ECE 20007

Experiment 14
Report

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Section: OL1

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Abstract

The project involves an audio equalizer which allows us to choose certain frequencies to amplify or reduce. Given a certain signal, the audio equalizer is able to filter out signals into three categories: Bass frequencies- which are considered signals with less than that of 320 Hz, Mid-frequencies- which are considered signals between 320 Hz and 3200 Hz, and treble frequencies- which are considered signals above 3200 Hz. After the filtering process, an inverting amplifier will be incorporated into each filter subcircuit and the user is able to amplify or reduce the magnitude of that signal using a potentiometer which varies the resistance of the inverting amplifier's feedback resistor. The three signals are then added up into a single signal using a summing amplifier. The final magnitude or volume of the signal can be adjusted using another potentiometer incorporated into the summing amplifier.

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Objectives

Investigate, construct, experiment, test and design the audio equalizer using concepts mainly from frequency filters and operational amplifiers learned through past experiments. Design the circuit such that we are able to control the relative strength of 3 main frequency bands namely Bass (Less than 320 Hz), Mid (Between 320 Hz and 3200 Hz) and Treble (Above 3200 Hz). The design of the circuit incorporates the criteria where we will have to separate frequency bands and have an independent controllable gain on each frequency band: Bass, Mid and Treble. We are to verify, understand and apply the concepts of frequency filters by using them to isolate the frequencies of certain signals. In this case, the low pass filter will help us isolate the Bass frequency, Band pass filter will help us isolate the Mid frequency and finally the High pass filter will help us isolate the Treble frequency. Similarly, we will verify, understand and apply the concepts of operational amplifiers by using them to apply a gain on certain signals. Part of the objective as well is to design the circuit such that the gain is controllable by integrating a potentiometer so that we may have a variable resistance. In addition to this, part of the design and experiment task is to restore and add the frequency signals together by using a summing amplifier. Another design consideration is the criteria in which we will have to be able to control the volume of the final output signal by incorporating circuit techniques, components and concepts learned in previous labs.

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Theory

To describe a high level working principle of the audio equalizer subsystem, we would first receive an input voltage which may contain various frequencies and design the circuit such that it splits to three paths which are placed in parallel. The first path is designed to isolate bass frequencies (Less than 320 Hz) by using a low pass filter. The second path is designed to isolate Mid frequencies (Between 320 Hz to 3200 Hz) using a bandpass filter. And finally the third path is designed to isolate treble frequencies (Above 3200 Hz) using a high pass filter. After isolating each of these signals in the respective paths, the circuit will implement a certain gain (which must be controllable) using operational amplifiers, specifically the LM324. Because the gain through the LM324 depends on the resistance in the circuit, by implementing this circuit design with potentiometers, we can vary the feedback resistor's resistance and therefore vary the gain and make it controllable. After each of the three isolated signals achieve the desired gain (which depends on the potentiometer's resistance) the three signals will be added up using a summing amplifier which utilizes the LM324 similarly to each of the frequency gain paths. However, this amplifier will add the 3 signals together using the principles of superposition. The final component or specification to meet using this circuit is the volume control which can be done by controlling the gain of the final signal. Similarly, this can be done by implementing a potentiometer in order to vary the feedback resistor's resistance and therefore it will allow us to successfully change the final output volume.

The initial part of the circuit heavily relies on filters to isolate each of the desired frequencies. By following the provided equalizer topology, we realize that we can use RC filters to get our desired frequencies through each respective path. An important point regarding the application of capacitors in this area is that the impedance of a capacitor will depend on the frequency of the signal. This point is further reinforced by the fact that a capacitor acts as an open with DC signals which means that at low frequencies (in this case 0), the impedance is infinite (open circuit). On the other hand, a capacitor acts as a short with extremely high frequency signals which means that at very high frequencies, the impedance is 0 (short circuit).

The first filter we are using is the low-pass filter to isolate bass frequencies (less than 320 Hz).

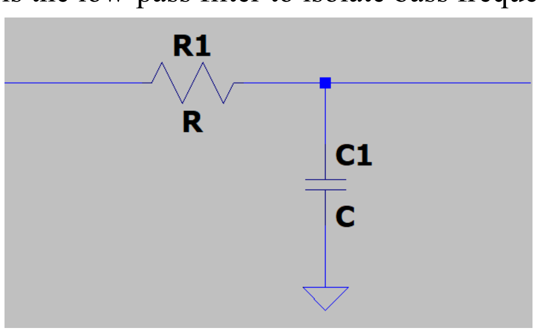


Figure 1: Basic schematic of low-pass filter

We can find the transfer function by applying the voltage divider rule.

$$Impedance\ (Z)\ of\ R1 = R$$

$$Impedance\ (Z)\ of\ C1 = 1/j2\pi fC$$

$$H(f) = Vout/Vin = Iout * Zc\,/\,(Iin * (ZR + Zc))$$

If we assume that there is only 1 path for current flow then Iin = Iout.

$$H(f) = Zc/(\mathrm{ZR} + \mathrm{Zc})$$

$$H(f) = (1/j2\pi fC)\,/\,(\,(1/j2\pi fC) + R)$$

Transfer function for low pass filter:

$$H(f) = 1/(1 + j2\pi fRC)$$

We can take a look at the high-pass filter next. The high-pass filter is to isolate treble frequencies (higher than 3200 Hz).

