ECE 223 Project Report
Digital Equalizer

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6/9/2022

I. Abstract

The goal of this project is to design a set of frequency filters that would allow specific ranges of the input audio signal through to LEDs, which would in turn light up to indicate which ranges are playing and at what amplitude.

II. Introduction

The team designed 5 filters: a first order active low-pass filter with the range of 0-115 Hz, three second order Sallen-Key band pass filters with the ranges of 140-200 Hz, 300-700 Hz, and 700-900 Hz, and a second order active high-pass filter with the range of 1.5 kHz and up. Due to limited options of standard components, the actual ranges are 0-113 Hz, 138-195 Hz, 402-516 Hz, 723-918 Hz, and 1.35 kHz and up.
The song chosen for the demo is Faded by Alan Walker. The topology of the five filters are displayed below.

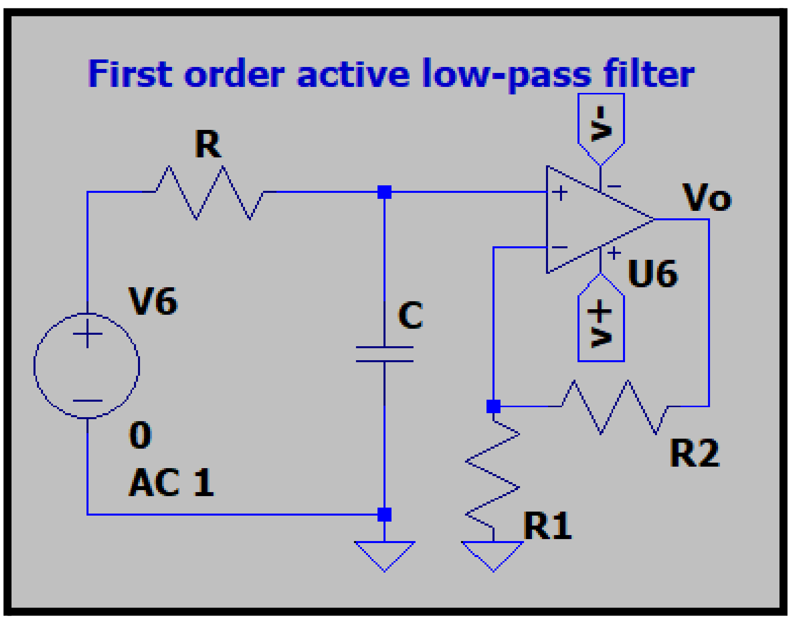


Figure 1: First order active low-pass filter

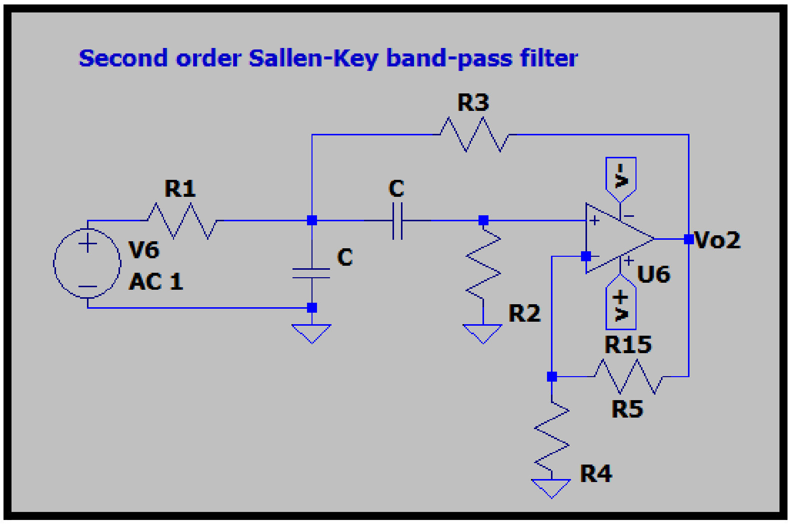


Figure 2: Second order Sallen-Key band-pass filter

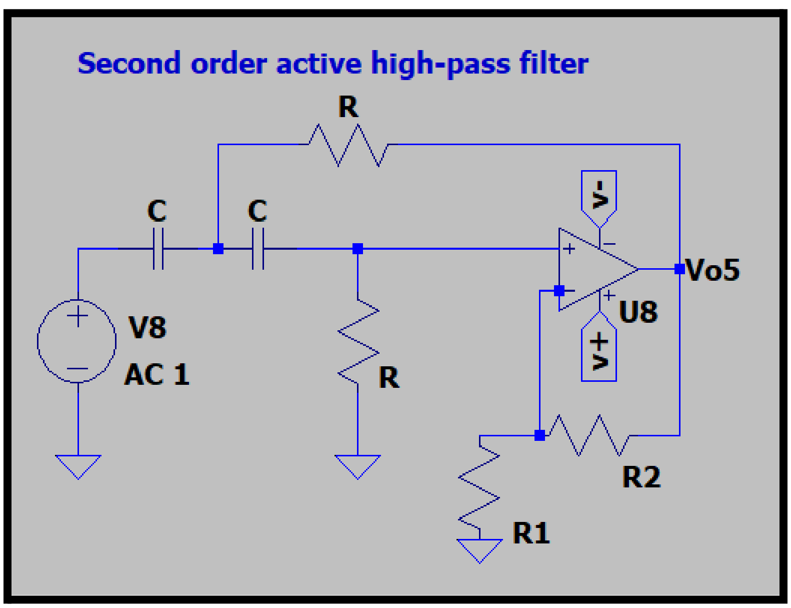


Figure 3: Second order active high-pass filter

A block diagram of the overall circuit is displayed below:

