ECE 342 Experiment 2

Active Filters

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Abstract

In this experiment two active filters are designed. A Multi Feedback Band-pass filter and a Sallen-Key (SK) mid-range audio filter. Only the SK mid-range filter is built and tested. Both circuits make use of operational amplifiers and are designed to act as band-pass filters. Online design tools for filter design are introduced and used for a faster design process. The built filter frequency response is investigated and its performance is demonstrated using audio playback through the filter.

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1 Introduction

The purpose of this experiment is to introduce the characteristics and design considerations of various styles of signal conditioning circuits, these circuits will be referred to as active filters. Signal conditioning consists of two main objectives: filtering and amplifying. Filtering is the process of limiting the output of a system by a set of frequencies. Filters are defined by a pass-band and cut-off-frequency(s). In a low pass filter there is one cut-off frequency and the band-pass is from zero to the cut-off frequency. A high-pass filter is the opposite (the pass-band is everything above the cut-off frequency). In this experiment, the active filter built is a band-pass filter. A band-pass filter consists of two cut-off frequencies, one lower bound and one upper bound. The band-pass is all frequencies between the two cut-off frequencies. The second component of signal conditioning is amplifying, which is increasing the magnitude of the signal by a specified amount. Without an active component (i.e. an op-amp) the signal will only be attenuated by the passive components.

In this experiment, two types of active band-pass filters are designed: a multiple feedback band-pass filter (MFBF) and a two stage Sallen-Key filter. Though these are both active band-pass filters, there are key differences between the two. An MFBFs gain and quality factor are dependent upon each other, as the gain increases the bandwidth decreases, this can be mitigated by creating multiple high gain filters and chaining them together in order to create a wider bandwidth. A single Sallen-Key filter is not a band-pass filter, but is instead either an active high-pass or active low-pass filter. In this experiment two Sallen-Key filters are combined to create an active band-pass filter with a large bandwidth. It is also important to note that unlike an MFBF, Sallen-Key filters are configured with unity gain buffers.

The team was given specifications for both filters, the MFBF is to have a center frequency of 10 KHz, a bandwidth of 2 KHz, and a gain of 40db. The Sallen-Key filter is specified to be a “mid-range” audio filter, in this case that is a band-pass from 200 Hz to 2 KHz. Though both the MFBF and the Sallen-Key will be designed, only the Sallen-Key filter will be constructed and tested. All circuit specifications were given in the lab manual.[1]

This document is split into three main sections. Section 2 features the circuit design and analysis. Section 3 includes the simulations. Section 4 features the experimental implementation, where the circuit is built and tested. The design and analysis section outlines how the two circuits were configured and the components selected. In the simulations section the circuits from the previous section were built in a simulation software to validate the designs. Only the Sallen-Key filter was constructed and measured both quantitatively with an oscilloscope and qualitatively by hearing its effects on an audio signal.

2 Circuit Design and Analysis

Two circuits are designed in this experiment. The first is a multi feedback band-pass filter (MFBF), and the second is a Sallen-Key mid-range audio filter. Both filters must attenuate a signal outside of a given bandwidth, but the MFBF also amplifies the signal. Both filters were designed using Texas Instruments' (TI) Filter Design Tool. This tool allows users to generate a working filter schematic by requesting a filter type (i.e. band-pass, high-pass).

2.1 Multiple Feedback Band-pass Filter

Figure 1 shows the schematic for the Multiple Feedback Band-pass Filter, as designed in the TI Filter Design Tool.

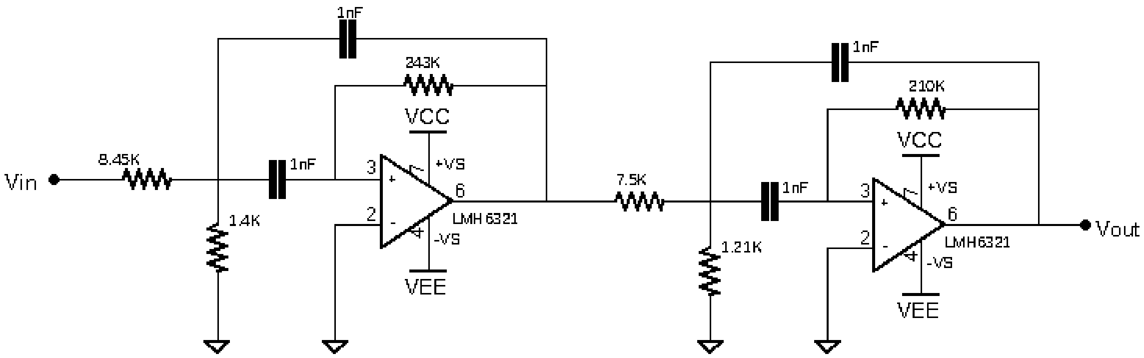

Fig. 1. Multiple Feedback Band-pass Filter Schematic.