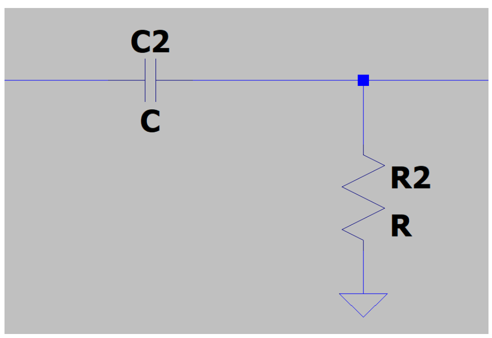


Figure 2: Basic schematic of high-pass filter

We can find the transfer function by applying the voltage divider rule.

$$Impedance\ (Z)\ of\ R2 = R$$

$$Impedance\ (Z)\ of\ C2 = 1/j2\pi fC$$

$$H(f) = Vout/Vin = Iout * ZR2\,/\,(Iin * (ZR2 + Zc2))$$

If we assume that there is only 1 path for current flow then Iin = Iout.

$$H(f) = ZR2/(\mathrm{ZR2} + \mathrm{Zc2})$$

$$H(f) = R\,/\,(\,(1/j2\pi fC) + R)$$

Transfer function for high-pass filter.

$$H(f) = j2\pi fRC/(1 + j2\pi fRC)$$

The band pass filter can be seen as a combination of the high-pass and the low-pass filter. The band-pass filter is to isolate mid range frequencies (320 Hz to 3200 Hz). Note that an inverting amplifier will be incorporated into this in the circuit design later. Because the bandpass will accept frequencies within the bandpass, it is therefore a reasonable strategy to switch the resistance values given that the capacitance values are the same for the high and low pass filters.

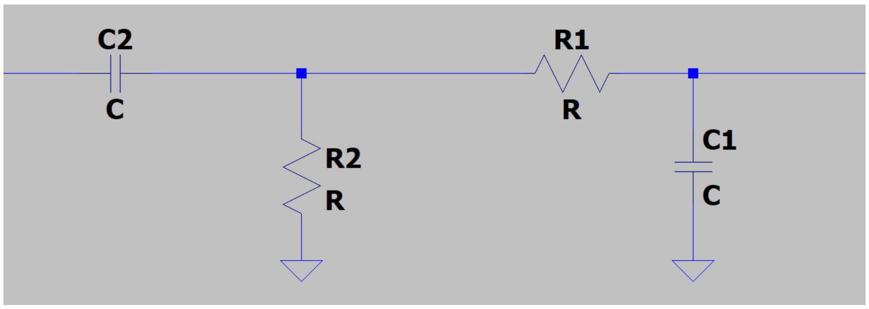


Figure 3: Basic schematic of band-pass filter

We can find the transfer function through the following calculations:

$$Impedance\ (Z)\ of\ R1 = R1$$
$$Impedance\ (Z)\ of\ C1 = 1/j2\pi f C1$$
$$Impedance\ (Z)\ of\ R2 = R2$$
$$Impedance\ (Z)\ of\ C2 = 1/j2\pi f C2$$
$$H(f) = Vout/Vin$$

Since R2 is in parallel with (R1 and C1), they have the same voltage drop across.

$$Vin = Iin * 1/j2\pi f C2 + Iout * (R1 + 1/j2\pi f C1)$$
$$Vout = IOut * 1/j2\pi f C1$$

With constraint equation:

$$(Iin - Iout) * R2 = Iout * (R1 + 1/j2\pi f C1)$$
$$Iin = (Iout * (R1 + 1/j2\pi f C1) + Iout * R2)\ /\ R2$$
$$H(f) = Vout/Vin = (IOut * 1/j2\pi f C1)/(Iin * 1/j2\pi f C2 + Iout * (R1 + 1/j2\pi f C1))$$

The -3dB is found when Vout/Vin = 0.707 or sqrt(2)/2. This is from the equation:

$$dB = 20\ log(Vout/Vin)$$

To show that this is true, we can plug in -3dB on the left and solve for Vout/Vin.

$$-3\ dB = 20 log(Vout/Vin)$$

10^(-3/20) = Vout/Vin

$$Vout/Vin = 0.707$$

For each of the filters, the equation that models the relationship between the cutoff frequency, impedance and capacitance can be written as follows:

$$Fc = 1/2\pi RC$$

The cutoff frequency is the frequency which corresponds to the frequency response graph at approximately -3dB. Since we are only given the cutoff frequency, we have 1 equation and 2 unknowns and will therefore have to either provide the resistance or capacitance values ourselves.