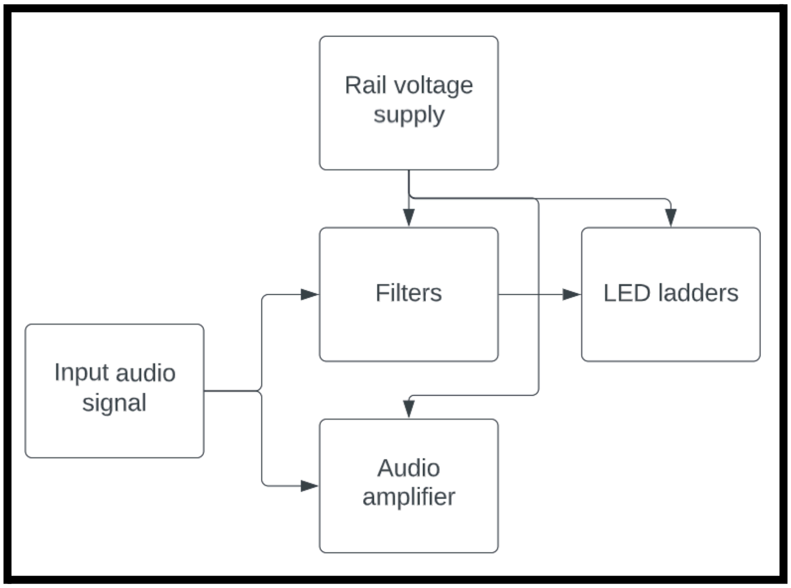


Figure 4: Block-diagram of the overall circuit

III. Design Summary

The low-pass filter was designed with frequency/impedance scaling based on the bandwidth with a 0.47 μF capacitor and the gain of 1 (i.e., $R_1=\infty\ \Omega$ and $R_2=0\ \Omega$). The calculations are shown below. Reference **Figure 1** for the filter topology.

$$H(s) = \frac{\frac{1}{RC}\left(1+\frac{R_2}{R_1}\right)}{s+\frac{1}{RC}} \quad => \quad R_2 = 0 \text{ } and \text{ } R_1 = \infty$$

$$f_c = \frac{1}{2\pi RC} = 115\ Hz \quad => \quad R = \frac{1}{f_c 2\pi C} = \frac{1}{115\ Hz \times 2\pi \times 0.47\ \mu F} = 2,945\ \Omega$$

The band-pass filters were designed with frequency/impedance scaling based on the bandwidth and Q to get realistic resistor values with 0.47 µF capacitors for filter 2 and 0.1 µF capacitors for filters 2 and 3.
For example, for filter 2 (140-200 Hz, Q=3, C=0.47 µF), the calculations are below. Reference **Figure 2** for the filter topology.

$$H(s) = \frac{s\frac{1}{R_1C}\times\left(1+\frac{R_5}{R_4}\right)}{s^2+\frac{2}{R_1C}+\frac{R_1+R_3}{2R_1R_3C^2}} \quad => \; R_5 = 0 \; and \; R_4 = \infty$$

$$w_o = \sqrt{f_1 * f_2} \qquad w_o = \sqrt{(140\,Hz * 200\,Hz)} = 167.3$$

$$K_f = 2\pi * w_o \qquad K_f = 2\pi * 167.3 = 1051.4$$

$$K_m = \frac{2 * Q}{C * K_f} \qquad K_m = \frac{2 * 3}{0.47\,uF * 1051.4} = 12142.1$$

$$R_1 = K_m \qquad R_1 = 12142.1\,\Omega$$

$$R_2 = 2 * R_1 \qquad R_2 = 2 * 12142.1 = 24284\,\Omega$$

$$R_3 = \frac{1}{8 * Q^2 - 1} * K_m \qquad R_3 = \frac{1}{8 * 3^2 - 1} * 12142.1 = 171.0\,\Omega$$

The second order high-pass filter was designed with frequency/impedance scaling based on the bandwidth with 0.01 µF capacitors. The calculations are shown below. Reference **Figure 3.** for the filter topology.

$$H(s) = \frac{s^2\times\left(1+\frac{R_2}{R_1}\right)}{s^2+\frac{1}{R_1C}+\frac{1}{R_1^{\,2}C^2}}$$

High pass Filter Calculations:

$$R = 10000\,\Omega$$

$$C = 0.01uF$$

$$R_1 = R_2 = 5000\,\Omega$$

$$f_c = \frac{1}{2\pi * 0.01uF * 10000\,\Omega} = 1590\,Hz$$

$$H(s) = 1 + \frac{R_2}{R_1} = 2$$

Component List:

The team used LM471 Op-Amps for all filters and amplifiers as these parts remained from prior lab kits, so there was no need to purchase more.
Op-Amp (LM471) x 11
LED Driver (LM3915) x 5
Audio-Op-Amp (386) x 1
Potentiometers x 10
Proto-boards (Large) x 6
AAA Alkaline Batteries (1.5 V) x 5
Audio to Proto-board Adapter x 1
Multiple Resistors (Various Values)
Multiple Capacitors (Various Values)
LEDs Total (Red, Orange, Yellow, Green, Blue, White, Pink) x 50
Two-way Switch x 1
Red Bull Can x 1
Piezoelectric Speaker x 1
Audio Jack adapter (3.5 mm)
Wires

"Something Extra":

- ★ 50 LEDs dashboard with 10 LEDs of different colors per band that indicated the band amplitude.
- ★ User interface using potentiometers with adjustable LED amplitude.
- ★ Circuit Casing with user-friendly potentiometer knobs and detachable cover.
- ★ Improved sound quality due to separate speaker-amplifier circuit and aluminum can sound enhancing.
- ★ Power supply switch with an independent battery power supply.

IV. Simulation Results

The final filter designs with standard resistor values and the corresponding simulation results with cursors placed at cut-off frequencies are displayed below.