The specifications for the MFBF are as follows. The gain must be 40dB at a center frequency of 10kHz, with a bandwidth of 2kHz. The filter is designed as a two stage active filter, meaning it features two operational amplifiers both configured as band-pass filters. When the center frequencies of each stage are set slightly offset from the desired center frequency, both pass-bands combine to create a larger overall pass-band, thus meeting the required 2kHz bandwidth.

2.1.1 Design Tool

The TI Filter Design Tool can be found at `https://webench.ti.com/filter-design-tool/filter-type`. To design the MFBF, band-pass is selected as the filter type. On the following screen, gain is set to 40dB, the center frequency is set to 10kHz, and the bandwidth to 2kHz all in the pass-band section. In the stop-band section, bandwidth is changed to 4.000e+4. All other values are left as default. In the *select a filter response* section, the default option is bessel, instead select butterworth. The butterworth design is used because it provides a constant frequency response in the pass-band. Selecting butterworth brings the user to the *Topology* section. Here, nothing is changed, the toggle for *use same topology for all stages* is set to on, and *multiple feedback* is selected in the drop down menu. In the following screen, the supply voltages are set to +5 and -5V. Under components, E96 resistors and E48 capacitors are selected. Table I shows the components values given by the TI Filter Design Tool.

TABLE I
Components of MFBF

Component	Nominal Value
R1	8.45kΩ
R2	243kΩ
C1	1nF
C2	1nF
R4	7.5kΩ
R5	210kΩ
R6	1.21kΩ
C3	1nF
C4	1nF
R3	1.4kΩ

Because this circuit is only simulated and not built, the component values are not adjusted to match part kit values. Using these values, the circuit can be simulated to ensure the design tool worked properly.

2.2 Sallen-Key Audio Filter

Figure 2 shows the schematic for the real Mid-Range Audio Filter, as designed in the TI Filter Design Tool, and recreated in Micro-Cap 12.

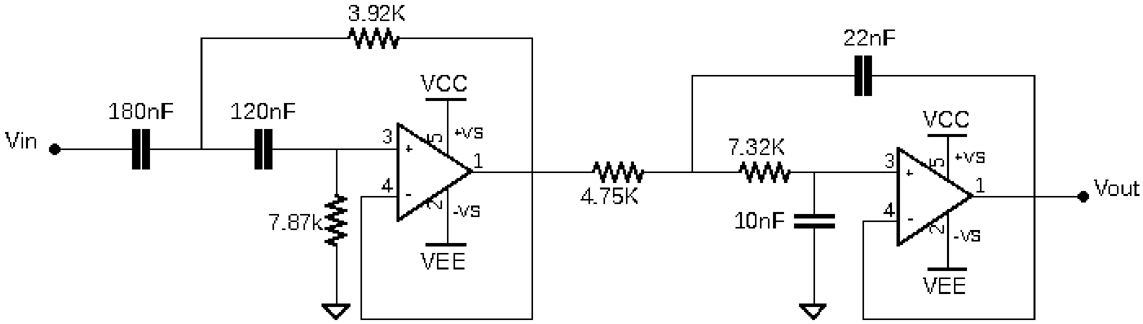

Fig. 2. Mid-Range Audio Filter Band-pass Filter Schematic.

The specifications for the second audio filter are as follows. The desired gain is 0dB or 1V/V, meaning the op amps should be configured as unity gain buffers. A second order active filter designed in this way is called a Sallen-Key filter. The desired pass-band of the filter is from 200Hz to 2kHz, and the Q value must be 0.707 in order to limit component selection. To investigate the effects of different capacitors on the output, one design is made using E48 (2%) series capacitors, the ”ideal” design, and the other is designed with E12 (10%) capacitors, the ”real” design. Both designs use E96 resistors with 1% tolerance because E96 resistors can often be found at the same price as higher tolerance 5% resistors.

2.2.1 Design Tool

To use the TI Design Tool, each half of the overall filter must be designed separately. First, a high-pass filter is selected as the filter type. The pass-band gain is set to 0dB, and the frequency set to 200Hz. Under the stop-band section, filter order is set to 2. The butterworth filter response is chosen, again to ensure a constant frequency response in the pass-band, and because the Q value is as desired, 0.707. In *Topology*, Sallen-Key is selected from the drop-down menu. In the design section, supply voltages are set to ±5V. For components, the ideal filter uses E96 resistors and E48 capacitors, and the real filter uses E96 resistors and E12 capacitors. The design for the second half of the filter is very similar, instead a low-pass filter is selected. The gain is set to 0, with a cutoff frequency of 2000. Again, the Stopband filter order is set to 2, and the filter response selected is Butterworth. In *Topology*, Sallen-Key is selected, and under *Design*, the supply voltages are set to ±5V. For components, each design uses the same component series as the high-pass section. Ideal components are E96 resistors with E48 capacitors, and the real components are E96 resistors with E12 capacitors. Figure 3 shows the audio filter with ideal values.

