive and output voltages in order to power +VCC and -VCC on the operational amplifiers respectively hence the four diodes ensure that each half-cycle of the input AC source is accounted for regardless of polarity.

Stage 3:

The final stage of the power supply involved adding a smoothing capacitor circuit to reduce the ripple and also have a constant ~15V by reducing the variations of the full-wave rectified waveform.So far the output that we have are 2 sinusoids of half cycles, each half cycle at either positive or terminal (an example of a half cycle is shown in the figure below) We want to reduce the oscillations and have a constant output so the capacitor charges and discharges such that we always have the desired output. This is shown in the figure below.



The smoothing circuit contained two extra components : a zener diode and a source resistance Rs. A zener diode is a special type of diode that allows current to flow through it in either direction, i.e. it is both forward and reverse biased. Just like a regular diode, if there is current from the anode to cathode then there is a voltage drop across the diode, additionally if there is current from the cathode to anode then there is a negative voltage drop. Different diodes have a maximum voltage that can drop across it, which we call a zener voltage. The diode we used was a **1N5245B** which has a zener voltage of 15.1 volts. This is sufficient to ensure that the output from the power supply was ~15 V. One advantage of the zener diode is that it produces a stabilized voltage output under varying load current conditions. The resistor Rs acted as a current limiter and hence was connected in parallel with the zener diode. This was to ensure that the zener will conduct sufficient current to maintain a voltage drop of Vout. The load (in this case the operational amplifiers) is connected in parallel with the diode such that the voltage across the load is always the same as the zener voltage, which in this case was ~15V. After having all the stages mapped out, our next task was to calculate the actual values of the components we were going to use for the smoothing circuit(filter), which were the capacitor, series resistance and load resistance.

Hand Calculations

To calculate the value of the capacitor, we needed to ensure that the upswing time constant (charging-up period) was short and the downswing time constant (discharging period) was long both relative to the period of the rectified waveform.

τup = $2R_dC$ where R_d is the resistance of the IN4004 diode and τup is the upswing time constant.

The diode resistance was 0.042 Ω.

During the discharging period, the diode turns off and the capacitor discharges through R_L(load resistance). The downswing time constant is given by:

τdn = R_LC .

Our goal was to have a ripple less than 2% so we calculated out time constants accordingly. The frequency of the input signal was 60$H_{z,}$ which means that the frequency of the rectified waveform was 120H_z. Using the formula $T = \frac{1}{f}$ where T is period and f is frequency, the period of the rectified waveform was therefore $\frac{1}{120}$ which was 8.33 milliseconds. In order to have a reasonably short upswing time, we used a capacitor value of 2200 μF .

Therefore τup = $2 \times 0.042 \times 2200 \times 10 \wedge - 6$ = 0.000185s. This also means that τup = $\frac{period\ of\ rectified\ waveform}{45}$.

Using a load of 5100 Ω ,

$\tau dn = 5100 \times 2200 \times 10 \wedge - 6$ = 11.22s.

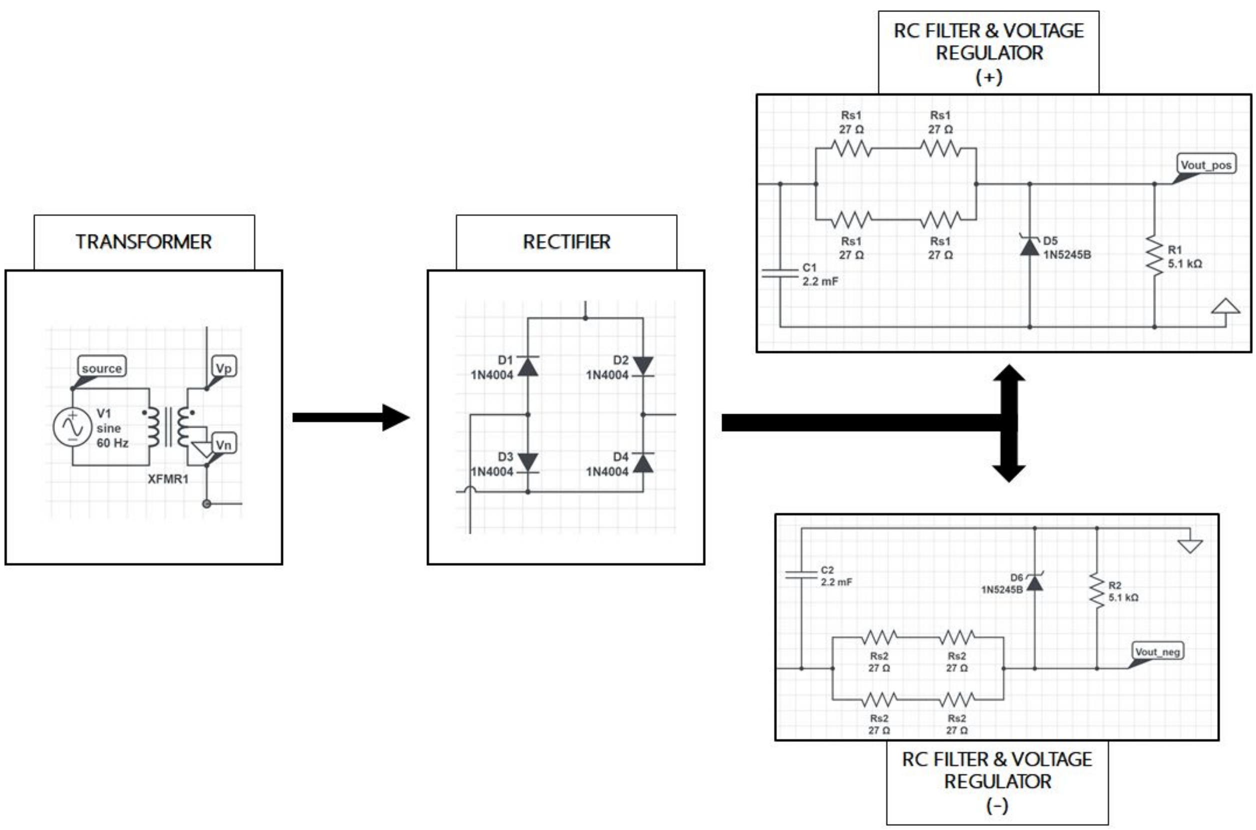
The peak to peak ripple voltage $V_r = \frac{[(Vs1-1.4)-Vz]Trect}{RsC} \times \frac{(Rz||Rl)}{Rs+(Rz||Rl)}$ where Vs1 is the magnitude of the ac signal at the output of the transformer, Vz is the zener voltage for the zener diode and Trect is the period of the rectified waveform, and Rz is the manufacturer specified value of the zener-diode resistance.

We used an Rs value of 27 Ω, and the rated value of the zener diode resistance was 16 Ω, giving us a peak to peak ripple voltage of $V_r = \frac{0.1\times8.33\times10\wedge-3}{27\times2200\times10\wedge-6} \times \frac{15.95}{42.95} = 5mV$.

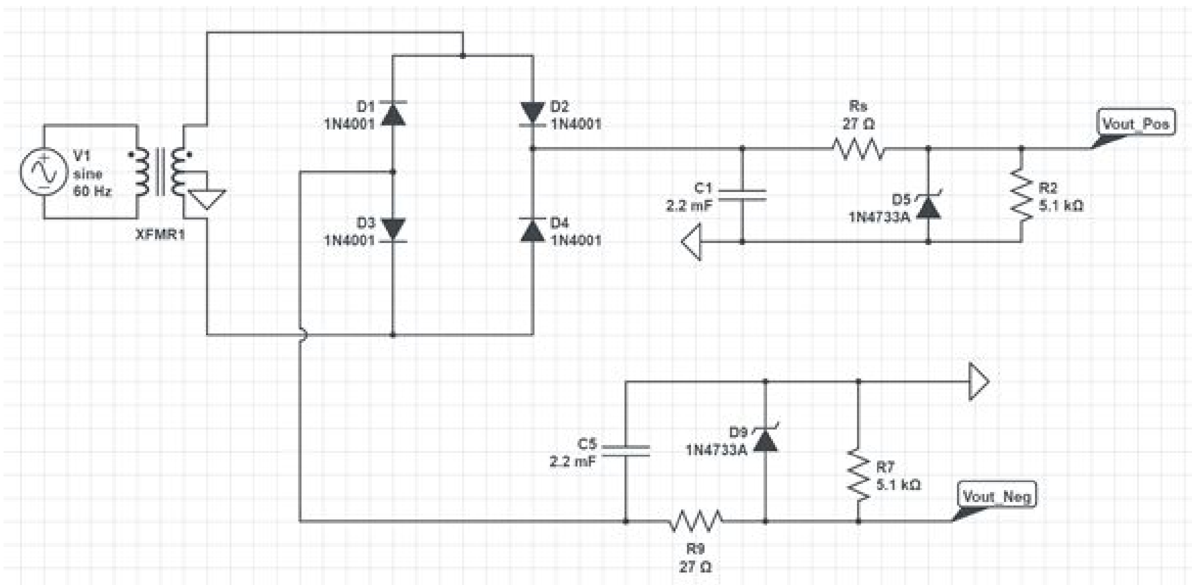
Power budget:

The thevenin voltage of the power supply was 16.2 - 1.4 = 15.1V. This is the final output voltage without a load attached. The current we calculated was 15mA.