Low-pass (up to 113 Hz)

$$H(s) = \frac{\frac{1}{RC}}{s+\frac{1}{RC}}$$

MatLab code:

```
R = 3000
C = 0.00000047
sys=tf([1/(R1*C)], [1 1/(R1*C)])
bodemag(sys)
h=gcr
setoptions(h,'FreqUnits','Hz')
```

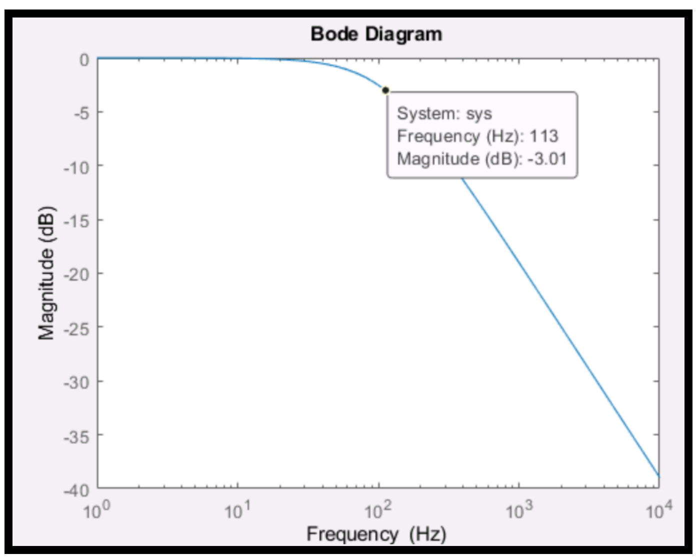


Figure 5: First order active low-pass filter (up to 113 Hz) MatLab Bode plot

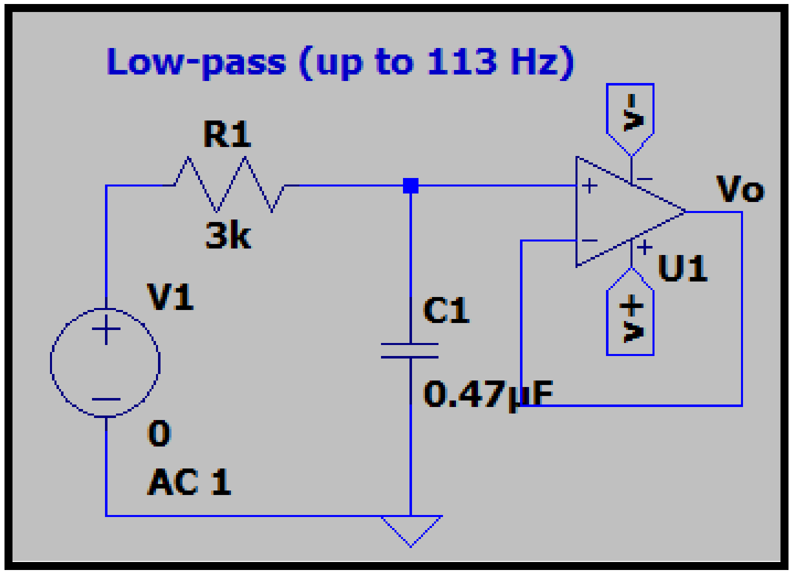


Figure 6: First order active low-pass filter (up to 113 Hz) with the final resistor values

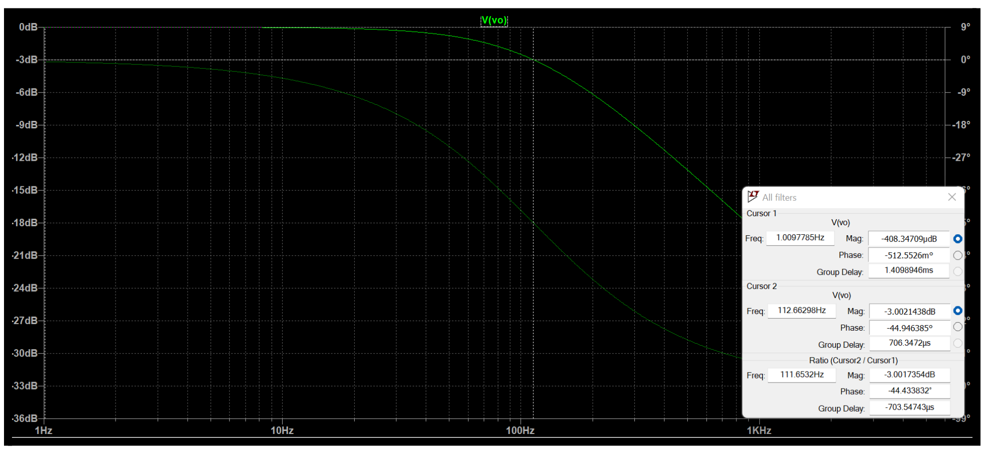


Figure 7: First order active low-pass filter (up to 113 Hz) cut-off simulation

Band-pass (138-195 Hz)

$$H(s) = \frac{s\frac{1}{R_1 C}}{s^2 + \frac{2}{R_1 C} + \frac{R_1 + R_3}{2R_1 R_3 C^2}}$$

MatLab code:

```
R1 = 12000
R3 = 170
C = 0.00000047
sys=tf([1/(R1*C) 0], [1 2/(R1*C) (R1+R3)/(2*R1*R1*R3*C*C)])
bodemag(sys)
h=gcr
setoptions(h,'FreqUnits','Hz')
```

