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ENGR 202 – Winter 2020
Lab 6 Report

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Overview

The main goal of this lab was to develop an audio filter for a subwoofer, tweeter, and mid-range speaker by designing a low-pass filter for the sub, a high-pass filter for the tweeter, and a band-pass filter for the mid-range speaker. Overall, the main problem faced in the design stage of the filters was coming up with a combination to meet the requirements of all the speakers. For the sub, the filter to be designed had to have a cutoff frequency of approximately 220 Hz. The filter for the mid-range speaker had cutoff frequencies of approximately 200 Hz and 15 kHz in order to cover the cutoff frequencies of the tweeter and sub to have a full range of sound. The tweeter had a cutoff frequency of 6 kHz, so the overlap of the mid-range and the tweeter was fairly significant, hinting that the tweeter and the mid-range would be working at approximately the same time.

This project seemed to be the first time that the procedure, design, and application of our knowledge was completely up to the groups themselves without much more than a few goals to reach for guidance. With this in mind, this lab was 100% applicable in any electrical engineering career. From what has been lectured to us in many classes, in the "real world" the company we work for or the project we will be working on will simply have goals we must achieve or a certain action we must complete, rather than having step-by-step guidance on a project that has already been done thousands of times.

Design

To achieve a working audio filter, three filters (high-pass, low-pass, and band-pass) were designed with cutoff frequencies that corresponded to the speaker specifications given by the documentation of the speakers. The low-pass filter was connected to the subwoofer with a cutoff frequency of 220 Hz, the high-pass filter was the filter attached to the tweeter with a cutoff frequency of 6 kHz, and the band-pass filter was connected to the midrange speaker with cutoff frequencies of 200 Hz and approximately 15 kHz.

The materials used to create the filters themselves were relatively simple, they consisted of 4 different resistors (2670 Ω, 7900 Ω, 1000 Ω, and 7340 Ω) and 4 capacitors (0.01 µF and 0.1 µF) - though the resistor values in the LTspice simulation were more accurate due to the lack of small-value resistors and spatial constraints on the protoboard. Each separate filter was connected to its own op-amp given to us in lab, along with speakers that were provided in lab as well. To create a feasible circuit that was compatible with the speakers and op-amps, extraneous lab materials (such as solder and many jumper wires) were used which will be demonstrated later in this report.

The filter specifications and exact component values are calculated and shown below, the first subsection of equations relate to the tweeter, the second to the subwoofer, and the third to the mid-range speaker.

High-Pass Filter – Tweeter:

$$H(\omega) = \frac{Vo}{Vi}, Vo = \frac{R1}{R1 + \frac{1}{j\omega C}} Vi \Rightarrow H(\omega) = \frac{R1}{R1 + \frac{1}{j\omega C}}$$

$$\frac{R1}{R1 + \frac{1}{j\omega C}} \times \frac{j\omega C}{j\omega C} = \frac{j\omega R1C}{1 + j\omega R1C}, \qquad \omega_c = \frac{1}{RC}$$

$$\omega_c = 2\pi f = 2\pi(6000) = 37699.11$$

$$\frac{1}{RC} = 37699.11 \Rightarrow RC = \frac{1}{37699.11} = 2.653 \times 10^{-5}$$

$$C = 0.01\ \mu F \ \Rightarrow R = \frac{2.653 \times 10^{-5}}{0.01 \mu F} = 2653\ \Omega$$

Where the value for our capacitor, C, was based off the availability of the values in lab.

Low-Pass Filter – Subwoofer:

$$H(\omega) = \frac{\frac{1}{j\omega C}}{R + \frac{1}{j\omega C}} \times \frac{j\omega C}{j\omega C} = \frac{1}{1 + j\omega RC}, \qquad \omega_c = \frac{1}{RC}$$

$$\omega_c = 2\pi f = 2\pi(200) = 1256.64$$

$$\frac{1}{RC} = 1256.64 \Rightarrow RC = \frac{1}{1256.64} = 7.9577 \times 10^{-4}$$

$$C = 0.1\ \mu F \Rightarrow R = \frac{7.9577 \times 10^{-4}}{0.1 \mu F} \rightarrow R = 7957\ \Omega$$

Where the value for C was, once again, based off the availability of capacitor values in lab.