The next part of the lab involves the use of operational amplifiers. In this lab's case and according to the given equalizer topology, we will use the inverting amplifier.

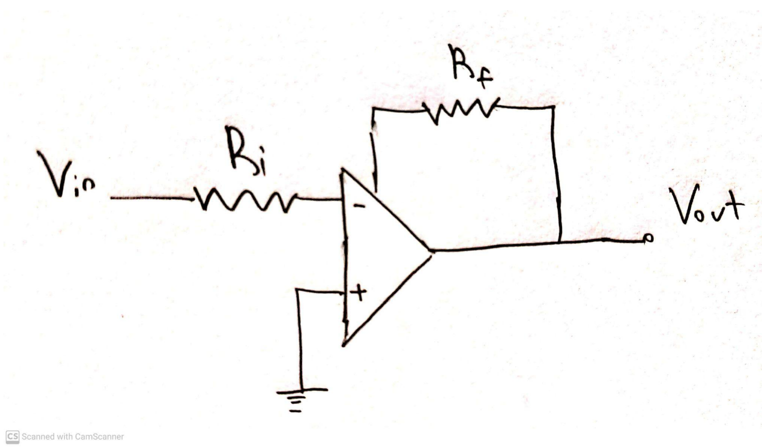


Figure 4a: Basic schematic of inverting amplifier

If we take V(+) to be the voltage at the positive terminal and V(-) to be the voltage at the negative terminal of the op amp then we can produce the following equation:

$$(Vin - V(-))/Ri + (Vout - V(-))/Rf = 0$$

Because V(+) is grounded we know V(+) is 0 V. We know V(+) and V(-) share the same voltage so V(-) is also 0 V. By plugging this into the previous equation:

$$Vin/Ri + Vout/Rf = 0$$

$$Gain = Vout/Vin = -Rf/Ri$$

Part of the design requirement of the circuit is to incorporate a summing amplifier. The summing amplifier allows us to sum up the three signals after passing them through filters and each of them receiving the desired gain.

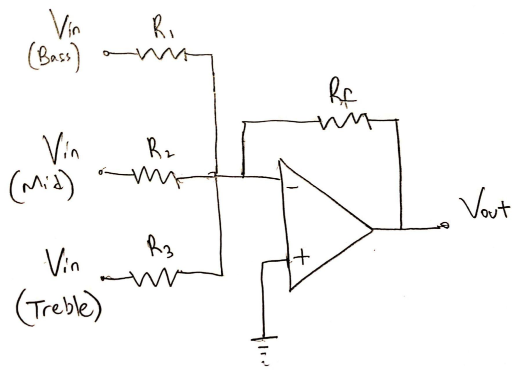


Figure 4b: Basic schematic of summing amplifier

By applying KCL we get:

$$(Vin(Bass) - V(-))/R1 + (Vin(Mid) - V(-))/R2 + (Vin(Treble) - V(-))/R3 + (Vout - V(-))/Rf = 0$$

Because V(+) is grounded we know V(+) is 0 V. We know V(+) and V(-) share the same voltage so V(-) is also 0 V. By plugging this into the previous equation:

$$Vin(Bass)/R1 + Vin(Mid)/R2 + Vin(Treble)/R3 + Vout/Rf = 0$$

Through superposition wee therefore get:

$$Vout = -Rf\sum_{i=1}^{n} Vin(i)/Ri$$

In order to achieve a controllable gain, we can manipulate the value of the feedback resistor by using a potentiometer. From the equation above we get:

$$Gain = Vout/Vin = -Rf/Ri$$

Based on the circuit design, the value of Ri is assumed to be constant and predetermined based on calculations that will be further evaluated in the next section of this report. Therefore, the only variable in this case is the value of Rf and we can use this as a way to give controllable gain. The value of Rf can range anywhere from the maximum resistance of the potentiometer to 0 ohms.

The potentiometer will allow us to change the feedback resistance which are illustrated by the following circuit schematics.