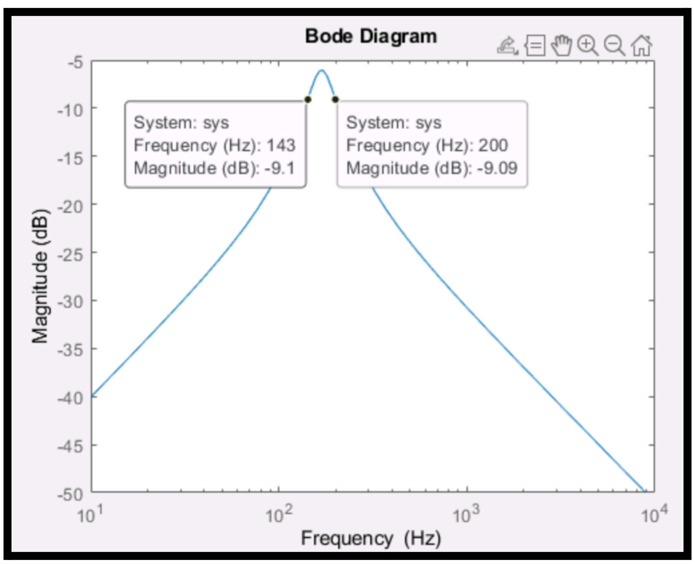


Figure 8: Second order Sallen-Key band-pass filter (138-195 Hz) MatLab Bode plot

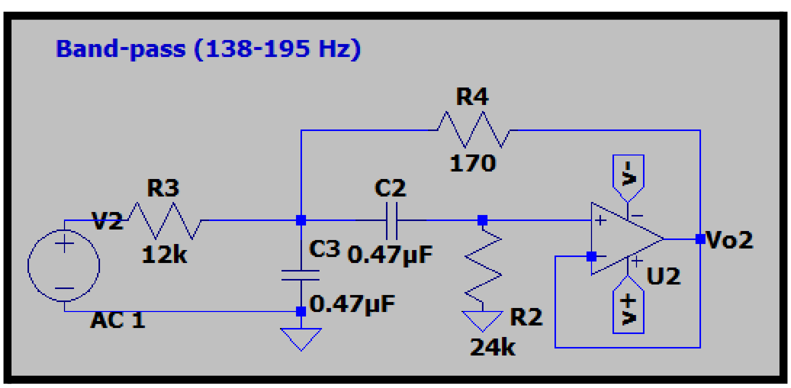


Figure 9: Second order Sallen-Key band-pass filter (138-195 Hz) with the final resistor values

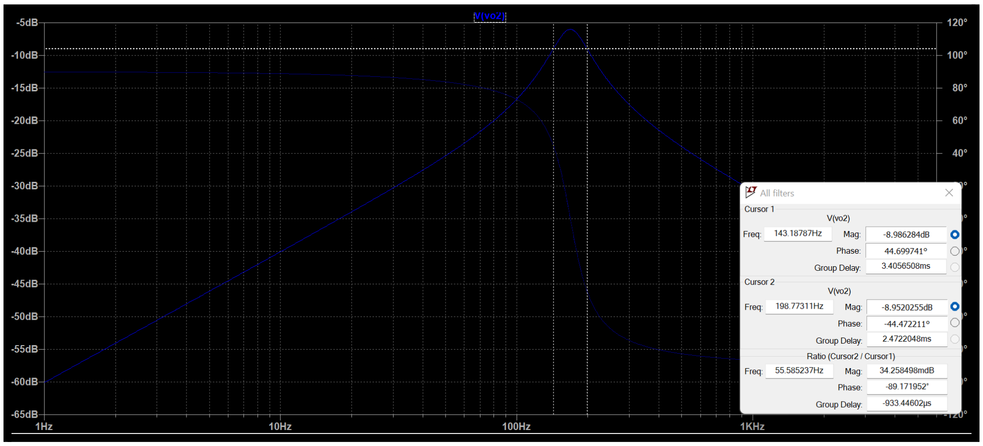


Figure 10: Second order Sallen-Key band-pass filter (138-195 Hz) cut-off simulation

Band-pass (402-516 Hz)

$$H(s) = \frac{s\frac{1}{R_1C}}{s^2+\frac{2}{R_1C}+\frac{R_1+R_3}{2R_1R_3C^2}}$$

MatLab code:

```
R1 = 28000
R3 = 220
C = 0.00000001
sys=tf([1/(R1*C) 0], [1 2/(R1*C) (R1+R3)/(2*R1*R1*R3*C*C)])
bodemag(sys)
h=gcr
setoptions(h,'FreqUnits','Hz')
```

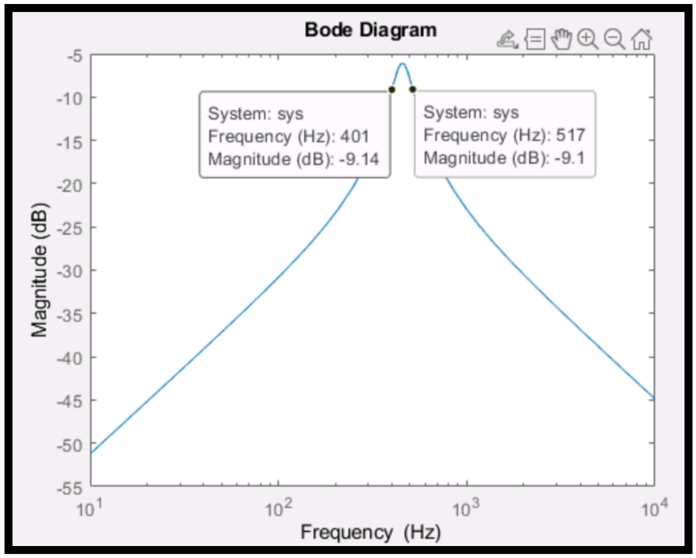


Figure 11: Second order Sallen-Key band-pass filter (402-516 Hz) MatLab Bode plot

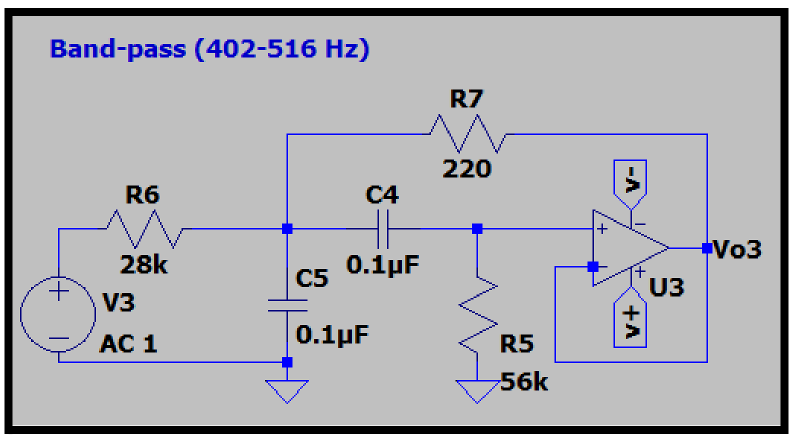


Figure 12: Second order Sallen-Key band-pass filter (402-516 Hz) with the final resistor values