Band-Pass Filter – Mid-Range:

The filter that was designed for the mid-range speaker was comprised of two filters (a low-pass and a high-pass) in order to achieve the cutoff frequencies needed to accommodate the frequency range for the mid-range speaker. The exact combination of the high-pass and low-pass filter can be found in figure 1 below. This combination of filters works since the transfer function of these filters is basically derived from the equation of a voltage divider, in which these two filters (high and low-pass) would be added linearly in the denominator of the voltage divider equation

$$V_O = \frac{Z_1}{Z_1 + Z_2 + Z_3} V_i$$

This linear addition of the impedance from the two filters allows for the cutoff frequencies to be found quite simply using the cutoff frequency from the high and low pass filters:

$$\omega_c = \frac{1}{RC}$$

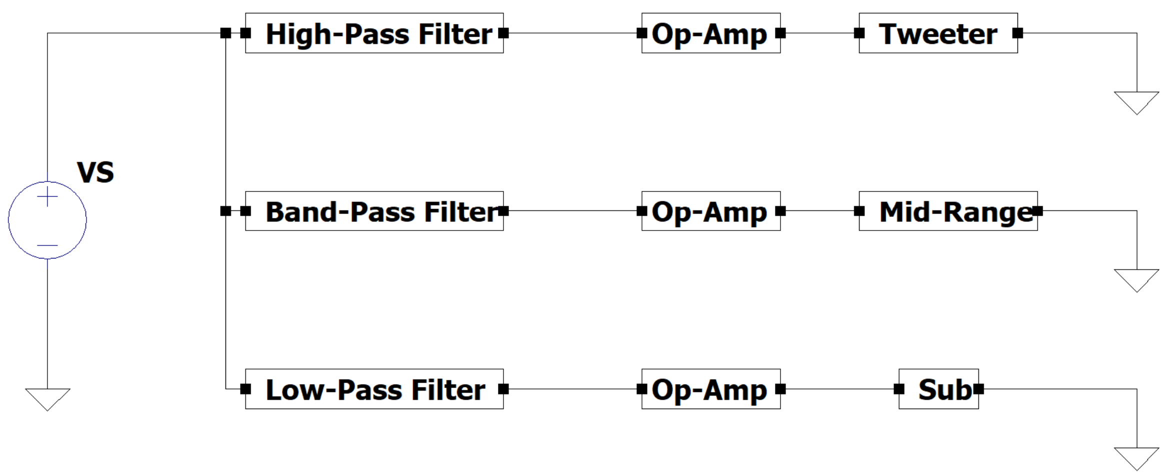
The two cutoff frequencies for the mid-range speaker were 220 Hz and 15 kHz, which implied:

$$\omega_1 = 2\pi f = 2\pi(220) = 1382.3$$

$$R_1C_1 = \frac{1}{1382.3} = 7.234 \times 10^{-4}, C_1 = 0.1\mu F \Rightarrow R_1 = \frac{7.234 \times 10^{-4}}{0.1\mu F} = 7234\,\Omega$$

$$\omega_2 = 2\pi f = 2\pi(15k) = 94247.78$$

$$R_2C_2 = \frac{1}{94247.78} = 1.055 \times 10^{-5}, C_2 = 0.01\mu F \Rightarrow R_2 = \frac{1.055 \times 10^{-5}}{0.01\mu F} = 1055\,\Omega$$



As it is apparent from the above calculation, the 3 filters were solely made up of resistors and capacitors in order to simplify the filters themselves – especially the band-pass as it is purely made of the two low and high-pass filters put together. The filters connected to the op-amps at pin 3, with the speaker connecting to pin 5, the DC power supply connecting to pin 6, and pins 2 and 4 connected to the ground node. Other than these 5 pins, the other 3 pins were left untouched as they didn't contribute to the necessary function of our audio filters.

A more in-depth description of the filter designs/schematics are given below in the "Simulation" section.

Frequency Sweep Tests

Vout Data: The Frequency sweep tests were used to show that the filters were working as theorized. The ideal corner frequencies for the low was 200Hz. The Corner frequency for the high was 6 KHz. The band-pass was 200 Hz and 6 KHz. Upon testing it was found that these corner frequencies were indeed accurate to the designed filters. Using the frequency generator and setting it to around 200 Hz (216 Hz verified by the Oscope) the Vout was read to be 0.76 V which is around the 70.7% of 1 volt pk-pk in. This shows that the Low pass filter is letting the right range through. Looking at the table showing the full sweep (Below) it can also be seen that the Low pass filter allowed frequencies to pass that were in the range it was designed for.