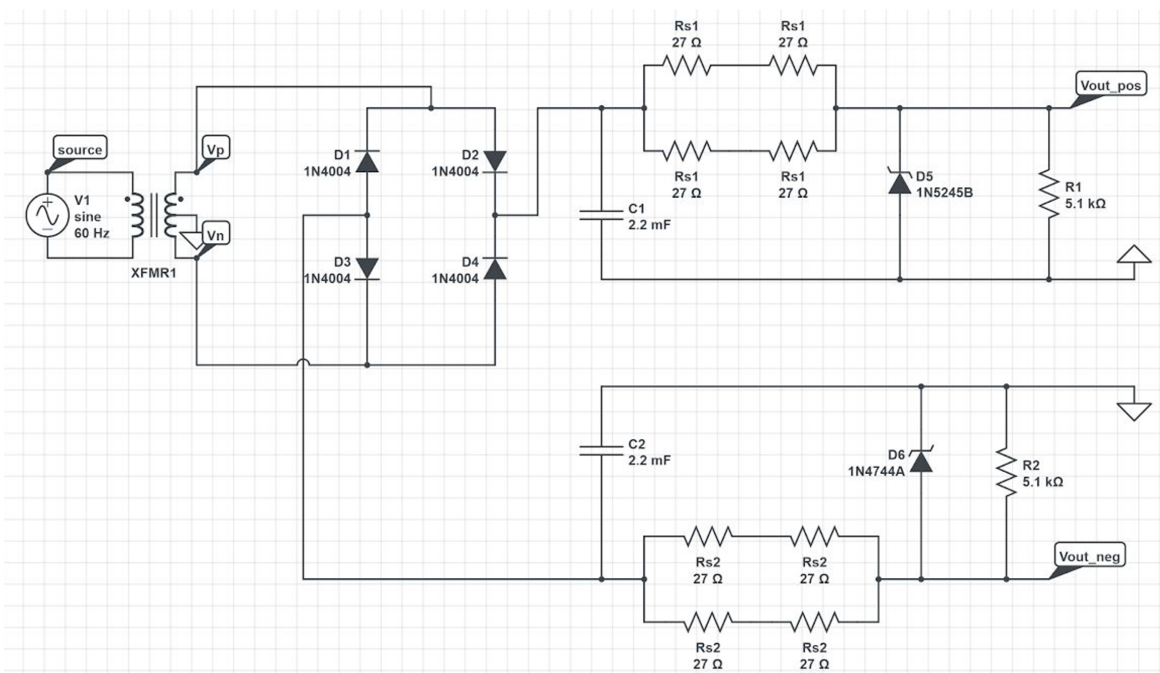
Final Block Diagram



We then constructed our overall schematic in CircuitLab and simulated the output as shown below:



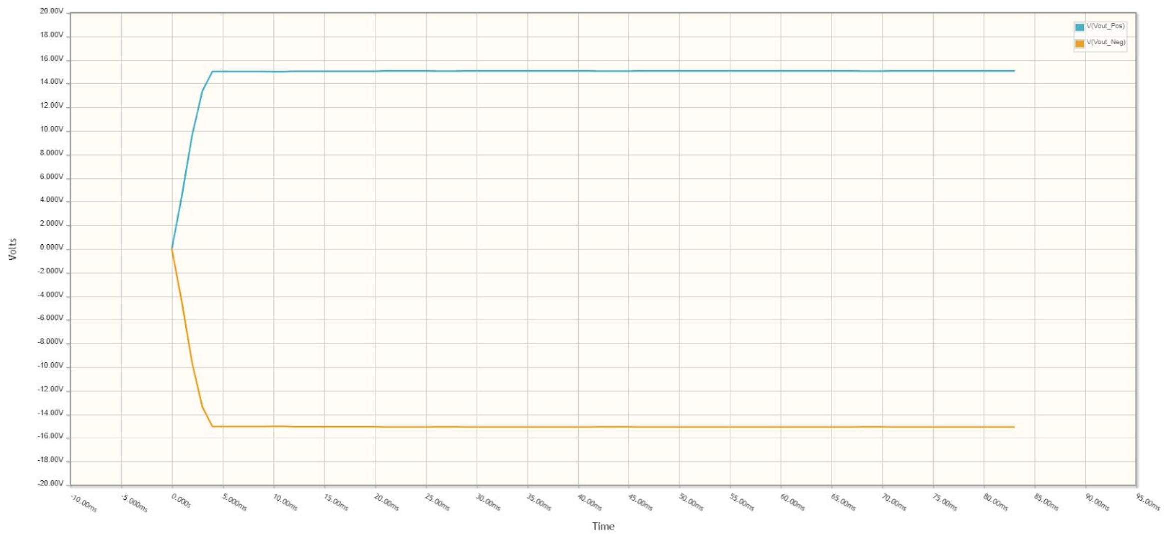
We then modified our design to help limit the overloading of our 27 Ohm resistor.



By putting resistors of the same desired value (27 Ohms) in parallel we were able to divide the current up between multiple resistors while still maintaining the desired equivalent resistance. This prevented the burnout we were previously experiencing.

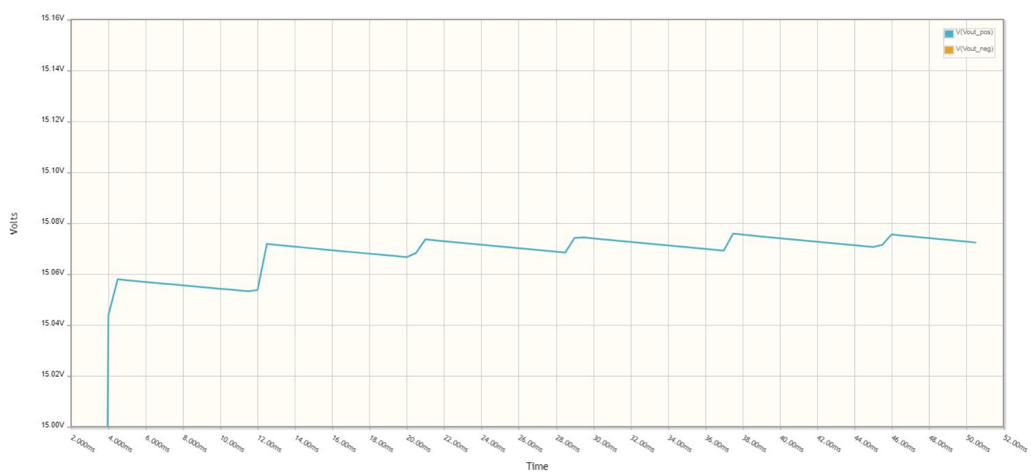
Lastly we ran a time domain sweep on our circuit from 1 Hz to 1e8 Hz at 200 points/decade and got the following output:

Power Supply Simulation Outputs



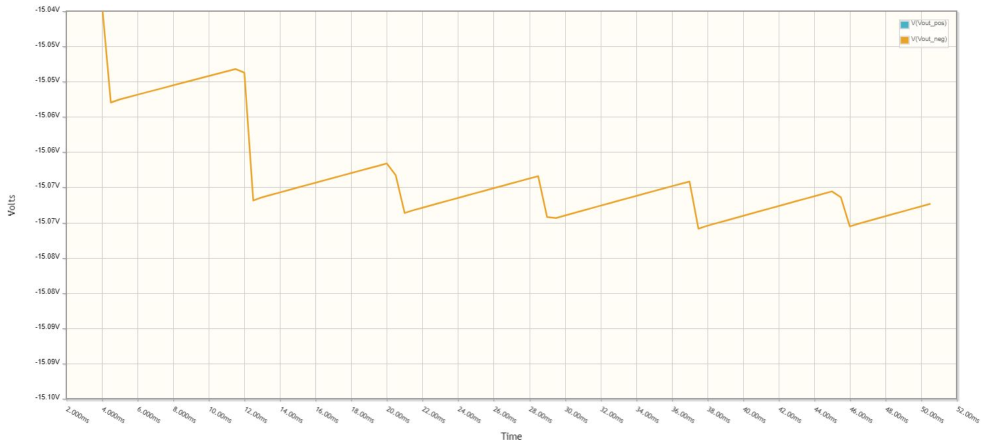
From our simulation we can saw that we outputted approximately +15 V and -15 V as we expected. According to our simulation we had a peak to peak ripple of approximately 30 mV on the positive terminal:

Positive Ripple

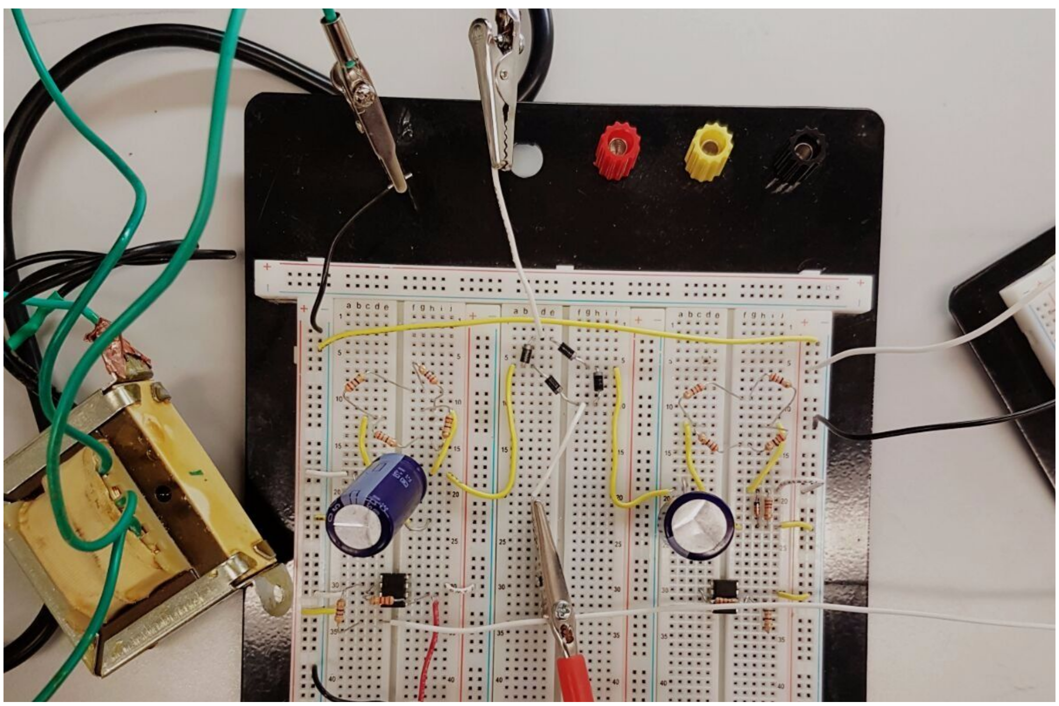


On the negative side our simulation returned to us a peak to peak ripple of approximately 30 mV too:

Negative Ripple



We deemed our power supply more than sufficient for the purpose of powering our filters. We then set out to physically build the circuit once our simulations proved satisfactory.