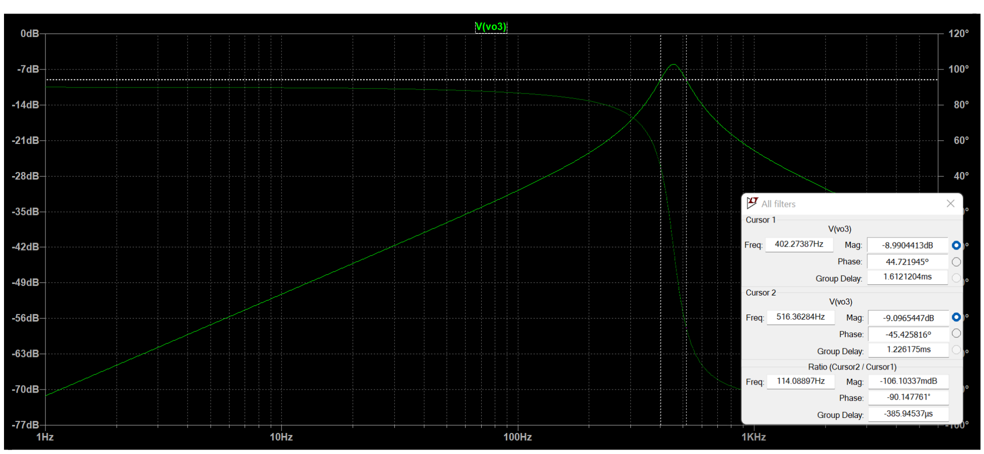


Figure 13: Second order Sallen-Key band-pass filter (402-516 Hz) cut-off simulation

Band-pass (723-918 Hz)

$$H(s) = \frac{s\frac{1}{R_1 C}}{s^2 + \frac{2}{R_1 C} + \frac{R_1 + R_3}{2R_1 R_3 C^2}}$$

MatLab code:

```
R1 = 28000
R3 = 220
C = 0.00000001
sys=tf([1/(R1*C) 0], [1 2/(R1*C) (R1+R3)/(2*R1*R1*R3*C*C)])
bodemag(sys)
h=gcr
setoptions(h,'FreqUnits','Hz')
```

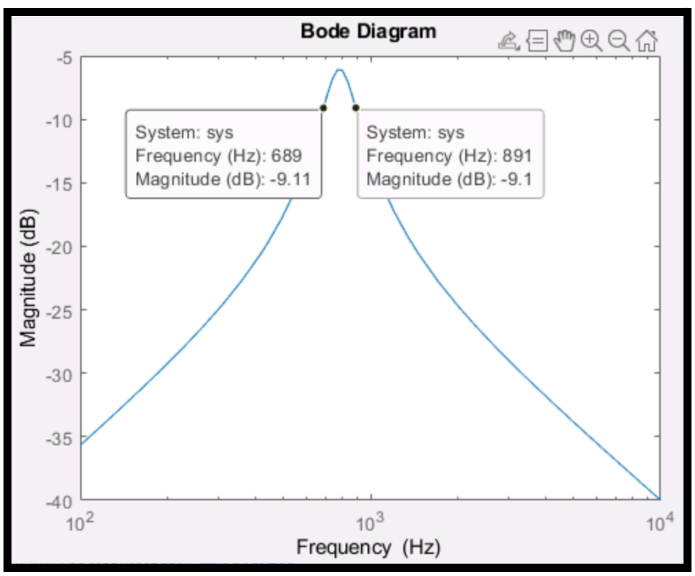


Figure 14: Second order Sallen-Key band-pass filter (723-918 Hz) MatLab Bode plot

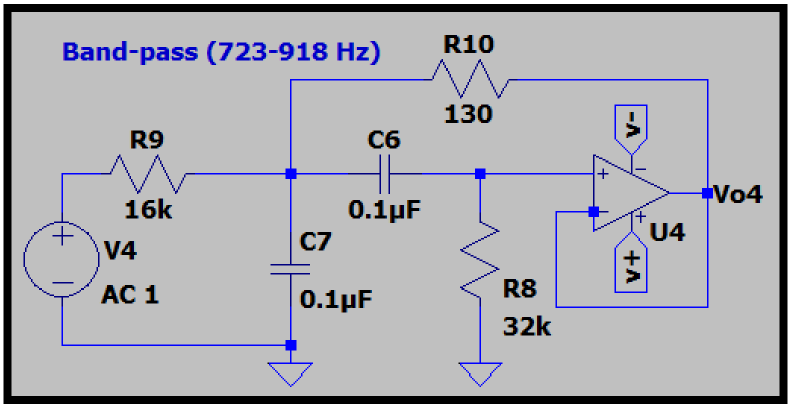


Figure 15: Second order Sallen-Key band-pass filter (723-918 Hz) with the final resistor values

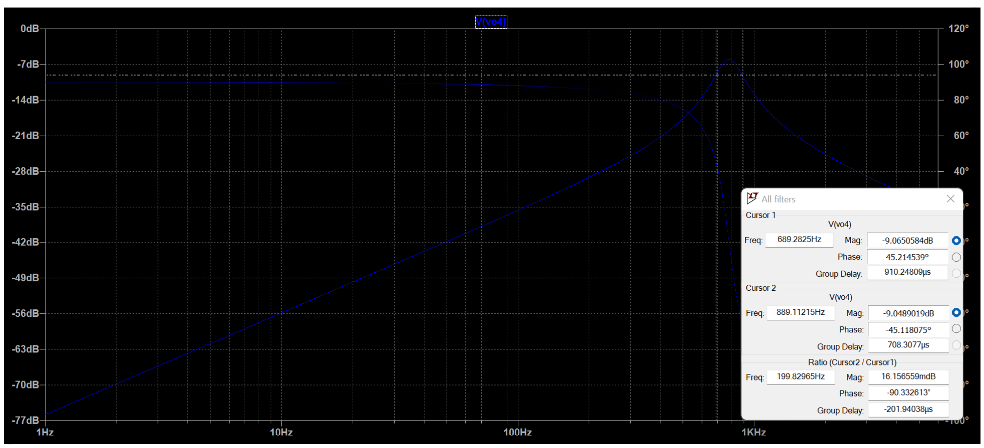


Figure 16: Second order Sallen-Key band-pass filter (723-918 Hz) cut-off simulation