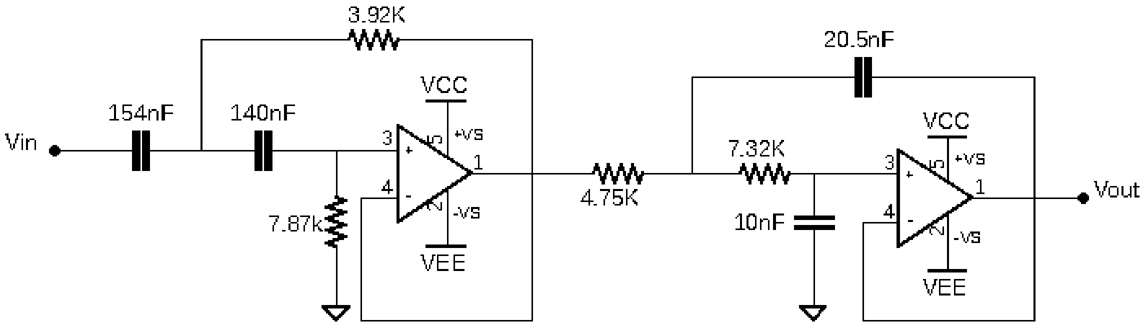

Fig. 3. Sallen-Key Audio Filter Band-pass Filter Schematic with ideal values.

The circuit as configured here will not be built, as E48 capacitors were not available. Instead, as mentioned above, the Filter Design Tool was rerun with E12 capacitors specified, as they are available in the parts kit. Figure 4 shows the audio filter with the new values that will be used for building and testing the circuit.

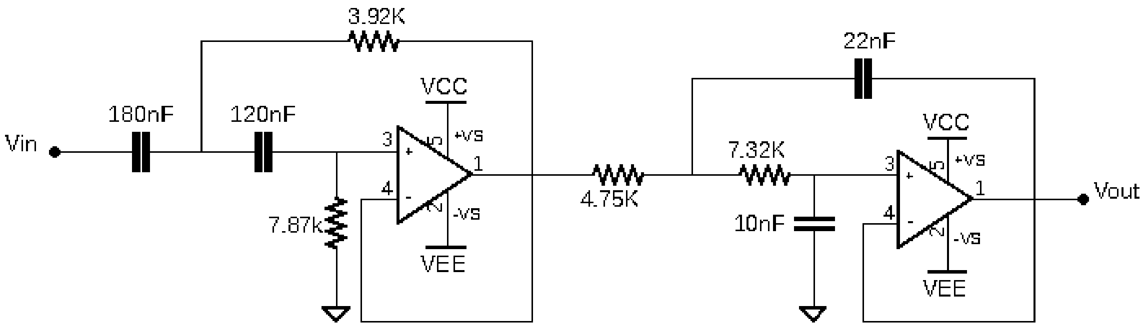

Fig. 4. Sallen-Key Audio Filter Band-pass Filter Schematic with real values.

Here, some resistors were not available at their exact values, so combinations had to be used. Table II shows the nominal values, and the combinations used to achieve these values.

TABLE II
Adjusted Component Values for Audio Filter

Component	Nominal Value	Adjusted Component values
R1	7.87kΩ	7.5kΩ+360Ω = 7.86kΩ
R2	3.92kΩ	3.9kΩ
R3	3.92kΩ	3.9kΩ
R4	7.2kΩ	6.8kΩ+510Ω = 7.31kΩ
C1	180nF	180nF
C2	120nF	120nF
C3	10nF	10nF
C4	22nF	22nF

All capacitor values were available in the parts kit, so they were not adjusted. However, as can be seen, series combinations of resistors were used for R1 and R4. Other small approximations were made, such as R2 and R3 being adjusted to 3.9kΩ, as 3.92kΩ resistors were not available.

3 Simulated Performance

To ensure specifications are met, the circuits created in the design section are simulated. All simulations were done using Micro-Cap 12 (64-bit), making use of the UMaine micro-cap parts library, specifically the LF347 operational amplifier, which is the op-amp used for both active filter circuits.

3.1 Multiple Feedback Band-pass Filter

Simulations are run to confirm the designs produced using the TI Filter Design tool are accurate. Figure 5 shows the MFBF schematic as seen in the TI Filter Design Tool.