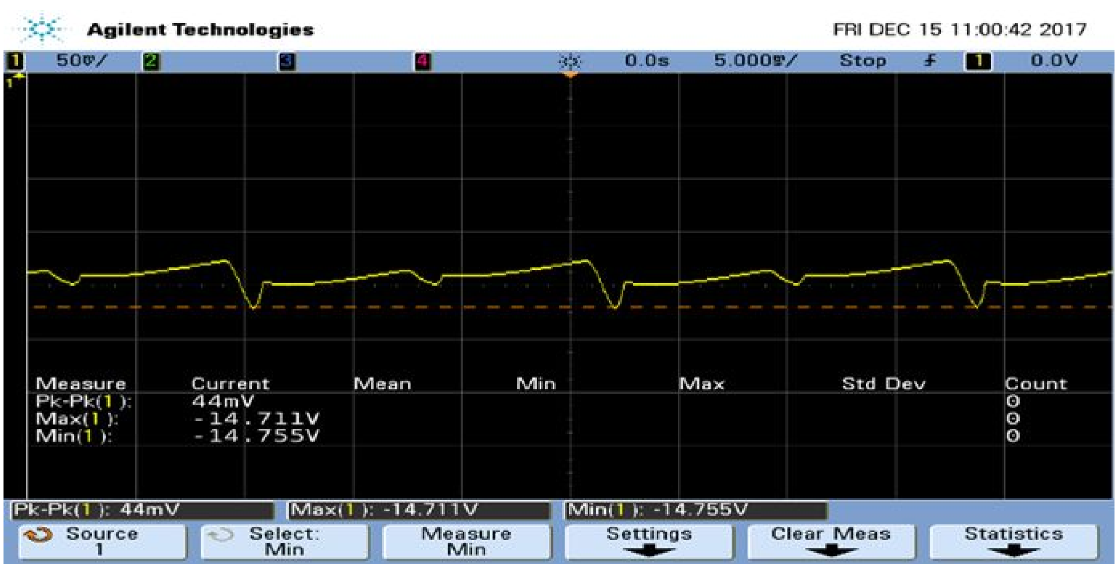


Physically Built Power Supply

Experimental Results/Analysis

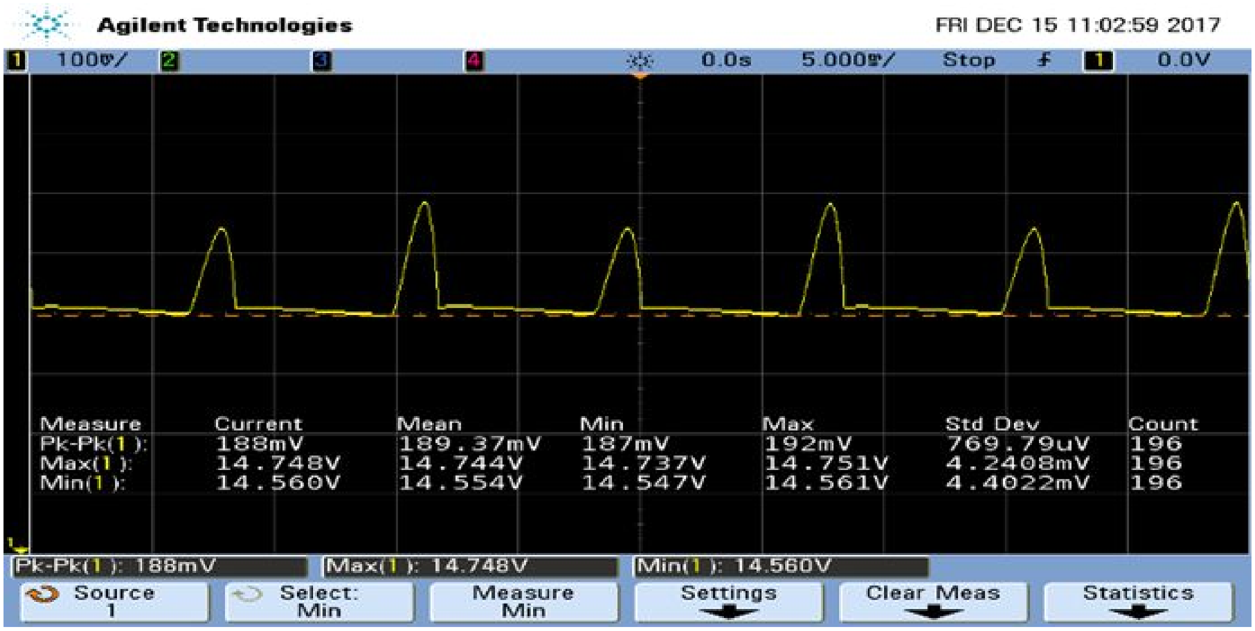
Once built we needed to measure the corresponding outputs of our power supply to ensure they fell in line with our ideal simulations. To document this we captured scope images using the 300 MHz, 4 Analog channel + 16 Logic channel input MSO7034B scope we had at our disposal. We measured the following from our terminals:

Negative Terminal



For our negative terminal a 44 mV peak to peak ripple which was still very small even though it garnered a 37.837 % difference from our simulation. The size was still reasonable enough for our power supply to be considered reliable. Our maximum output was 14.755V which garnered a 1.646782053 % difference from our idealized 15 V output which was too satisfactory.

Positive Terminal



For our positive terminal a 188 mV peak to peak ripple which was also still very small even though it garnered a much larger 144.9541284 % difference from our simulation. The size was still reasonable enough for our power supply to be considered reliable. Our maximum output was 14.748 V which garnered a 1.694231545 % difference from our idealized 15 V output which was satisfactory.

Error Analysis

1N5245B 15 V Zener Diodes have a tolerance of 5%.

Percentage Differences Table

Power Source

	Measured	**Simulated**	**Calculated**	**Percentage Diff**
Rs1	27.01698801 Ohms	27 Ohms	27 Ohms	0.06289876806 %
R1	5.0356 kOhms	5.1 kOhms	5.1 kOhms	1.270768381 %
Rs2	26.89746427 Ohms	27 Ohms	27 Ohms	0.3804844305 %
R2	5.0468 kOhms	5.1 kOhms	5.1 kOhms	1.048606457 %
C1s	1710 uF	2200 uF	2200 uF	25.06393862 %
C1p	485 uF	N/A		
C2s	1760 uF	2200 uF	2200 uF	22.22222222 %
C2p	301.1 uF	N/A		
D1	N/A	0.042 Ohms	0.042 Ohms	
D2	N/A	0.042 Ohms	0.042 Ohms	
D3	N/A	0.042 Ohms	0.042 Ohms	
D4	N/A	0.042 Ohms	0.042 Ohms	
zD1	N/A	0.042 Ohms	0.042 Ohms	
zD2	N/A	0.042 Ohms	0.042 Ohms	

Section Conclusion

The goal of this section was to build a 15V DC power supply from a 120 Vrms AC source. The power supply worked very well. There was one occasion where we blew a fuse on the transformer because we had short-circuited the source resistance. We were able to quickly realise this and changed the fuse accordingly. The final output voltage that the power supply was able to deliver was ~14.7 V at the positive and negative outputs. Although not precisely 15V, it was within the margin of error that we had determined ourselves. The attached load was able to utilise the power supply fully and draw enough current to sustain it ~15mA for the T1071 operational amplifier.

PART II – Filter Component

Introduction

We set out to design two filters to handle an unamplified audio signal of voltage that ranged from 0 to approximately 300 V_{RMS} and frequency from 20 Hz to 20 kHz (the audible spectrum). Our first filter we designed was to filter the bass frequencies of our input signal, and our second to filter out the treble frequencies of our input signal. Our given filter specifications were as follows:

Bass Filter

Frequency Range (Bandpass Specification): 150 Hz to 350 Hz

Roll-Off Rate: -20 dB

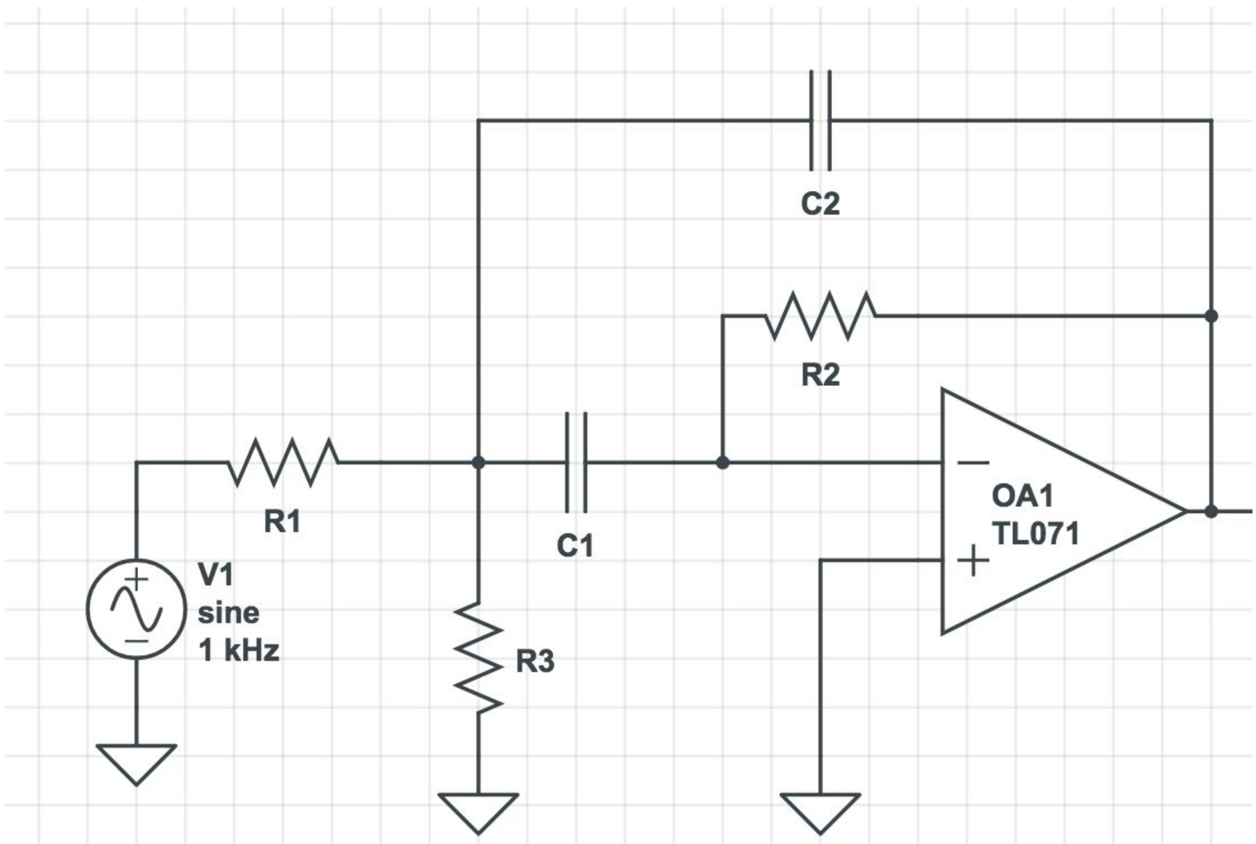
Treble Filter

Frequency Range (Bandpass Specification): 7.9 kHz to 9.9 kHz

Roll-Off Rate: -20 dB

This meant that we needed to build a filter with a bandpass that ranged from 150 Hz to 350 Hz for the bass filter and 7.9 kHz to 9.9 kHz for the treble filter.

A bandpass filter passes frequencies between its two cutoff values known as cutoff frequencies. The filter progressively attenuates signals not between the cutoff frequencies. A bass filter produces a bass heavy output to the ear while suppressing sharper sounds of higher frequencies. A treble filter does the same thing but in reverse. We approached this by building a first order bandpass filter by cascading an active low pass and an active high pass filter. The cutoff frequency for the low pass was supposed to serve as the upper cutoff for the bandpass filter and the cutoff for the highpass was supposed to serve as the lower cutoff frequency. Although this worked well, the bandwidth was wider than the required bandwidth (more than double) and did not fit the requirements. We increased the order to a second order by cascading two low-pass and two high pass filters but the bandwidth was still too high, even after attempting a third order. We then decided to change our design and decided to use a single operational amplifier but instead incorporate a multiple feedback system for better quality.



The operational amplifier(op-amp) we used was a low-noise TL071. We decided to use this particular model because of its low-noise characteristics. This filter was used for both the bass and treble filters. We calculated the transfer function by taking the ratio of

$$\frac{V_o}{V_i} = -\left(\frac{R_3}{R_1 + R_3}\right)\left(\frac{j\omega R_2 C}{-\omega^2(\frac{R_1 R_3}{R_1+R_3})C^2 R_2 + j\omega(\frac{R_1 R_3}{R_1+R_3})2C + 1}\right)$$

the output voltage to the input voltage, the final result is show in the equation above.

Bass filter:

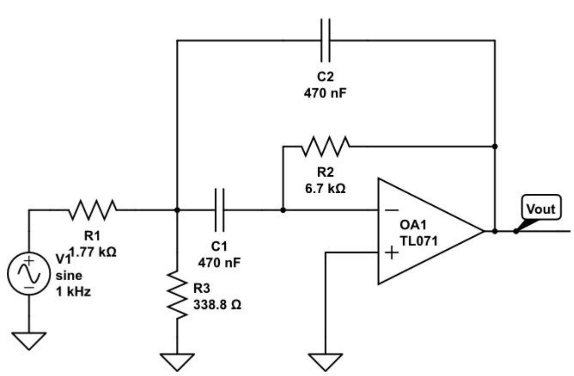
The frequency range was 150 Hz to 350 Hz but we decided to make a narrower bandwidth for the extra credit. Our new targeted frequency range was 200Hz to 300Hz. Converting to radians per second by multiplying by 2 pi gives us corner frequencies of 1256.64 rad/s and 1884.96 rad/s respectively. This gives us a bandwidth(B) of 1884.96 - 1256.64 = 628.32. The corner frequency is given by the formula $\omega o = \sqrt{\omega c1 \times wc2}$. So our corner frequency was $\omega o = \sqrt{1256.64 \times 1884.962}$ = 1539 radians/sec. The quality factor Q is given by $\frac{\omega o}{B}$ = $\frac{1539}{628}$ = 2.45

First we calculated a scaling factor k which has the formula, k = $2\pi\ \omega oC$. For a low k of 0.0045, C = $\frac{0.0045}{2\pi \times 1539}$ = 470 nF. The next step was to calculate the values of the resistors R1,R2 and R3 respectively, shown in the diagram above.

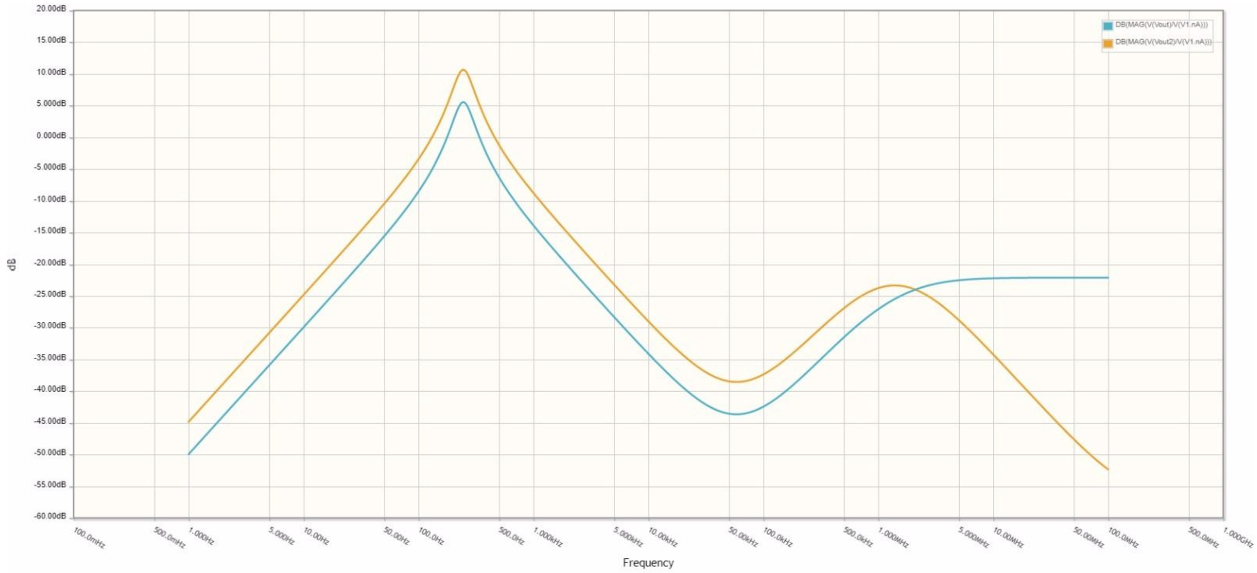
For R1, we used the formula R1 = $\frac{Q}{Hk}$ where H is the gain that we set . R2 is given by the formula R2 = $\frac{2Q}{k}$, and R3 is given by $\frac{Q}{(2Q2 - H)K}$.

Our calculated values were thus R1 = 1.77kΩ, R2 = 6.7KΩ, R3 = 338.8Ω.

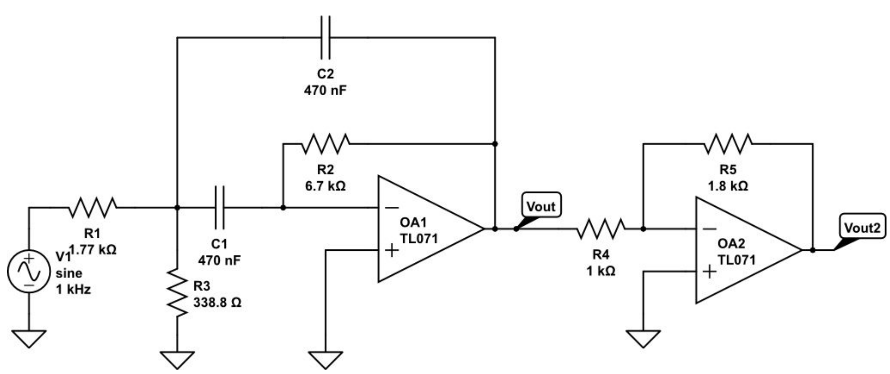
Bass Filter Schematic



Simulated Bass Filter Bode Plot



We decided to increase the gain by cascading the filter with a simple inverting amplifier circuit. This increased the volume and boosted the sound of the music. The gain for the inverting amplifier = $\frac{RF}{Rs} = 1.8$. The final version of the filter is shown below. The simulated bode plot above shows two plots. The one in blue is the plot without the extra inverting amplifier at the end and the plot in orange shows the output with the inverting amplifier at the end. This increased the gain just as we wanted it to.