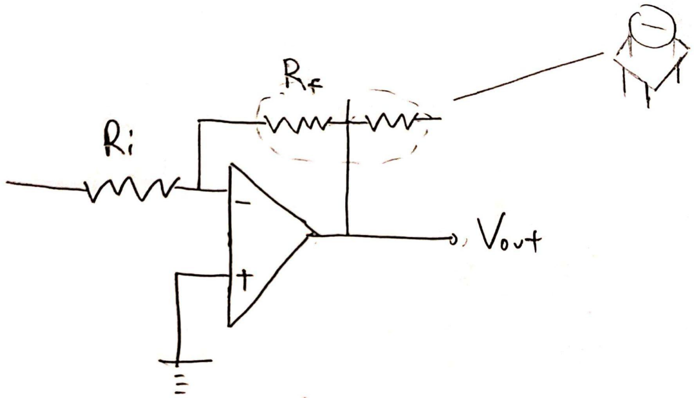


Figure 4c: Basic schematic of inverting amplifier with potentiometer adjusted mid-range

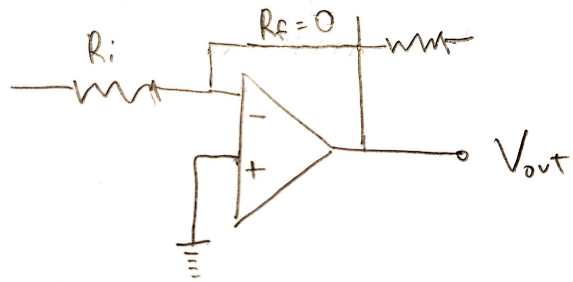


Figure 4d: Basic schematic of inverting amplifier with potentiometer adjusted to 0 ohms

Throughout the circuit, we would have a total of 4 potentiometers which act as the “knobs” or controls of the audio equalizer. The first 3 potentiometers will be placed in order to manipulate the gain of each of the frequency signals namely: Bass, Mid and Treble. The 4th potentiometer will be placed together with the summing amplifier such that it is able to manipulate the gain of the total signal and therefore allow the user to change the volume of the signal.

Procedure

1. Design Steps

To calculate the cutoff frequency, we can use the equation: $Fc = 1/2\pi RC$

$$320Hz = 1/2\pi RC$$

Take C as 0.1 μF

$$R = 1/2\pi(320\ Hz) * 0.1\mu F$$

$$R = 4973.6\ \Omega$$

Because the closest resistor value available is 4.7k ohms, we will try to find a more compatible resistor value by placing two capacitors in series.

$$320Hz = 1/2\pi RC$$

Take C as two 0.1μF in series = 1/(1/0.1μF + 1/0.1μF) = 0.05μF

$$R = 1/2\pi(320\ Hz) * 0.05\mu F$$

$$R = 9947.18\ \Omega$$

Since we have a 10k ohms resistor, which is very close to the value 9947.18 ohms, our margin of error will be minimalized.

Therefore selected values for the low pass RC filter are

$R = 10k\ \Omega$ and C = 0.05μF (two 0.1μF in series)

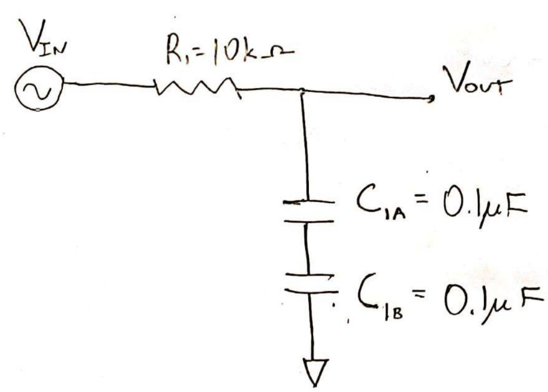


Figure 5: Circuit schematic of low pass RC filter

For convenience, we will calculate the values for the high pass filter next. The target frequencies to isolate for the high pass filter are the treble frequencies (3200 Hz or above).

To calculate the cutoff frequency, we can use the equation: $Fc = 1/2\pi RC$

$$3200Hz = 1/2\pi RC$$

By previous experience we can try taking 2 capacitors in series to produce an easier resistor value to find in the kit.

Take C as two 0.1 μFcapacitors in series
= 1/(1/0.1μF + 1/0.1μF) = 0.05μF

$$R = 1/2\pi(3200\ Hz) * 0.05\mu F$$
$$R = 994.718\ \Omega$$

Since we have a 1k ohms resistor, which is very close to the value 994.718 ohms, our margin of error will be minimalized.

Therefore selected values for the high pass RC filter are
$R = 1k\ \Omega$ and C = 0.05μF (two 0.1μF in series)

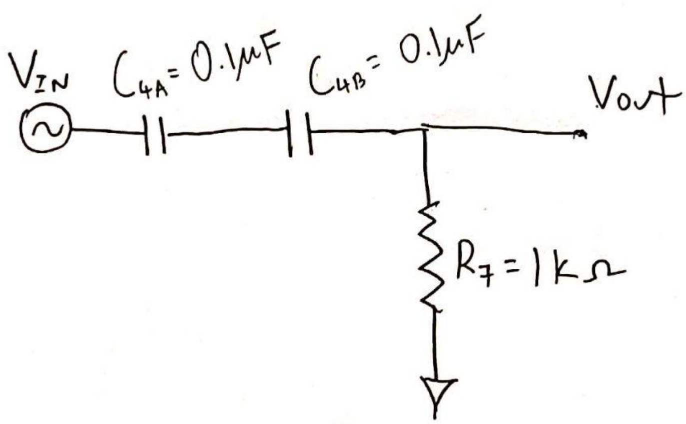


Figure 6: Circuit schematic of high pass RC filter

Finally, for the bandpass filter, we can combine the high-pass filter and low-pass filter together to get our desired mid range frequencies. Because the cutoff frequencies are the same, we can use the same values as well. However, since we are aiming to pass the frequencies in the middle instead of the frequencies before and after, we can switch the two resistor values in order for this to work.