On the High pass the ideal corner frequency in the lab was 6 KHz. Upon testing this with the designed High pass filter, the Frequency generator was set to 6.01 KHz (Verified by the Oscope) and the Vout was measured to be 0.74 V. This lines up with what would be expected from a working high pass filter with a corner frequency of 6 KHz. Looking at the Table (Below) the filter was allowing the high frequencies to pass through up to its corner frequency which is consistent with the expectations of the filter.

The Band-pass is expected to let the “mid-range” frequencies pass. These would be the frequencies between 200 Hz and 15 KHz. The first thing tested was that the designed band-pass filter was exhibiting these corner frequencies. Using the function generator at 201 Hz (Verified by the Oscope) 0.64 Vout was observed which is close to the 70.7% of 1V pk-pk that is to be expected to show a corner frequency. On the other end of the spectrum 13.5 KHz was tested (verified by the Oscope) and the Vout was measured to be 0.73 V. This lines up with expectations again showing that the band-pass filter design was effective. Looking at the table the band-pass filter allowed the frequencies which were between 200 Hz and 15 KHz which was to be expected of it.

Freq (Hz):	**VIN (V):**	**VOUT Low (V):**	**VOUT Band-pass (V):**	**Vout High (V):**
10	1	1	.001	0.04
30	1	1	0.1	.06
100	1	0.94	0.43	0.08
300	1	0.6	0.72	0.1
1k	1	0.26	0.83	0.2
3k	1	0.02	0.83	0.4
10k	1	0.1	0.75	0.85
30k	1	0.01	0.45	1

Table 1: A comparison of the voltage generated by the function generator against the voltage over the component that would connect to the op-amp. The peak-to-peak voltage of the function generator was maintained at 1 V, and the frequencies varied to test for correct cutoff frequencies of the filters.

Filter Type:	**Corner Frequency(s) (Hz):**	**V_{out} (V)**
Low-Pass	216	0.76
High-Pass	6.01k	0.74
Band-Pass	201, 13.5k	0.64, 0.73

Table 2: Testing output voltage with our calculated cutoff frequencies. The values generated by the oscilloscope were very close to the values calculated earlier in this lab.

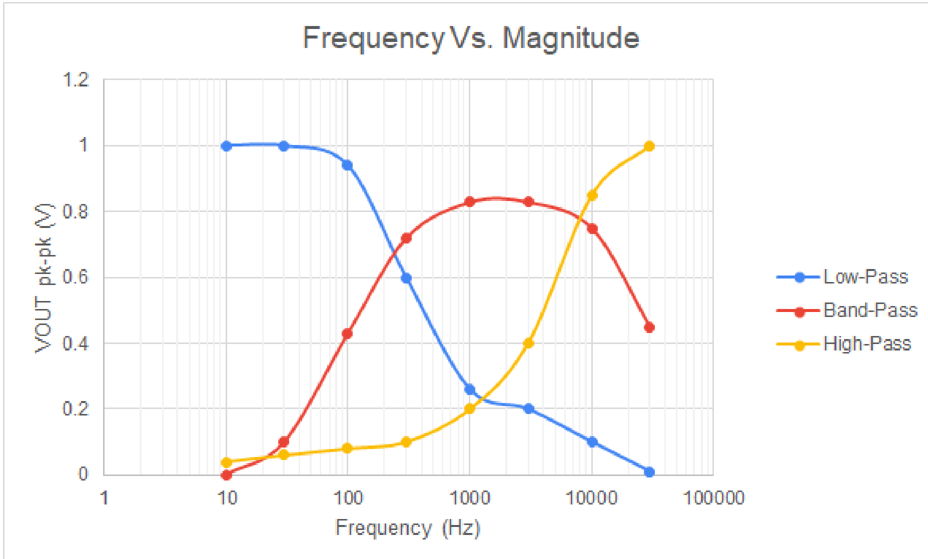


Figure 1: A plot of frequency vs the magnitude of our output voltage of the passive filters. As apparent in the plot, the filters worked well in creating a well-rounded range of frequencies to generate the best sound in the speakers.

Simulation

The schematic of the filters themselves are given below. To clarify the connection of the filters to the op-amp, each of the filters all attach to pin 3 on the op-amp as designated by the manufacturer and shown on the documentation of the op-amp given on the class website. Though not shown on figure one, there was also a 250 μF capacitor between each op-amp and its corresponding speaker that pin 5 was connected to in order to further decrease output noise to the speaker after travelling through the op-amp.