Treble filter:

The frequency range was 7.9 KHz to 9.9 KHz but we decided to make a narrower bandwidth for the extra credit. Our new targeted frequency range was 8.15KHz to

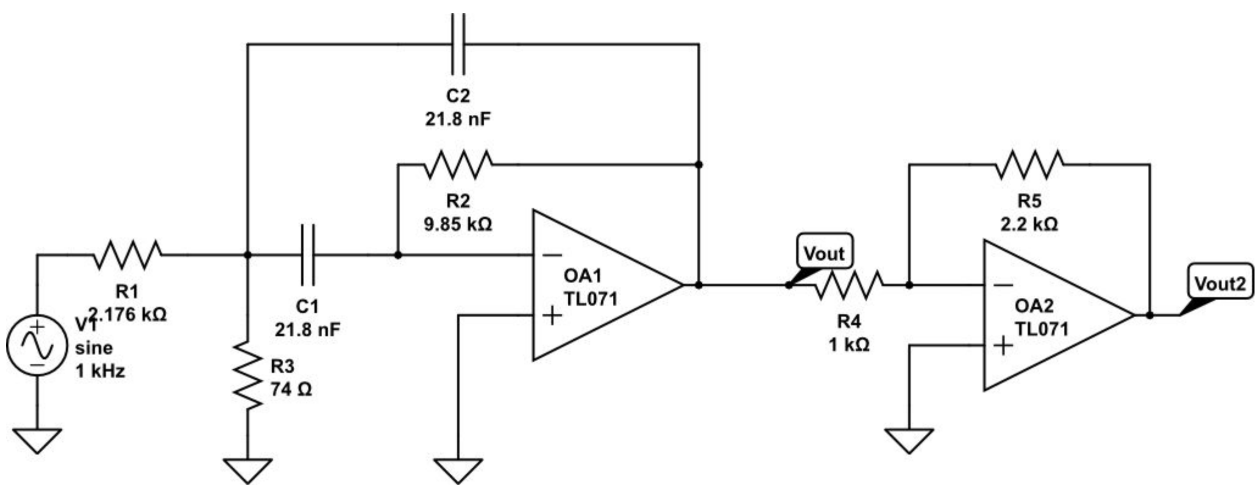
9.65KHz. We used the same approach as with the treble filter. Converting to radians per second by multiplying by 2 pi gives us corner frequencies of 51207.96 rad/s and 60632.738 rad/s respectively. This gives us a bandwidth(B) of 51207.96 - 60632.738 = 9424. The corner frequency is given by the formula $\omega o = \sqrt{\omega c1 \times wc2}$. So our corner frequency was $\omega o = \sqrt{51207.96 \times 60632.738}$ = 55721.43 radians/sec. The quality factor Q is given by $\frac{\omega o}{B} = \frac{55721.43}{9242}$ = 6.029.

The scaling factor k which has the formula, k = $2\pi\ \omega o C$. For a low k of 0.0076, C = $\frac{0.0076}{2\pi \times 55721.43}$ = 21.8 nF. T

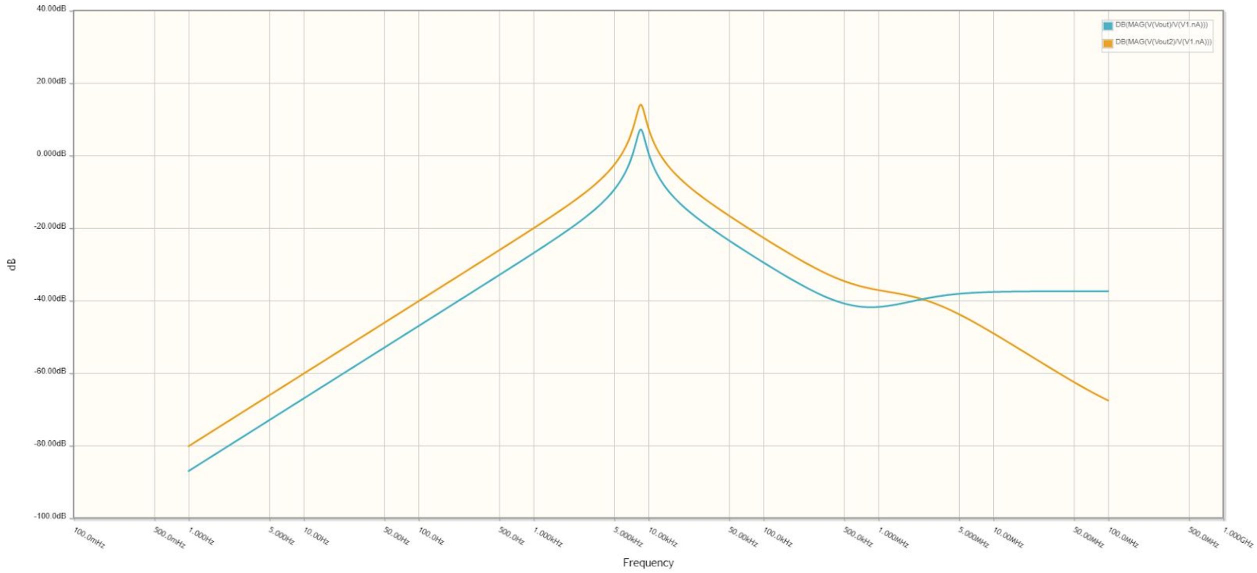
For R1, we used the formula R1 = $\frac{Q}{Hk}$ where H is the gain that we set . R2 is given by the formula R2 = $\frac{2Q}{k}$, and R3 is given by $\frac{Q}{(2Q2 - H)K}$.

Our calculated values were thus R1 = 2.176kΩ, R2 = 9.85KΩ, R3 = 74Ω.

Treble Filter Schematic



Simulated Treble Filter Bode Plot



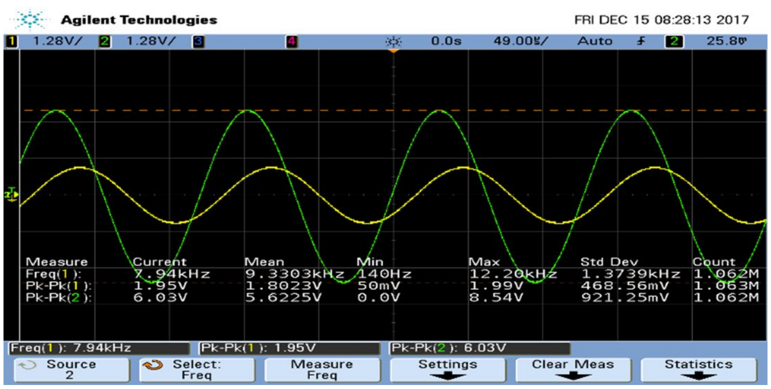
As with the bass filter, we cascaded an inverting amplifier circuit to the output of the treble filter to increase the gain. The blue plot in the Bode diagram above shows the original output of the filter without the inverting amplifier at the end and the orange diagram shows the output of the filter with the extra gain at the end. The gain of the inverting amplifier was $\frac{2200}{1000}$ = 2.2.

Experimental Results/Analysis

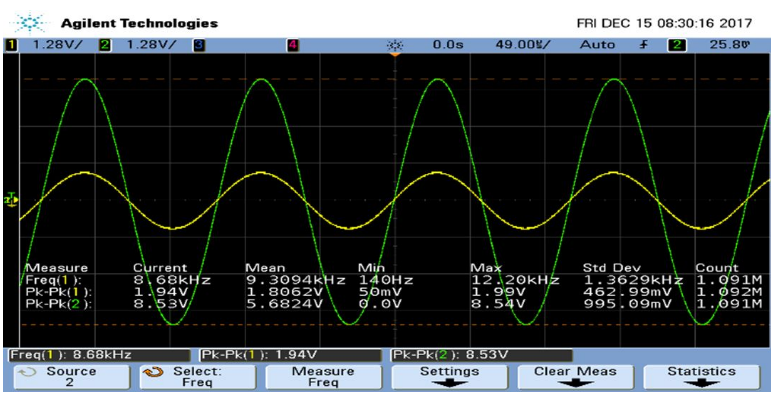
In order to measure the outputs of our filters and test that they were working according to our specifications we needed to connect them to an oscilloscope. We utilised the 300 MHz, 4 Analog channel + 16 Logic channel input MSO7034B scope in the lab.

To effectively measure and test our filters we needed to identify the corner frequencies using the oscilloscope. We did this by manually sweeping through the frequencies until the center frequency was identified (the middle most frequency such that adjusting frequency either up or down would cause a decrease in the maximum peak to peak voltage). We then multiplied the maximum Voltage peak to peak by $\frac{\sqrt{2}}{2}$ which gave us the voltage at which the corner frequencies would lie on either side of the center frequency. Our resultant cut off frequencies are below. They fell well within our specifications:

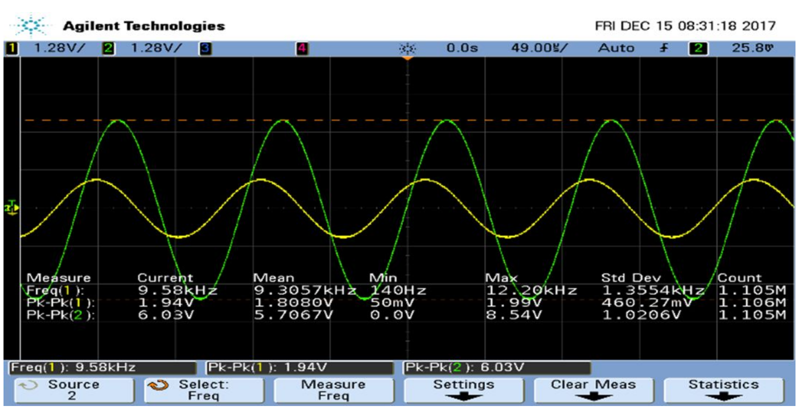
Treble Filter Oscilloscope Readings



Left Cutoff - 7.94 kHz

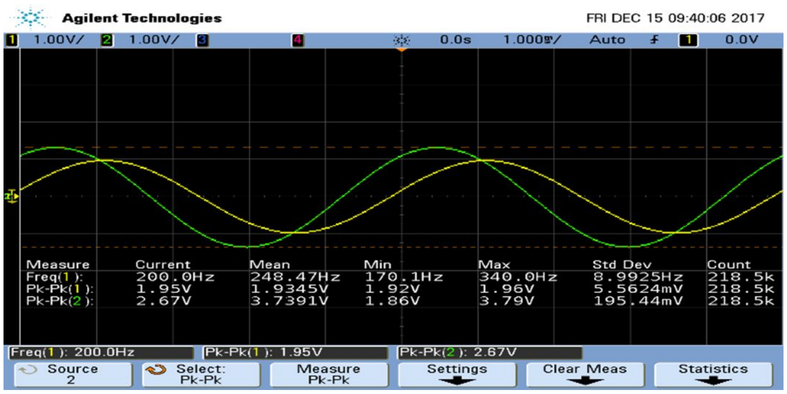


Center Freq - 8.68 kHz

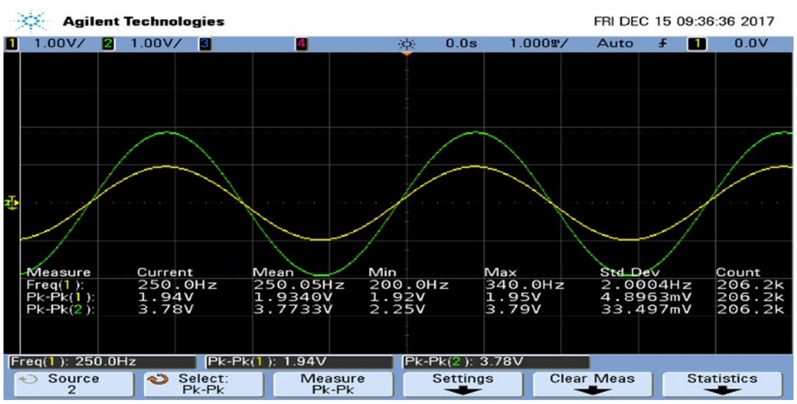


Right Cutoff - 9.58 kHz

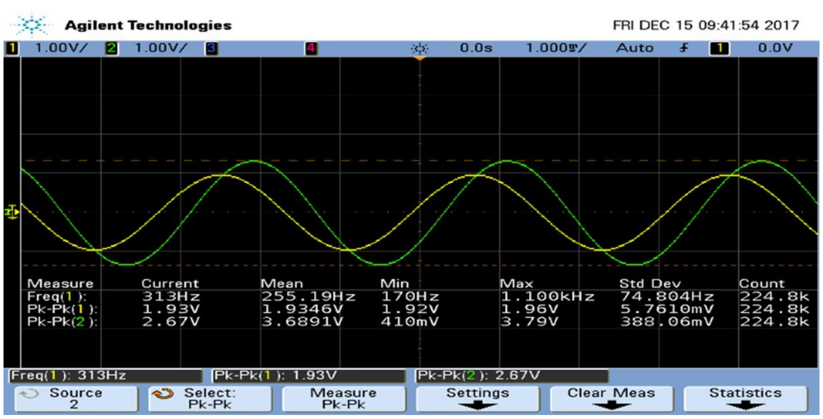
Bass Filter Oscilloscope Readings



Left Cutoff - 200 Hz



Center Freq - 250 Hz



Right Cutoff - 313 Hz

To summarize, our given specifications were the following:

Bass Filter

Frequency Range (Bandpass Specification): 150 Hz to 350 Hz

Roll-Off Rate: -20 dB

Treble Filter

Frequency Range (Bandpass Specification): 7.9 kHz to 9.9 kHz

Roll-Off Rate: -20 dB

Our achieved specifications were the following:

Bass Filter

Frequency Range (Bandpass Specification): 200 Hz to 313Hz

Roll-Off Rate: -20 dB

Treble Filter

Frequency Range (Bandpass Specification): 7.94 kHz to 9.58 kHz

Roll-Off Rate: -20 dB

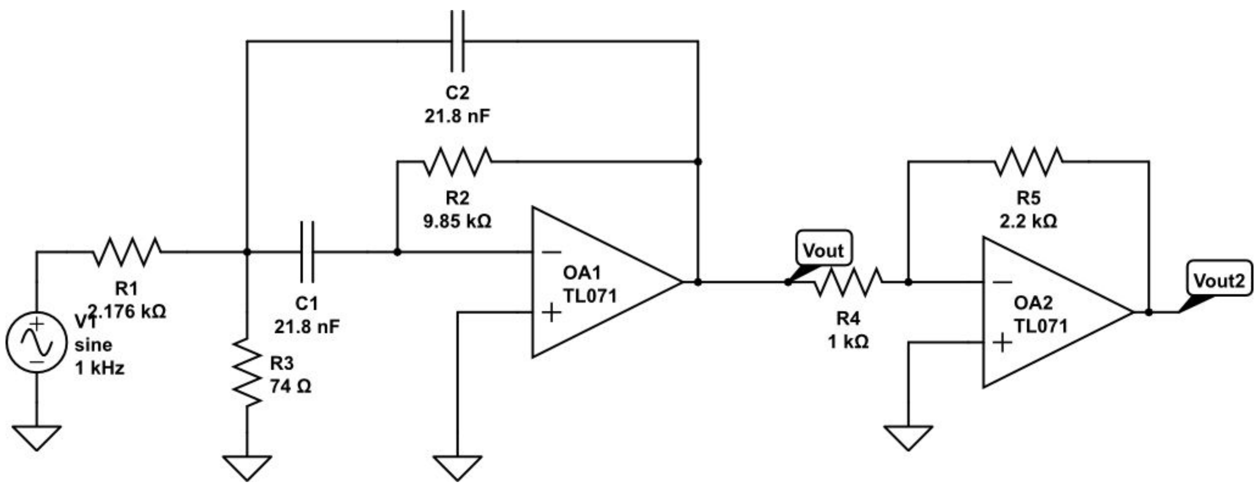
Hence we achieved our specifications in the end.

Error Analysis

Error occurs between the ideal calculated values of circuit components and their actual measured values when the real circuit components are evaluated. The discrepancy between labelled component values and actual component values is known as tolerance and its resultant error is accounted for in the following figures below:

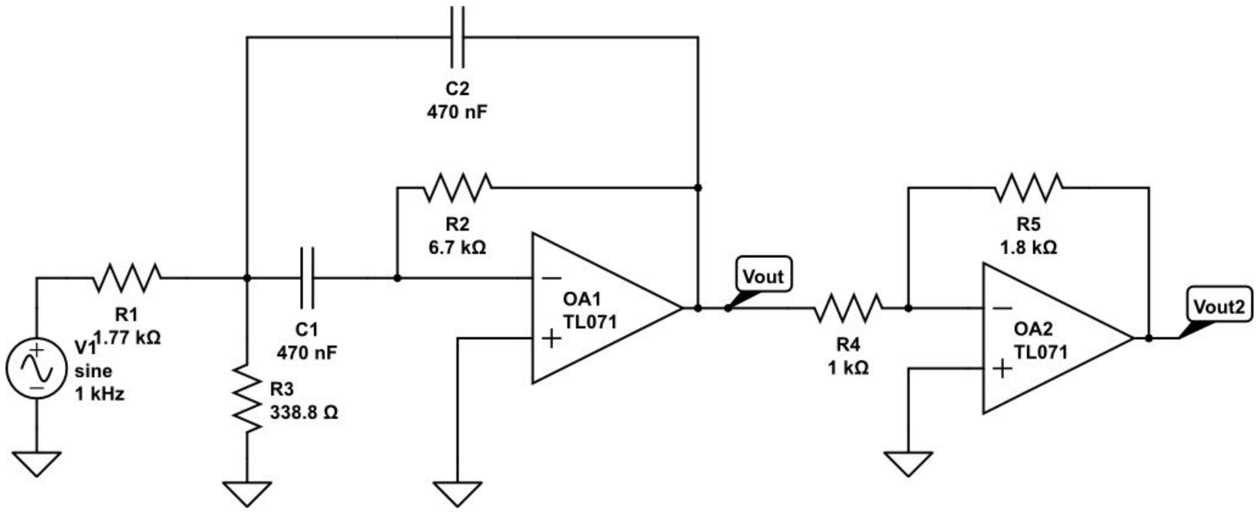
Percentage Difference Tables

Treble Filter



	Measured	Simulated	Calculated	Percentage Diff
R1	2.176 kOhms	2.176 kOhms	2.176 KOhms	0.000000000 %
R2	9.85 kOhms	9.85 kOhms	9.85 kOhms	0.000000000 %
R3	72.56 Ohms	74 Ohms	74 Ohms	1.965065502 %
R4	988 Ohms	1 kOhm	1 kOhm	0.2002002002 %
R5	2.178 kOhms	2.2 kOhms	2.2 kOhms	1.005025126 %
C1s	18nF	21.8 nF	21.8 nF	19.09547739 %
C1p	3 nF	N/A	N/A	
C2s	17.8 nF	21.8 nF	21.8 nF	20.2020202 %
C2p	3.8 nF	N/A	N/A	