$R1 = 1k\,\Omega$ and C1 = 0.05μF (two 0.1μF in series)

$R2 = 10k\,\Omega$ and C2 = 0.05μF (two 0.1μF in series)

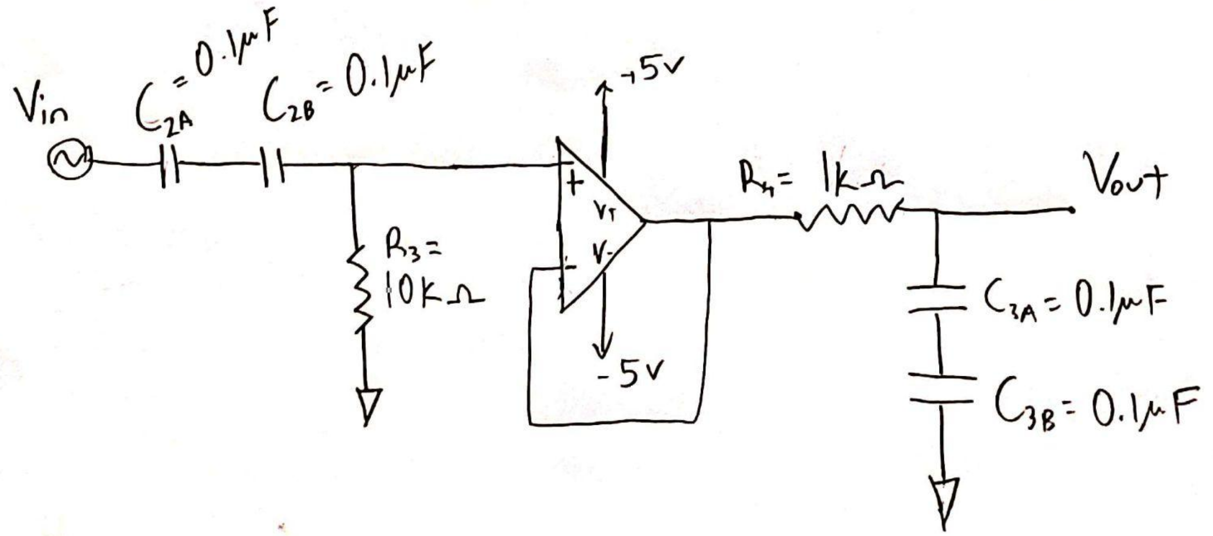


Figure 7: Circuit schematic of band pass filter

For the inverting amplifiers, we have to take in the potentiometer as a consideration for the variable voltage. Note that there may be a slight gain when the signal passes through the filter. However, we can estimate the gain to be one given that the signal has not passed the cutoff frequency in other words above -3dB.

$$Magnitude\ of\ Gain = Rf/Ri$$

Because the provided potentiometers range of resistance is between 0 to 10k ohms we can write the following :

$$(0/Ri) * (0/Ri(summer) <= Magnitude\ of\ gain <= (10k/Ri) * (10k/Ri(summer))$$

Based on the specifications, given that the input voltage is a 1Vpeak to peak sine wave, Vamp must be 100 mV RMS.

Max gain is is therefore:

$$Vout/Vin \ = \ 0.1/(0.5/\sqrt{2}) \ = \ (10k/Ri)(10k/Ri(summer))$$
$$100M/(Ri \ * \ Ri(summer)) \ = \ 0.2828$$
$$Ri \ * \ Ri(summer) \ = \ 353553390.6\,\Omega^2$$

$Take\ Ri\ as\ 33k\Omega$- a known resistor value in the master kit

$$Ri(summer) \ = \ 353553390.6\Omega^2/33k\Omega \ = \ 10713.74\Omega$$
$$\approx \ 11k\Omega$$