High-pass (1.35 kHz and up)

$$H(s) = \frac{s^2}{s^2 + \frac{1}{R_1 C} + \frac{1}{R_1^{\,2} C^2}}$$

MatLab code:

```
R1 = 10000
C = 0.00000001
sys=tf([2 0 0], [1 1/(R1*C) 1/(R1^2*C^2)])
bodemag(sys)
h=gcr
setoptions(h,'FreqUnits','Hz')
```

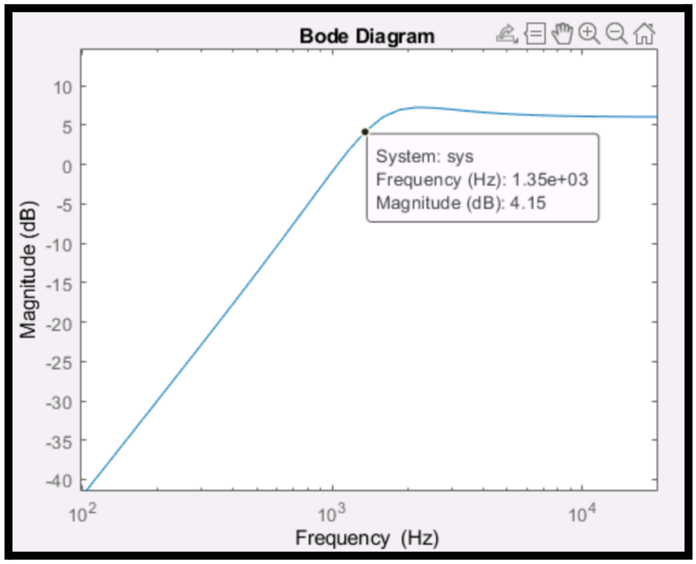


Figure 17: Second order high-pass filter (1.35 kHz and up) MatLab Bode plot

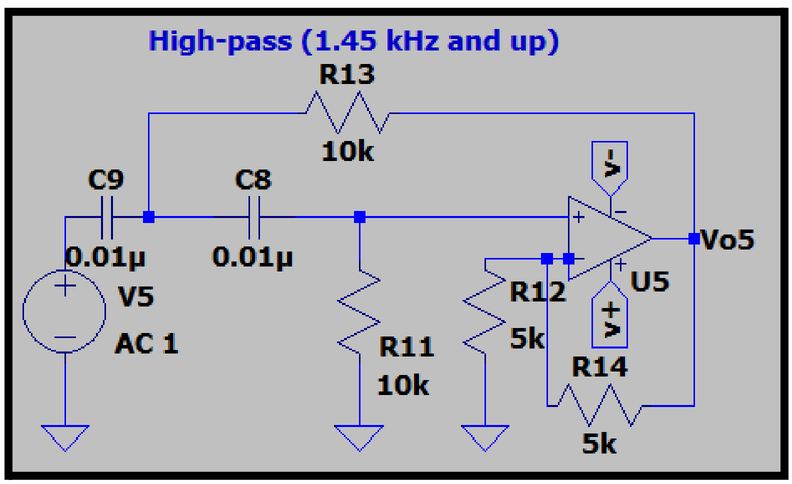


Figure 18: Second order high-pass filter (1.35 kHz and up) with the final resistor values

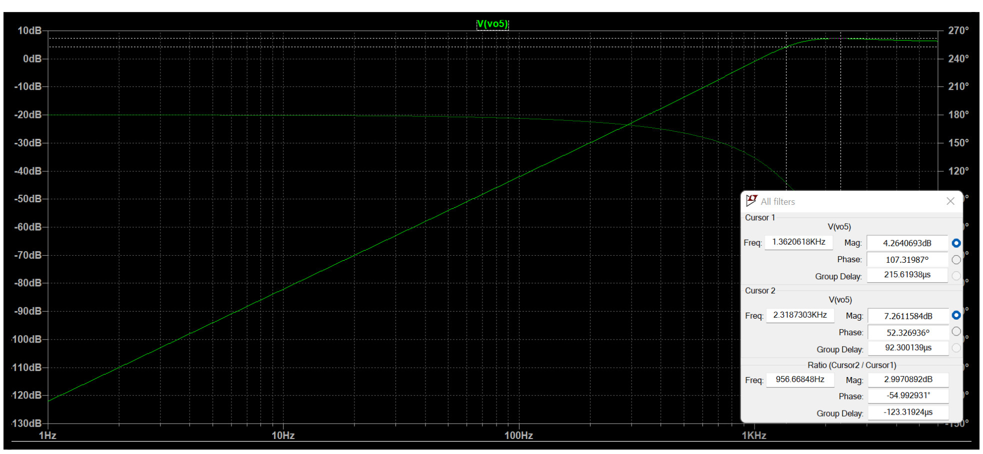


Figure 19: Second order Sallen-Key band-pass filter (1.35 kHz and up) cut-off simulation

V. Test Results

For our test result data, we took voltage measurements at different frequencies to plot a Bode plot using the data points collected for voltage at different frequencies. Using this method we were able to create a bode plot graph with voltage on the Y-axis and Frequency on the X-axis.

To drive our LED brightness we used the filtered and amplified signal from the filters to the LM3915 LED driving IC. The IC uses an internal op amp and resistors which allow current to flow depending on how strong the signal is to different LEDs. The LEDs are placed backwards with ground being connected to the IC and the power rail is set up on the board. Sensitivity of the LEDs to the signal being pushed can be adjusted using the potentiometer knobs on the interface on the side of the case.