Bass Filter

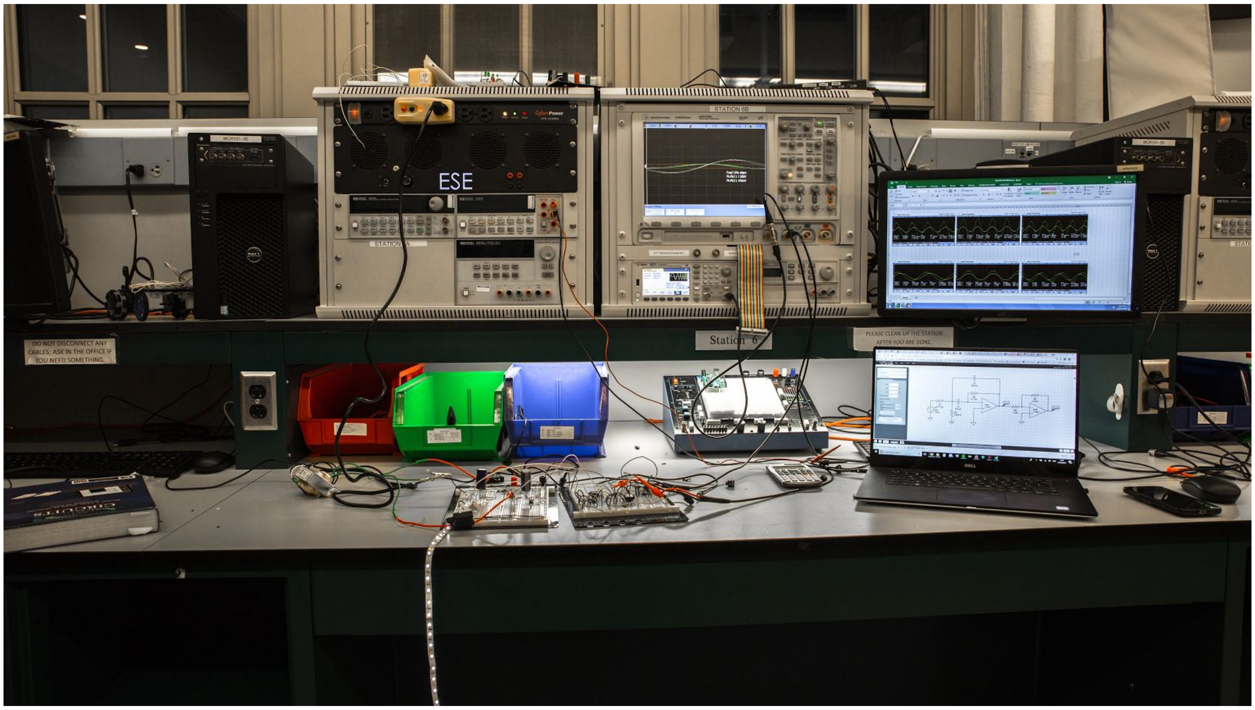


	Measured	Simulated	Calculated	Percentage Diff
R1	1.77 kOhms	1.77 kOhms	1.77 kOhms	0.00000000 %
R2	6.7 kOhms	6.7 kOhms	6.7 kOhms	0.00000000 %
R3	338.8 Ohms	338.8 Ohms	338.8 Ohms	0.00000000 %
R4	979 Ohms	1 kOhm	1 kOhm	2.122283982 %
R5	1.76 kOhms	1.8 kOhms	1.8 kOhms	2.247191011 %
C1s	436 nF	470 nF	470 nF	7.505518764 %
C1p	33.6 nF	N/A	N/A	
C2s	420 nF	470 nF	470 nF	11.23595506 %
C2p	43 nF	N/A	N/A	

Section Conclusion

The aim of this section was to build two fully functional filters that could allow low and high frequencies within a certain range to pass through. This was achieved with two differently calibrated bandpass filters. One accurately filtered low frequencies and the other filtered high frequencies. The music sounded great and our measurements corresponded with our simulations with minor percentage differences due to differences in the manufacturer ratings of the resistors and actual resistance. A few of the resistors had to change slightly, for example the 1.77kOhm resistor was changed from a 1.56 kOhm resistor because it was hard to find that in the lab. This change resulted in an increase in the capacitor value to 470nF.