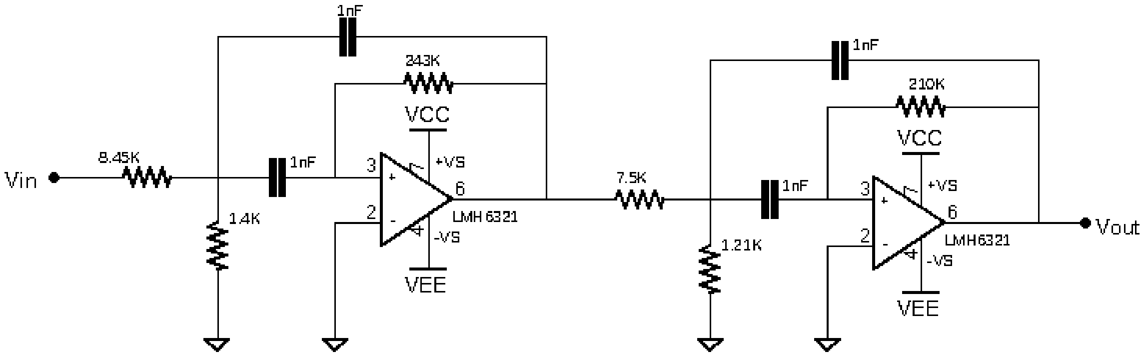

Fig. 5. Multiple Feedback Band-pass Filter Schematic.

The frequency response of the filter is simulated to ensure there is 40dB of gain on a 2kHz pass-band centered at 10kHz.

3.1.1 Frequency Response

A frequency response simulation is run by simulating an AC voltage source as the input to the filter and sweeping the frequency over a desired range. For the MFBF, simulations were run over two frequency ranges. The first range is the wide band, from 1kHz to 100kHz. Figure 6 shows the simulation over the wide-band.

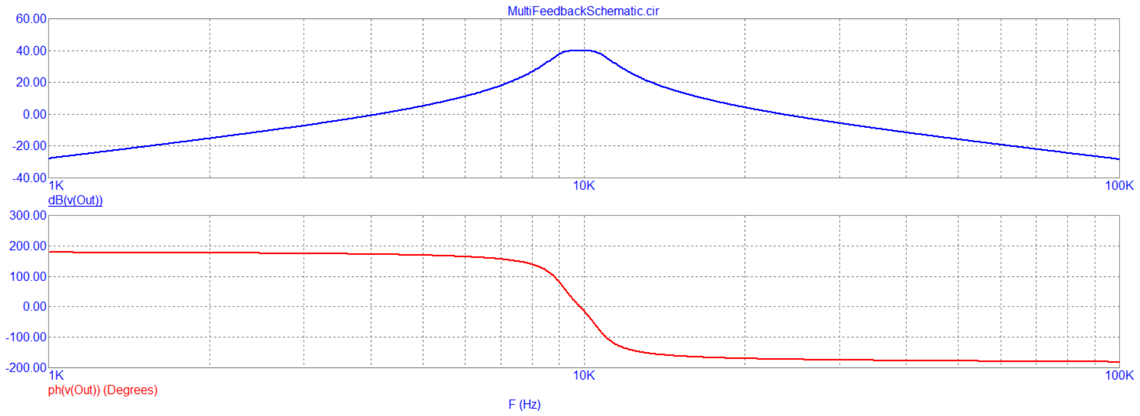

Fig. 6. MFBF wide-band simulation.

The second range is a ”zoomed-in” view of the pass-band, from 8kHz to 12kHz. Figure 7 shows the simulation over the pass-band.

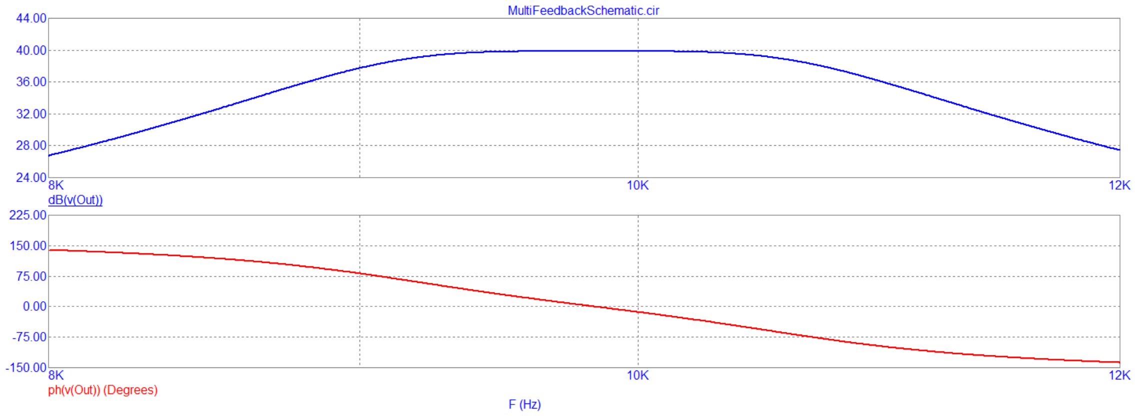

Fig. 7. MFBF pass-band simulation.