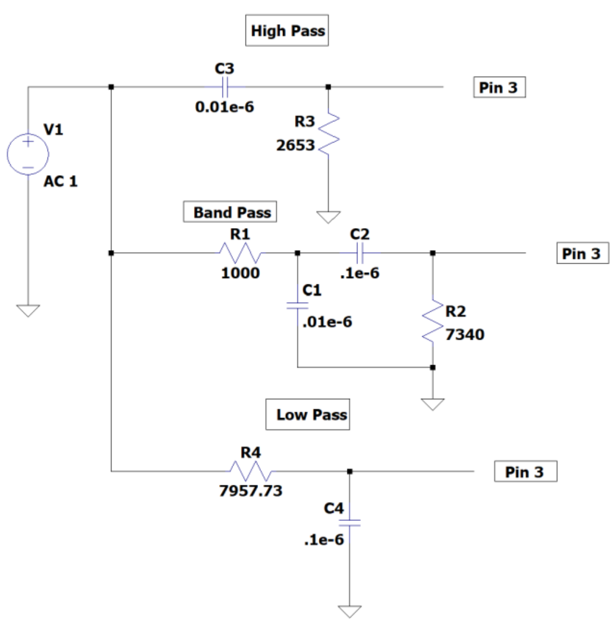


Figure 1 (above): Schematics of the filter-side of our audio filters, the op-amps are not included in this figure, however the pin that V_{out} from the filters attach to have been labeled (pin 3).

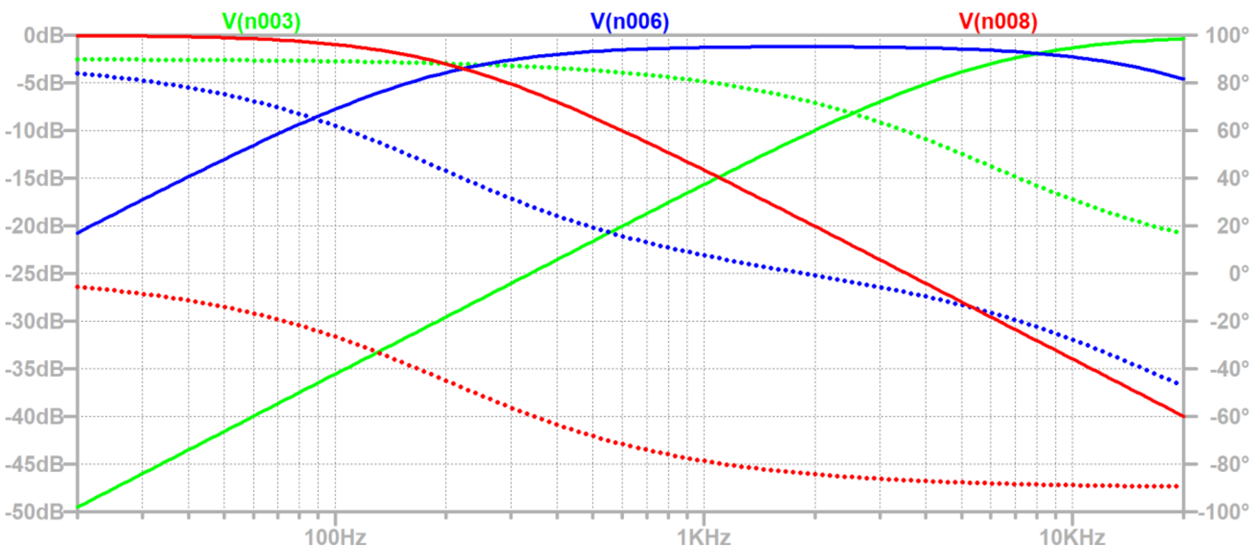


Figure 2: The magnitude and phase angle vs frequency plots for each of the filters. V(n003) corresponds to the high-pass filter for the tweeter, V(n006) is the plot for the mid-range filter, and the traces of V(n008) is the plot of the low-pass filter that connects to the subwoofer.