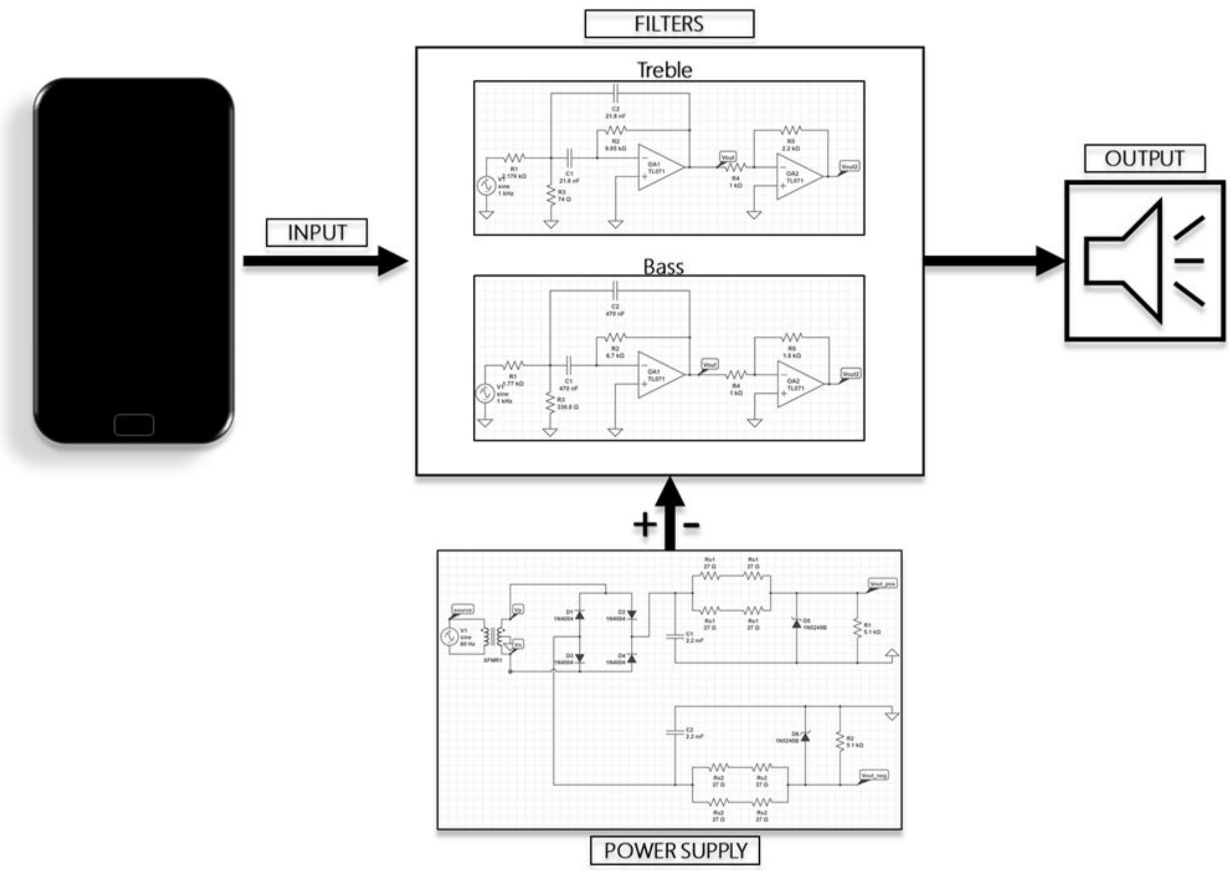
PART III – Final Integration

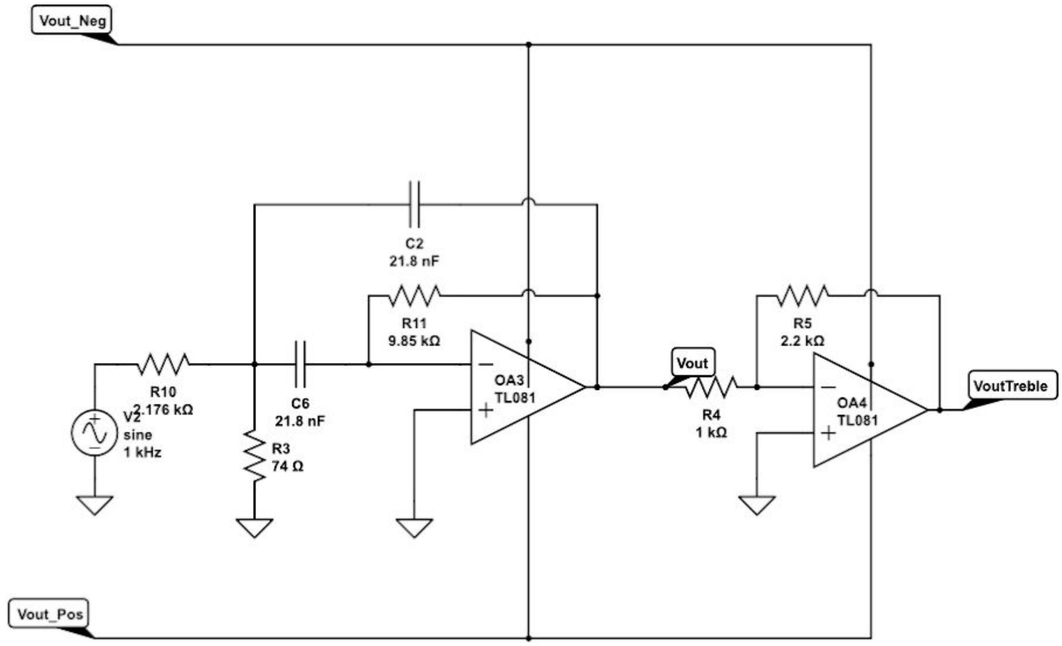


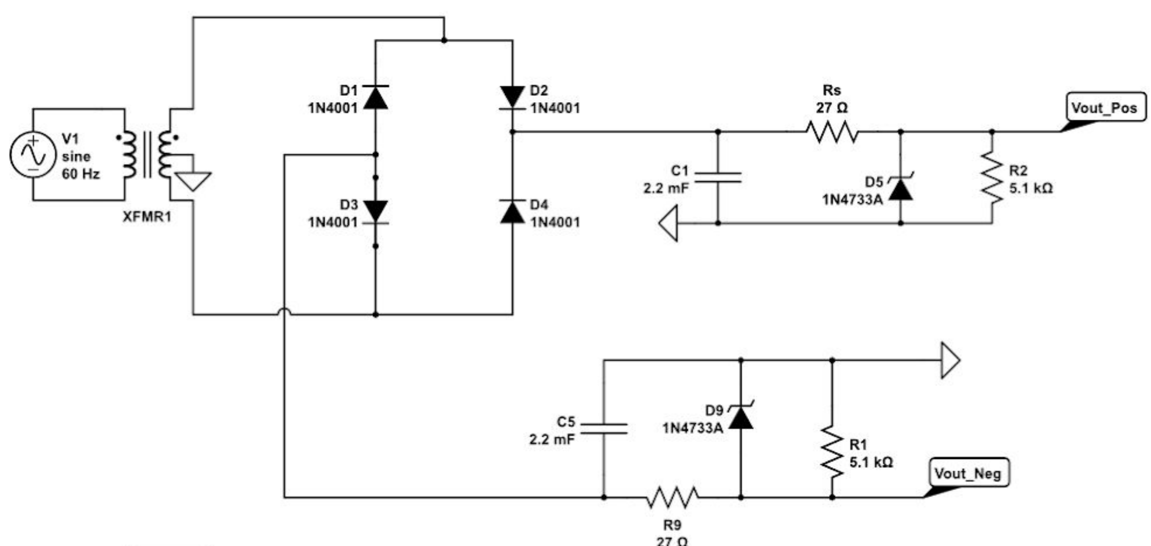
Introduction

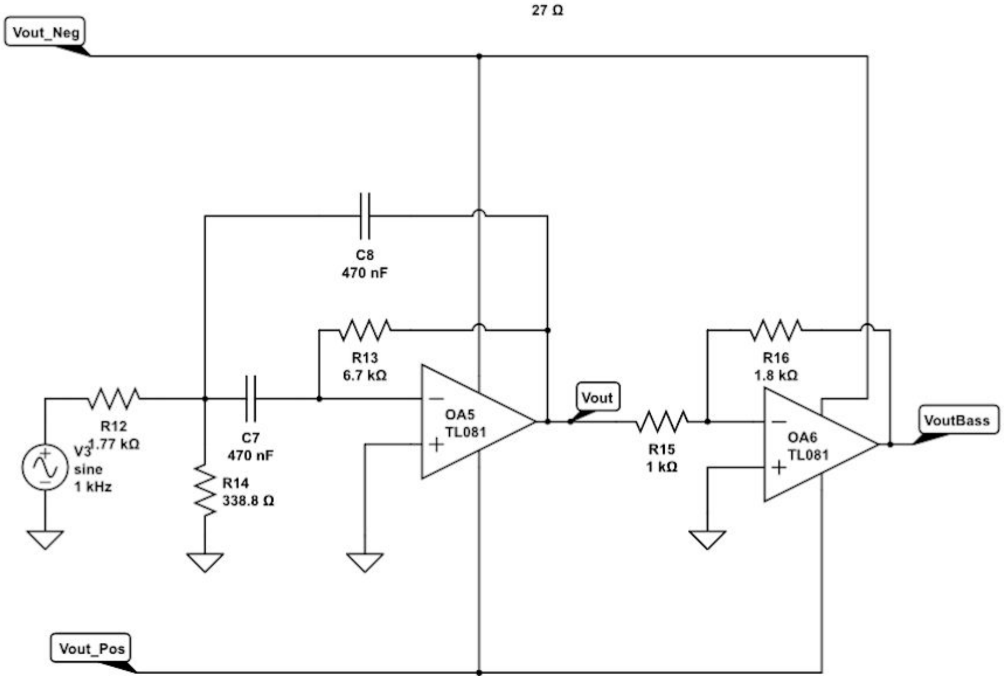
Ultimately we intended to use the power supply to power our active filters. We needed to integrate our power supply and filters and feed audio input into our filters. We needed to connect our power supply outputs to the negative and positive rails of our OpAmps to ensure they were powered. We then needed to pass a signal in the audible frequency range of 0 to 300 V RMS. We mapped out a block diagram and a detailed schematic below of our approach.

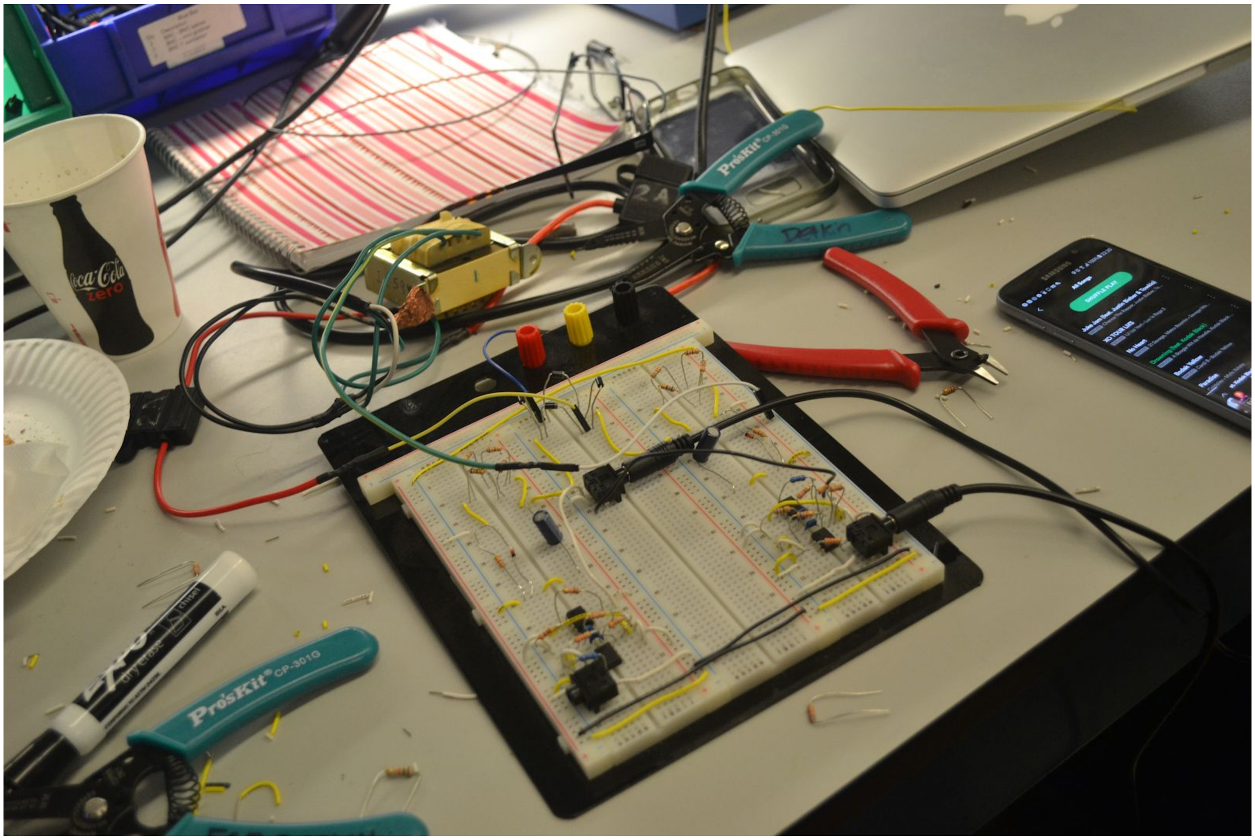
Block Diagram




Vout_Neg
C2
21.8 nF
R11
9.85 kΩ
R5
2.2 kΩ
R10
2.176 kΩ
V2
sine
1 kHz
C6
21.8 nF
R3
74 Ω
OA3
TL081
Vout
R4
1 kΩ
OA4
TL081
VoutTreble
Vout_Pos


V1
sine
60 Hz
XFMR1
D1
1N4001
D2
1N4001
D3
1N4001
D4
1N4001
Rs
27 Ω
Vout_Pos
C1
2.2 mF
D5
1N4733A
R2
5.1 kΩ
C5
2.2 mF
D9
1N4733A
R1
5.1 kΩ
Vout_Neg
R9
27 Ω


Vout_Neg
C8
470 nF
R13
6.7 kΩ
R16
1.8 kΩ
R12
1.77 kΩ
V3
sine
1 kHz
C7
470 nF
R14
338.8 Ω
OA5
TL081
Vout
R15
1 kΩ
OA6
TL081
VoutBass
Vout_Pos



We hooked up a splitter cable to our input and took the one aux to the input of the treble and another to that of the bass. Finally we connected a third aux output to the speaker.

Final Conclusion

The final integration was seamless. This is because we had thoroughly tested each subcomponent before hand and all we had to do was just plug the terminals of the op-amps in the filters into the positive and negative terminals of the power supply. The op-amps were able to draw enough current from the power supply. We learnt a lot in this project. We had gone through multiple filter designs before settling on our final one which sounded great and met the specifications. The biggest differences between our hand calculations and simulated values had to do with the differences between the manufacturer rated values and actual values. Also due to the nature of the filters, the values were very sensitive such that tiny deviations in the value of a resistor for example changes the bandwidth. For some of the precise measurements we could not calculate the exact resistor value from the values we had in the lab so we had to compensate for that.

Appendix

Specification Sheet

Zener Diode	http://pdf.datasheetcatalog.com/datasheet/central/1N5239B.pdf
IN4004	http://www.onsemi.com/pub/Collateral/1N4001-D.PDF
TL071	http://www.ti.com/product/TL071/datasheet/pin-configuration-and-functions
Hammond / 166K18	http://www.chipicsource.com/datasheets/ad/166F28.pdf