As can be seen in both simulations, there is significant attenuation outside the 2kHz pass-band centered at 10kHz. The two -3dB frequencies are 8.91kHz and 10.87kHz. This gives a bandwidth of 1.96kHz, only a 2% error. Inside the pass-band the gain reaches a peak of 39.84dB at a frequency of 9.71kHz. This gain is only a 0.4% error from the expected 40dB. Ultimately, the circuits simulated performance is as expected from the design stage.

3.2 Sallen-Key Audio Filter

Simulations were run to confirm the TI Filter Design Tool designs, and to prepare for the circuit to be built. Figure 8 shows the real Mid-Range Audio Filter schematic as seen in Micro-Cap.

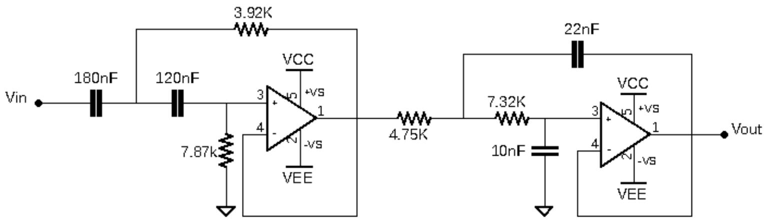

Fig. 8. Sallen-Key Audio Filter Band-pass Filter Schematic with real values.

The frequency response of the filter is simulated to ensure there is 0dB of gain in the 200-2kHz pass-band.

3.2.1 Frequency Response

The frequency response simulation is run in a similar way as the MFBF. An AC voltage source is set as the input to the filter, and the frequency is swept over a desired range. Again, two ranges are simulated, from 10Hz to 40kHz, the wide-band, and from 200Hz to 2kHz, the pass-band. Both the real and ideal configurations are simulated together in order to observe the difference in the output given different component tolerances and values. Figure 9 shows the simulation over the wide-band.

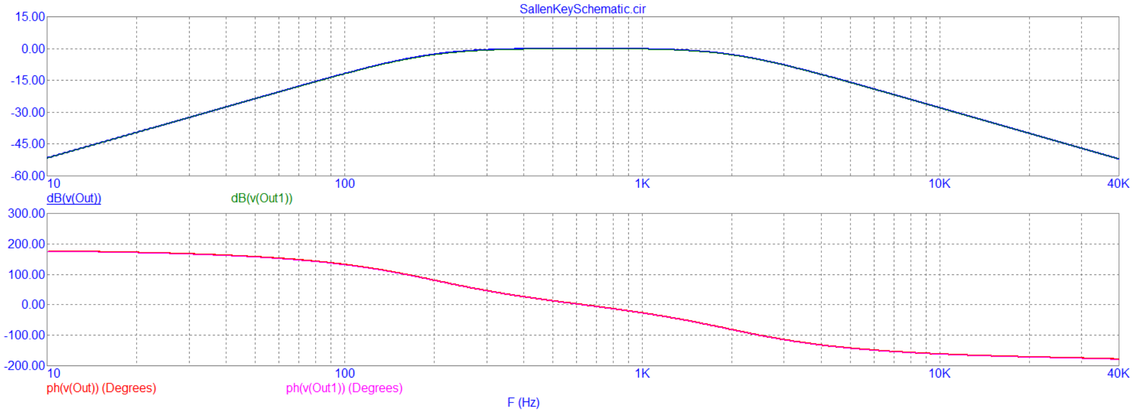

Fig. 9. Sallen-Key Audio Filter wide-band simulation.

Figure 10 shows the simulation over the pass-band.

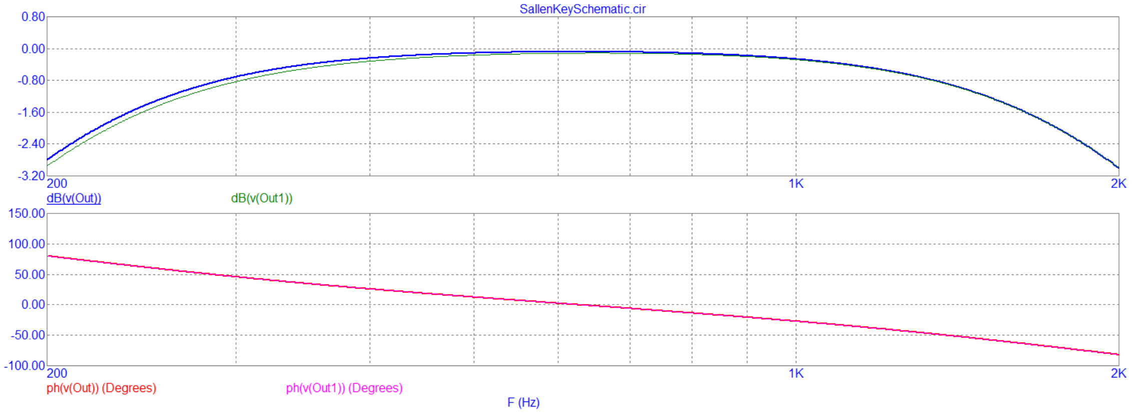

Fig. 10. Sallen-Key Audio Filter pass-band simulation.