Results

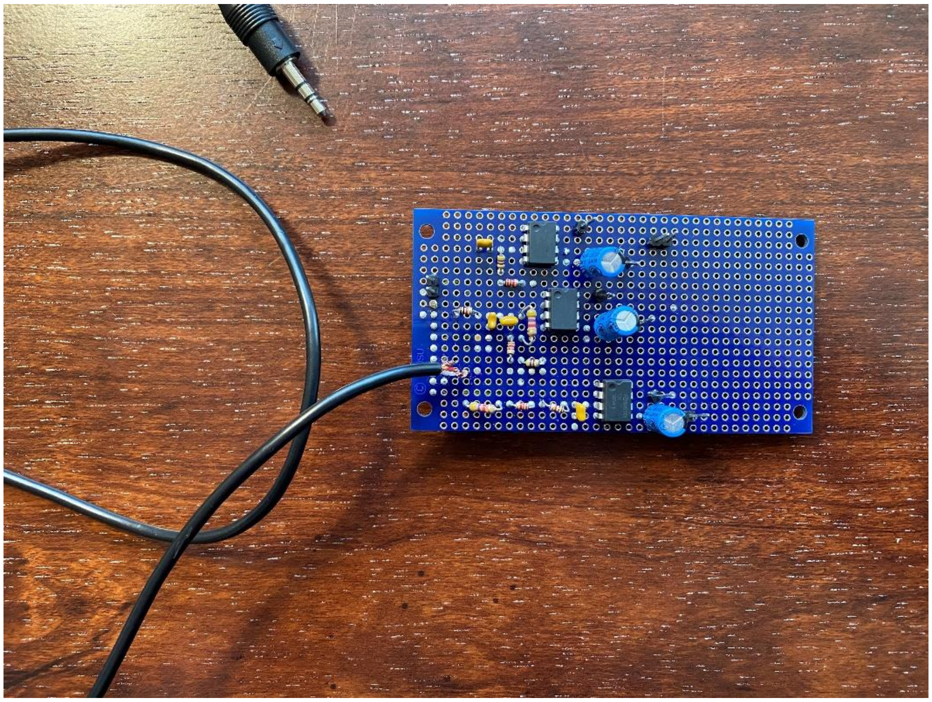
This project was successful, yet there were some faulty features when testing the quality of the filters. Though the music coming from the speakers was noticeable and somewhat recognizable, there was quite a lot of noise when there was an audio signal going through our filters and out of each of the speakers - specifically the mid-range and high-pass filters. One of the sources of this noise can be attributed to the bandwidth produced by the filters – something that could not be traced back to developer error. With an increased bandwidth, there is more noise produced by the speaker. Considering the large ranges of "allowed" frequencies that both the band and high-pass filters have (200 Hz – 15 kHz and greater than 6 kHz respectively) compared to the frequency range for the low-pass filter (up to 220 Hz) shows how much of a larger bandwidth (and therefore more noise) is to be expected from the high and band-pass filters.

Another reason that there was unnecessary noise can be traced back to the use of high resistor values in the filters. Carbon composition resistors (which is what we believe is used in our labs) cause noise in audio systems due to the reverberating carbon molecules that create the resistance seen in the resistors' practical use (Stamler, nd.). Decreasing the resistance (which would in-turn increase the values of our capacitors to maintain the same cutoff frequencies) could decrease the noise created by these resistors by decreasing the amount of material that is causing the noise/resistance in the components.

Another issue that came up when testing the audio filters was that the low and mid-pass filters both sounded better under 6 V of DC voltage through the op-amps, while the high-pass filter sounded better under 12 V. Theoretically, this could emanate from the noise of the power supply, yet the reason why the sound was *clearer* in the low and mid-pass filters under lower voltages doesn't necessarily correspond with that assumption. One possibility that may have caused this difference could be the fact that the impedance of the mid and low-pass filters was almost double that of the high-pass filter, meaning the current required to dissipate a certain amount of power over these filters is about half of that needed to have the same amount of power dissipated by the high-pass filter using the equation $P = IV$ or $P = I^2Z$. According to the documentation of the speakers, the maximum power that the tweeter could handle was 40 W, while the max power for the midrange was around 1.5 W, much lower than the tweeter's max power. Had the impedance of the band and low-pass filters been lower (implying less resistance and more capacitance), then the voltage supplied to the op-amp could have been higher to produce a cleaner sound.

Conclusion

In attempting to complete this project a second time, implementing more capacitors (and therefore lower resistance) in our filters would have made the output from our speakers much clearer and allowing the voltage supply to the op-amps to be similar, if not the same. Also, focusing more on the impedance of the filters themselves rather than just the cutoff frequencies would've allowed for a more successful circuit design in terms of sound clarity, however, we still accomplished the goal of developing a passive audio filter for a tweeter, subwoofer, and midrange speaker as well as developing new problem-solving and circuit design skills that we had never had the opportunity to develop and/or practice.



Resources

Stamler, Paul. (n.d.). *Replacing passive components to improve sound quality*. Retrieved from https://bext.com/replacing-passive-components-to-improve-sound-quality/