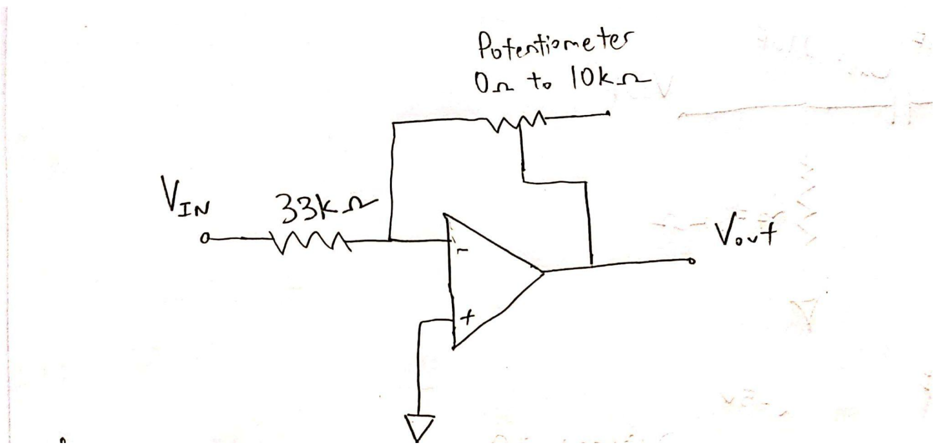


Figure 8a: Circuit schematic of inverting amp for each filter

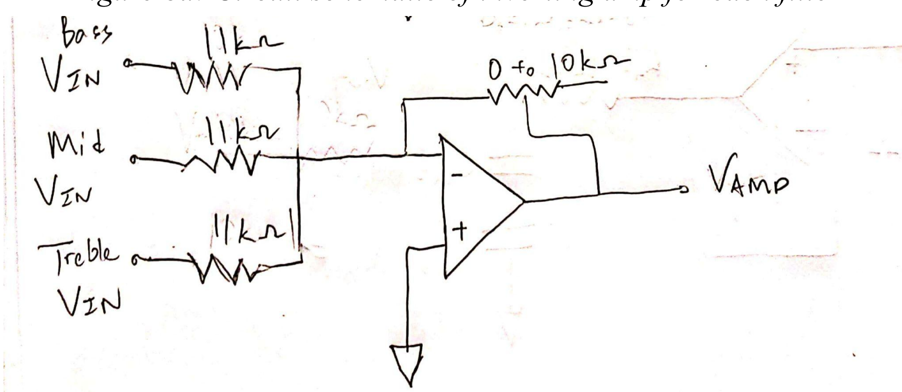


Figure 8b: Circuit schematic of summing amplifier

Subcircuit	Components and values
Bass filter	R1 = 10k Ω C1 = 0.05 uF (0.1uF || 0.1uF in parallel)
Mid filter	R3 = 1k Ω C2 = 0.05 uF R5 = 10k Ω C3 = 0.05 uF (0.1uF || 0.1uF in parallel)
Treble filter	R7 = 1k Ω C4 = 0.05 uF
Bass EQ	0 <= Rf <= 10kΩ Ri = 33k Ω
Mid EQ	0 <= Rf <= 10kΩ Ri = 33k Ω (3kΩ+3kΩ+15kΩ+15kΩ in series)
Treble EQ	0 <= Rf <= 10kΩ Ri = 33k Ω
Summing amplifier	0 <= Rf <= 10kΩ Ri =11k Ω Ri1 = 22kΩ||22kΩ in parallel Ri2 = 10kΩ + 1kΩ in series Ri3 = 4.7kΩ+4.7kΩ+1kΩin series

Table 1: List of final component values used to construct circuit

2. **Test Procedure**

The filters were tested individually and independently. An input voltage with a certain frequency is passed into the filter and the output is measured using an oscilloscope. The output and input will then be analyzed using the transfer function at the cutoff frequency to determine whether the filter meets the required specifications.

Low Pass filter: (Passing 320 Hz frequency signals or less):