As can be seen in both simulations, the circuit performs as expected. The -3dB cutoff frequency of the ideal high-pass filter is 195.27Hz. For the real high-pass filter, the cutoff frequency is 198.9Hz. This is an error of 2.37% and 0.55%, respectively. The ideal low-pass cutoff frequency is 2000.0kHz, and 1999.0kHz for the real filter. Here, the error is 0% and 0.05%, respectively. In this range, the gain reaches a peak of -113mdB. Outside the pass-band there is 40dB per decade of attenuation, as expected. The difference between the real and ideal configurations cannot be seen from the wide-band simulation, but the pass-band simulation shows the real configuration (green line) performing slightly better, with the high-pass cutoff frequency being slightly closer to specifications. Overall, the audio filter's simulated performance matches the design specifications.

4 Experimental Implementation

All measurements were taken using the Digilent Analog Discovery 2 (DAD2) in conjunction with Digilent's WaveForms software. Component values were measured with a Neotek NT8233D Pro multimeter. The multi feedback band-pass filter was not built in this experiment. Instead, the Sallen-Key audio filter was built, tested, and demonstrated with both oscilloscope measurements and by hearing the effects of the filter on an audio signal.

4.1 Sallen-Key Audio Filter

Figure 11 shows the Mid-Range Audio Filter schematic with the real measured component values.

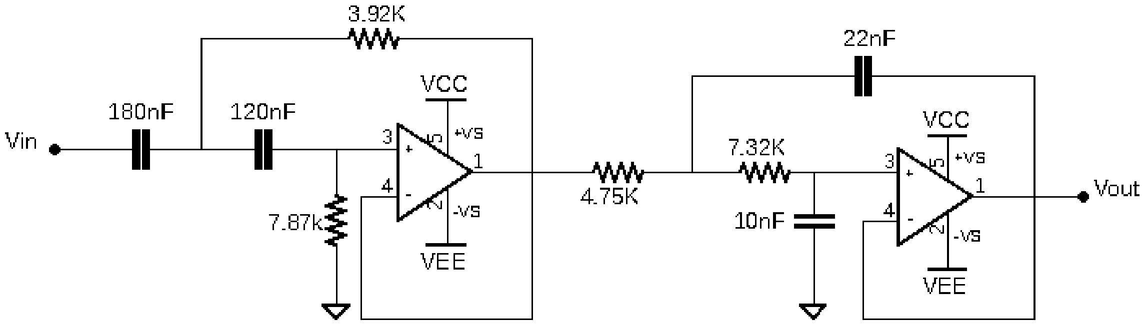

Fig. 11. Mid-Range Audio Filter Band-pass Filter Schematic with measured values.

Table III shows the nominal and measured component values. Some series resistor combinations were used to obtain the appropriate component values, namely R1 and R4. The ideal configuration was not built, as 2% tolerance capacitors were not available.

TABLE III
Measured Components of Audio Filter

Component	Nominal Value	Measured Value
R1	7.5kΩ+360Ω = 7.86kΩ	7.43kΩ + 358.2Ω = 7788.2Ω
R2	3.9kΩ	3.875kΩ
R3	3.9kΩ	3.874kΩ
R4	6.8kΩ+510Ω = 7.31kΩ	6.77kΩ + 508.4Ω = 7278.4Ω
C1	180nF	182.4nF
C2	120nF	122.8nF
C3	10nF	10.04nF
C4	22nF	22.1nF

4.1.1 Frequency Response

Measurements are taken using WaveForm's network analyzer tool with oscilloscope C1 connected to the input of the circuit, and C2 connected at the output. The limits are set from 10Hz to 40kHz for the wide-band measurement, and from 200Hz to 2kHz for the pass-band measurement. Figure 12 shows the wide-band measurement.