The LED turn on voltage is determined by the signal strength on that frequency signal. If the frequency amplitude is low then the signal comparison will determine that the voltage is below the threshold mark and will only light up a certain number of the LEDs based on the signal amplitude ranging from 0 to 10 LEDs. The threshold could be adjusted using the potentiometer knobs on the surface of the case.

Table 1. All LEDs turn on at Voltage:

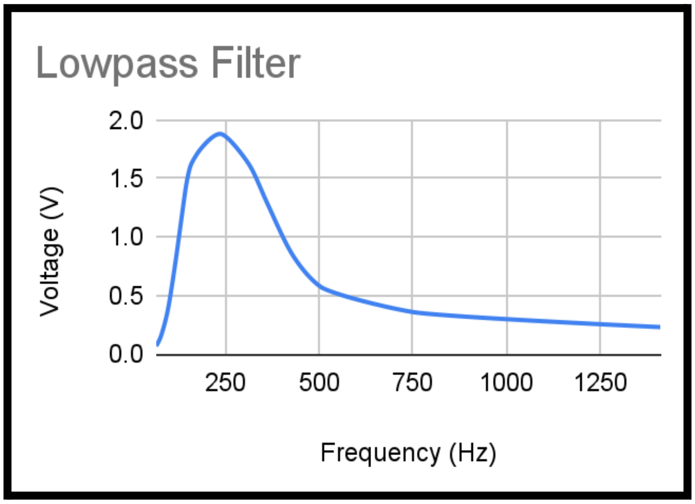
Aux Cord Voltage x 10: 1.28 V

Filter Type	Max LED voltage Amplitude (V)
Low Pass	1.121
Band pass 1	0.989
Band pass 2	2.912
Band pass 3	2.76
High pass	2.3

"Something Extra:"
--Casing dimensions--

Width: 21 cm
Height: 12.5 cm
Length: 32 cm

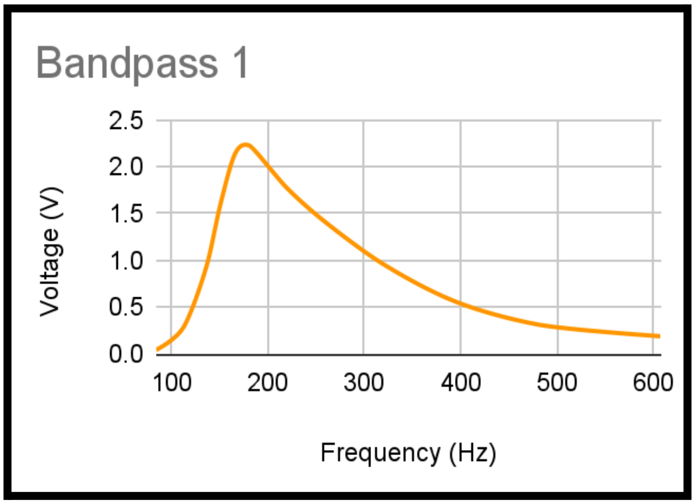
Data table with Voltage and Frequency for Graph:



Graph 1. Shows Low pass Filter with Voltage Magnitude with corresponding frequency.

Table 1. Low pass Data

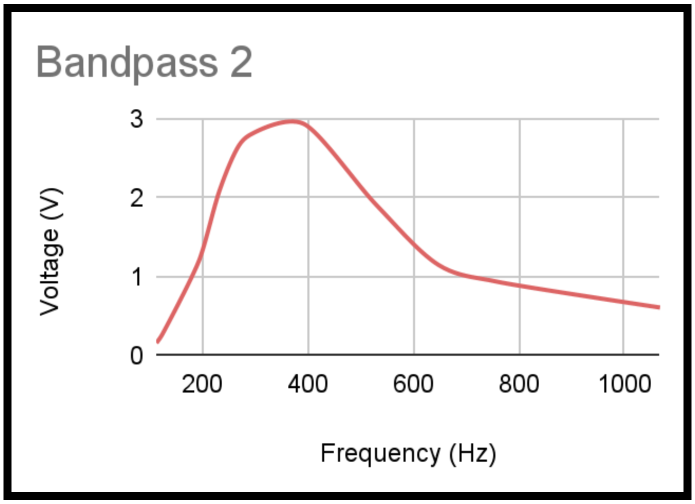
Low Pass Filter	
Voltage (V)	**Frequency (Hz)**
0.069	64
0.145	76
0.372	95
0.75	114
1.438	144
1.6	155
1.74	180
1.88	**237**
1.605	315
1.287	361
0.849	428
0.575	503
0.359	749
0.23	1411



Graph 2. Shows Band pass 1 with Voltage Magnitude with corresponding frequency.

Table 2. Band-pass 1 Data

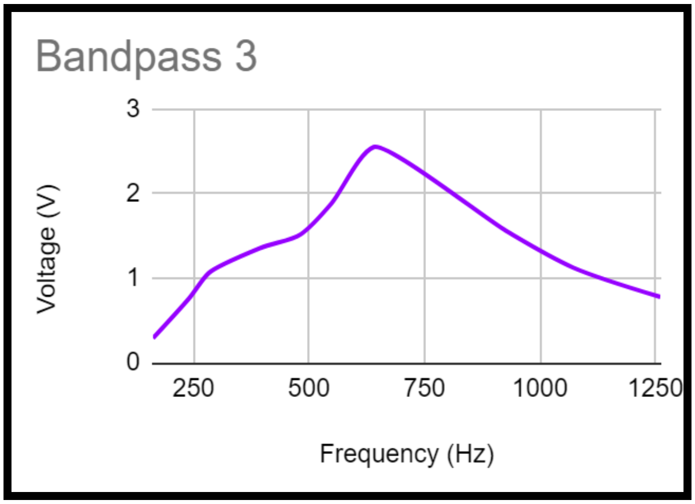
Band pass 1	
Voltage (V)	**Frequency (Hz)**
0.044	84
0.296	113
0.965	137
1.607	150.9
2.142	166
2.23	**180**
1.78	219
1.48	251
0.99	315
0.57	392
0.315	480
0.19	607



Graph 3. Shows Band pass 2 with Voltage Magnitude with corresponding frequency.