Input Voltage	Output voltage	Vout/Vin

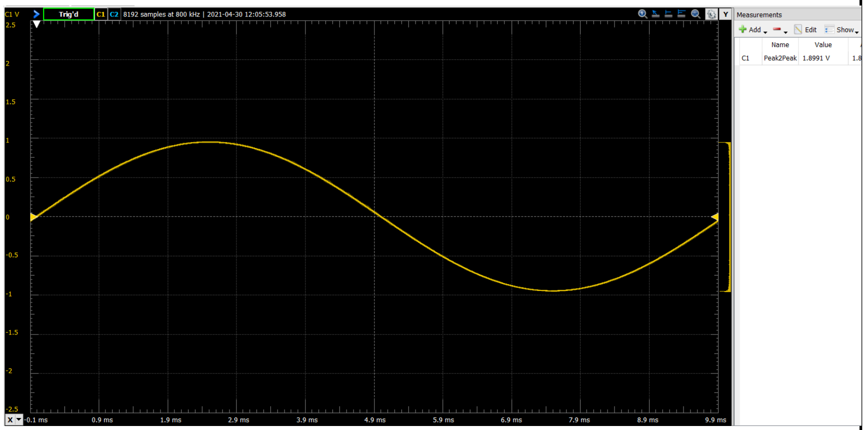
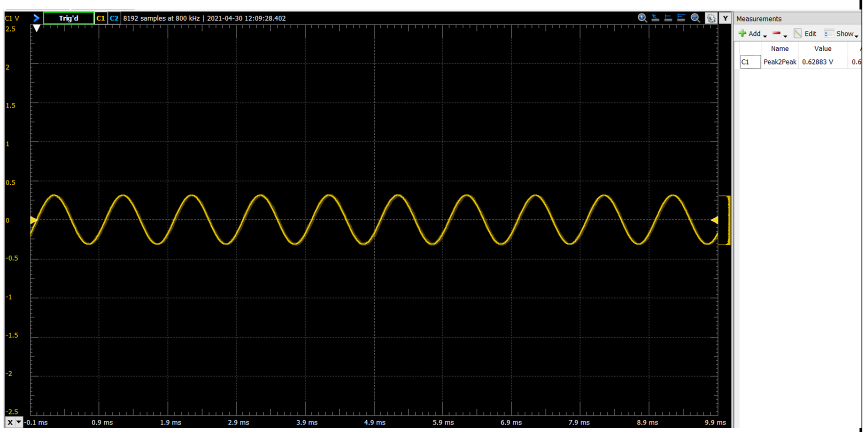
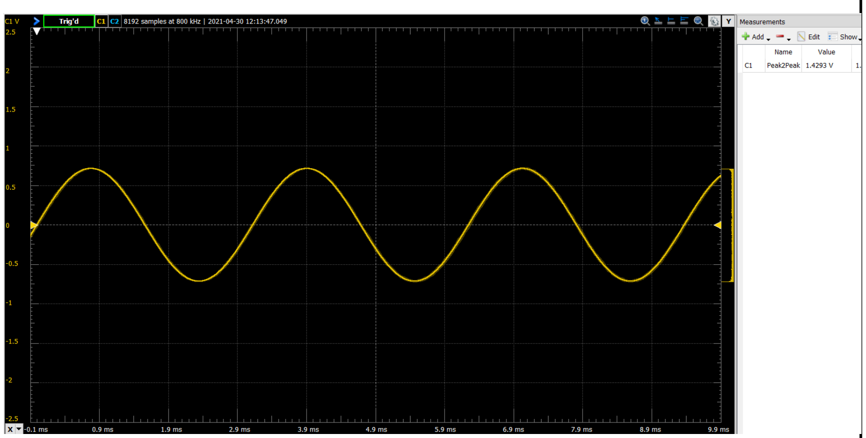
Testing for frequencies below 320 Hz Input voltage: Peak to peak amplitude: 2 V Frequency: 100 Hz Offset: 0 V	 Output peak to peak measured: 1.8991 V	0.95 V/V
Testing for frequencies above 320 Hz Input voltage: Peak to peak amplitude: 2 V Frequency: 1k Hz Offset: 0 V	 Output peak to peak measured: 0.62886 V	0.314V/V
Testing for frequency AT 320 Hz (-3 dB) Expected VOut/Vin = 0.707 Input voltage: Peak to peak amplitude: 2 V Frequency: 320 Hz Offset: 0 V	 Output peak to peak measured: 1.4292 V	0.714 V/V

Table 2: Testing procedure and data on low pass filter

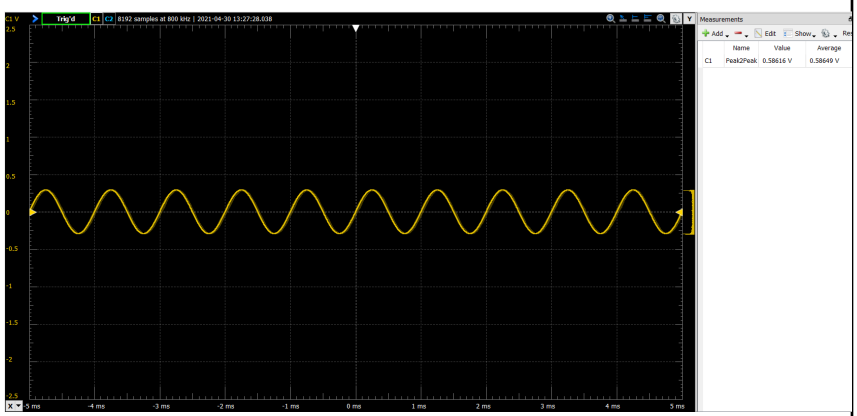
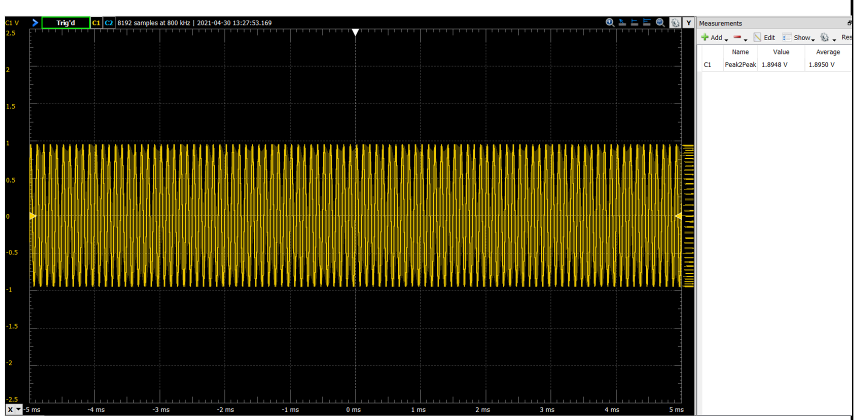
Low pass filter result evaluation:
Expected Vout/Vin = 0.707 V/V