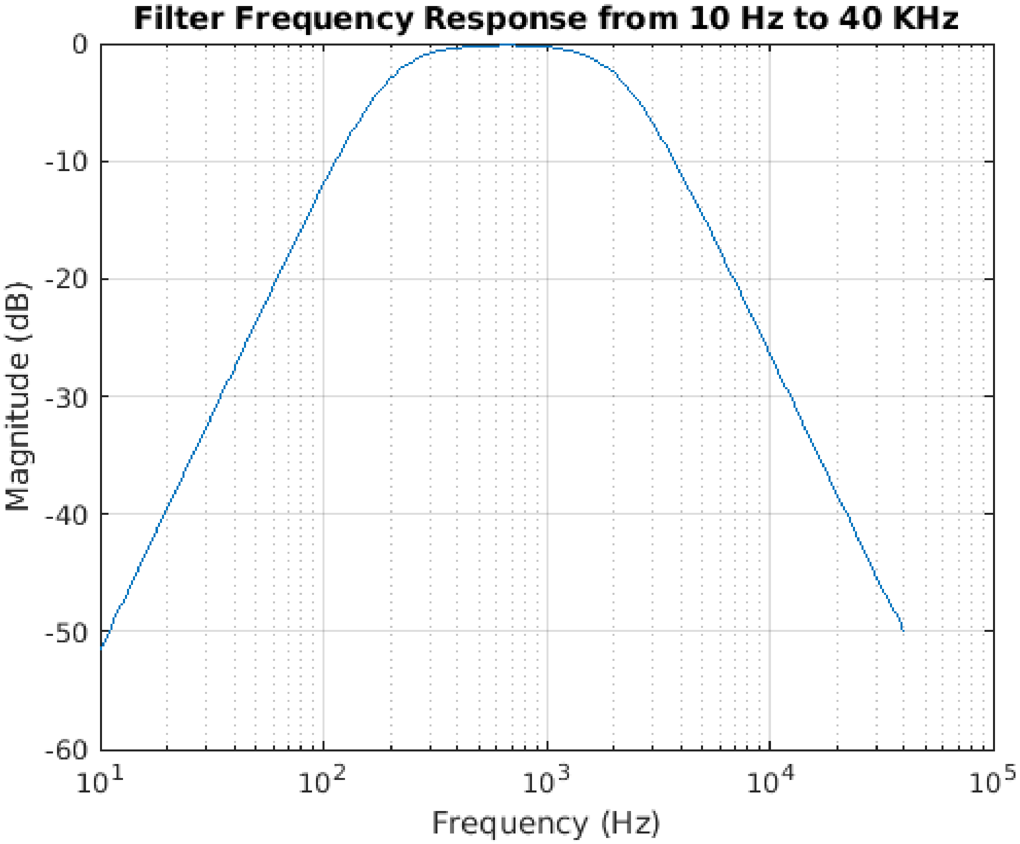

Fig. 12. Mid-Range Audio Filter wide-band frequency response measurement.

z As can be seen, the gain is -51dB at 10Hz, then climbs to -0.17dB in the 200Hz to 2kHz pass-band. The -3dB frequencies are measured to be 198.03Hz on the low-end and 2134.67Hz on the high-end. This frequency is slightly high on the high-end but the music demonstration still worked as expected. This error can likely be attributed to the component tolerance values, and the use of resistor combinations, compounding the error. Figure 13 shows the pass-band measurement.