Table 3. Band pass 2 Data

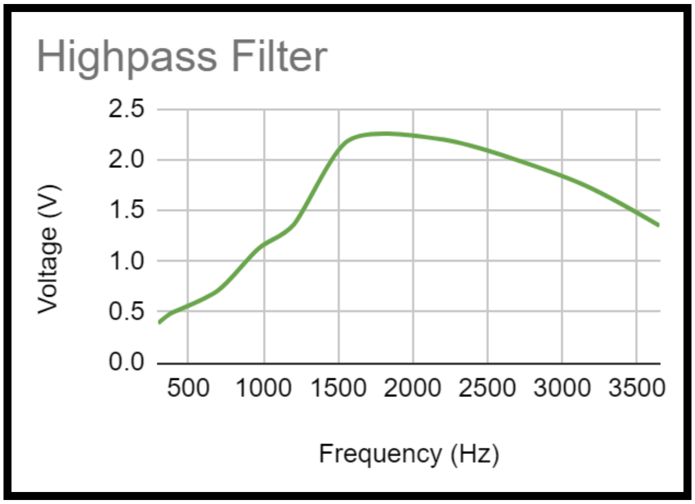
Band pass 2	
Voltage (V)	**Frequency (Hz)**
0.16	113
0.256	123
1.226	195
2.101	233
2.66	269
2.826	298
2.94	**392**
1.91	530
1.149	648
0.938	758
0.609	1068



Graph 4. Shows Band pass 3 with Voltage Magnitude with corresponding frequency.

Table 4. Band pass 3 Data

Band pass 3	
Voltage (V)	**Frequency (Hz)**
0.29	162
0.76	240
1.062	283
1.353	393
1.519	482
1.88	548
2.55	**640**
1.558	927
1.125	1072
0.778	1261



Graph 5. Shows High pass with Voltage Magnitude with corresponding frequency.

Table 5. High pass Data

High pass	
Voltage (V)	**Frequency (Hz)**
0.389	297
0.485	380
0.714	700
1.124	968
1.357	1202
2.176	1556
2.2	**2200**
1.768	3121
1.35	3650

VI. Discussion

Comparison Table

Filter	**Designed values**	**LT Spice with realistic component values**	**Measured filter results**
LP	K = 1	K = 1	K = 1.13
	f_c= <115 Hz	f_c= <113 Hz	f_c= <349 Hz
	Roll-off = -16.4 dB/dec	Roll-off = -16.5 dB/dec	Roll-off = -17 dB/dec
BP 1	K = 1	K = 1	K = 1.11
	f_c= 140-200 Hz	f_c= 138-195 Hz	f_c= 128-242 Hz
	Roll-off = -23.6 dB/dec	Roll-off = -23.3 dB/dec	Roll-off = -23.1 dB/dec
BP 2	K = 1	K = 1	K = 1.09
	f_c= 300-700 Hz	f_c= 402-516 Hz	f_c= 292-464 Hz
	Roll-off = -20.4 dB/dec	Roll-off = -20.4 dB/dec	Roll-off = -20.7 dB/dec
BP 3	K = 1	K = 1	K = 1.05
	f_c= 700-900 Hz	f_c= 723-918 Hz	f_c= 541-868 Hz
	Roll-off = -20.2 dB/dec	Roll-off = -20.1 dB/dec	Roll-off = -21 dB/dec
HP	K = 2	K = 2	K = 2.08
	f_c= >1.5 kHz	f_c= >1.35 kHz	f_c= >1,197 Hz
	Roll-off = -40 dB/dec	Roll-off = -40 dB/dec	Roll-off = -40.4 dB/dec

Challenges and Solutions:

The biggest challenge, aside from writing this report, was rearranging the whole circuit to fit in a box and wire management in general. Designing and building the filters and amplifiers was fairly straightforward, but it's figuring out the speaker amplifier circuit and the LED ladder circuit added complexity.

Another challenge we faced was trying to figure out the issues with the potentiometers. It turned out that soldering potentiometers is not a very good idea unless done properly and quickly. We have lost multiple potentiometers to heat damage to the soldering iron trying to solder wires to the potentiometers to have a connection to the outside of the box. After we figured out that the potentiometers were burned after replacing it, we understood that it is not a good idea to try to solder them to the wires. Instead, we found a way to attach female port wires to the legs on the potentiometers which allowed us a safe but not very durable connection to the board from the potentiometers. Multiple times the connections broke off, and it was not obvious all the time.

VII. Teamwork

The team followed a particular workload structure based on objectives covered in lab sessions. In most lab sessions teammates split filters/LED ladders into equal parts, and the weekly check-in reports were also split in half. Both teammates worked on organizing the circuit in the case to create the neatest package, and the progress and final reports. Kiryl focused on building the speaker amplifier circuit and Dmitrii built the case.

Overall, the team performed well together, both teammates were cooperative, excited to work on the project and focused on completing weekly objectives and keeping the project on track.

VIII. Conclusion

The project allowed the team to learn more about filters, the practical value of using higher order filters and separating bandwidths. The team gained experience in debugging filter outputs, scaling first and second order filters to achieve desired output. The practical application of theory helped understand concepts and the bigger picture when it comes to the entire circuit and filter design than by doing isolated lab sessions.

The biggest improvement would be to adjust filter ranges to stop them from bleeding into each other. Due to two points in the circuit where the signal was amplified, the LEDs from different ranges would light up at the same time. The way to do that would be to develop higher order filters and consider the potentiometer gains with more attention to the overlap.

We would like to add a separate switch for the speaker specifically to allow turning it off without turning off the LEDs for testing purposes. We would also consider soldering the LED ladders, the LEDs, and the potentiometers to custom PCBs for better wire management and to make sure LEDs and wires don’t pop-out when the case is being transferred. The team would also like to add the option to recharge the batteries with a micro USB port.