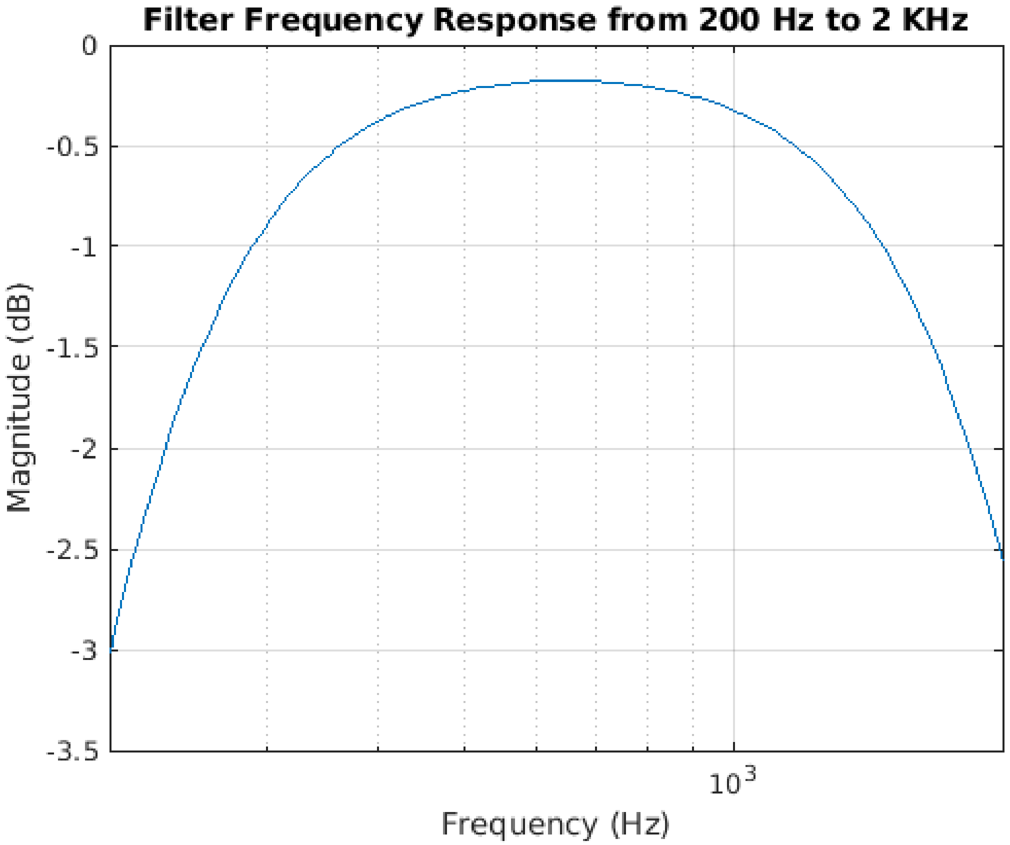

Fig. 13. Mid-Range Audio Filter pass-band frequency response measurement.

Here the cutoff frequencies can be observed more accurately. At 200Hz, there is -3.01dB of attenuation and at 2kHz, there is -2.56dB of attenuation. Clearly, the low-pass filter's cutoff frequency is slightly higher than expected, but this does not effect circuit performance. Additionally, given component tolerances and the limitations of the DAD2, this slight error is understandable. Ultimately, the filter's measured performance matches the designed performance specifications.

4.1.2 Music Demonstration

Another way to confirm the filter circuit is working properly is to play music through the filter, to hear the lack of low and high ranges. This works particularly well with songs featuring a high dynamic range, as the lack of certain sounds will be more noticeable. A video demonstration of the effects of the filter can be found at the following link. `https://video.maine.edu/media/Kaltura+-+ECE342+Lab+2+Audio+Demo/1_2sxtlpvd` Here, the DAD2 shows it's limitations again, as the maximum playback rate is 8kHz, limited by the 8000 samples per measurement of the DAD2. Luckily, the difference between the filtered and unfiltered tracks is still clearly audible, indicating the filter circuit works as anticipated.

5 Discussion

The Multi Feedback Band-pass filter was not built, as instructed, however simulations suggested that if it were to be built, it would perform as expected. The simulated performance of the MFBF matched the design specifications, with only a 2% error on the bandwidth and 0.4% error on the gain. The audio filter was built and tested, and worked as expected. Between 200Hz and 2kHz the signal is passed through with little to no attenuation. Outside this pass-band the signal is attenuated at a rate of 40dB per decade, as expected from design and simulations. As noted in Section 4, the cutoff frequency of the low pass filter was slightly higher than expected, with a 6.734% error, however the high-pass cutoff frequency only had an error of 0.985%. Ultimately, this did not effect the filter's performance, especially with audio playback. When playing music through the filter, the attenuation can clearly be heard, indicating the filter works as anticipated. Table IV shows the design, simulated, and measured values.

TABLE IV
Audio Filter Performance Comparison

Metric	Design	Simulation	Measurement
MFBF Gain (dB)	40	39.84	NA
MFBF Pass-band (Hz)	9k - 11k	8.91k - 10.87k	NA
MFBF Bandwidth (Hz)	2	1.98	NA
Audio Gain Peak (dB)	0	-0.113	-0.17
Audio High-pass Cutoff (Hz)	200	198.9	198.03
Audio Low-pass Cutoff (Hz)	2000	1999	2134.68

5.1 Sources of Error

There was little error throughout the experiment. Most values were within 5% of their expected values, with the measured low-pass cutoff filter having the highest error at 6.734%. This error was likely introduced by the series combination of resistors needed. When combining resistors to achieve one value, the error associated with their tolerances compounds on each other. Additionally, the Digilent DAD2 has it's own limitations when measuring circuit performance, especially with the Network Analyzer. Instead of directly measuring the frequency response, the DAD2 does a fast Fourier transform to create the frequency response plot. This likely introduced slight error in measurements.

6 Conclusions

In this experiment the process and procedures of signal conditioning are investigated. The amplification of a filtered signal is simulated, and a mid-range audio filter is built. The audio filter is built using a Sallen-Key topology, where the op-amps are configured in unity gain. The design of both filters was efficent and effective via the use of the TI design tool. The design tool provides a useful look into real world circuit design where tools can be used to improve efficiency and speed. The MFBF is only simulated, but shows a relatively simple method for amplifying a specific bandwidth, an ability often needed in a broad range of signal conditioning applications. Simulations in Micro-Cap 12 allowed designs to be tested and confirmed before they were built. The Sallen-Key filter was successfully built and tested using the DAD2 and WaveForms software. A frequency response measurement was run on the filter to ensure it was meeting specifications. Playing music through the filter provided qualitative proof of the circuit working properly. The Sallen-Key design provides an incredibly easy setup for a circuit with a real world application of signal conditioning.

References

[1] N. Emanetoglu, “Laboratory experiment #2: Active filters,” University of Maine, Orono, ME, USA, 2020.