Actual Vout/Vin = 0.714 V/V

$$\%Error = |0.714 - 0.707| / 0.707 * 100\% = 0.99\%$$

Since the %Error is within the specified range, the low pass filter passes the test.

High Pass filter: (Passing 3200 Hz frequency signals or greater):

Input Voltage	Output voltage	Vout/Vin
Testing for frequencies below 3200 Hz Input voltage: Peak to peak amplitude: 2 V Frequency: 1000 Hz Offset: 0 V	 Output peak to peak measured: 0.5865 V	0.293 V/V
Testing for frequencies above 3200 Hz Input voltage: Peak to peak amplitude: 2 V Frequency: 10k Hz Offset: 0 V	 Output peak to peak measured: 1.895 V	0.948 V/V

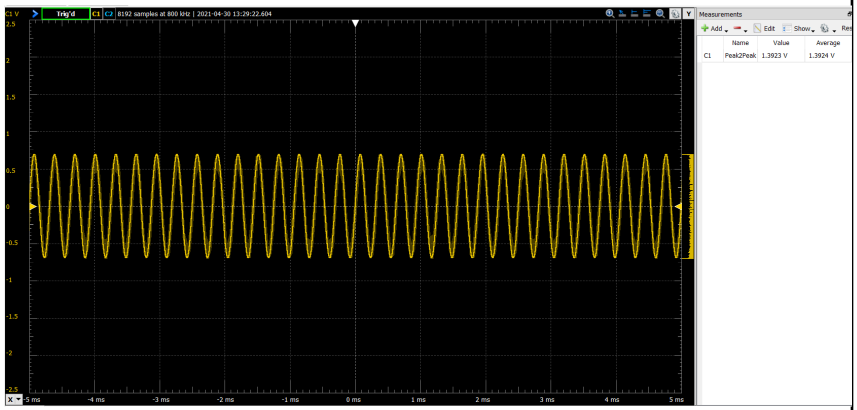
Testing for frequency AT 3200 Hz (-3 dB) Expected VOut/Vin = 0.707 Input voltage: Peak to peak amplitude: 2 V Frequency: 1k Hz Offset: 0 V	 Output peak to peak measured: 1.3924 V	0.696 V/V

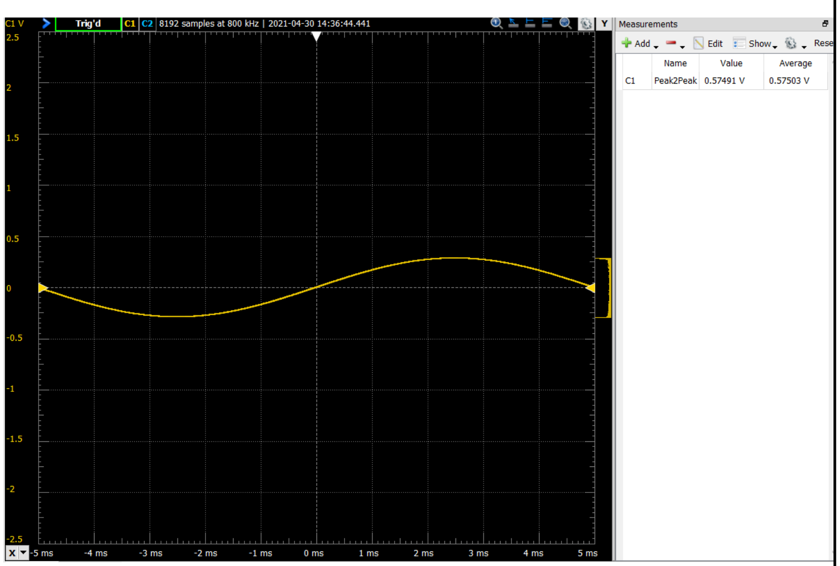
Table 3: Testing procedure and data on high pass filter

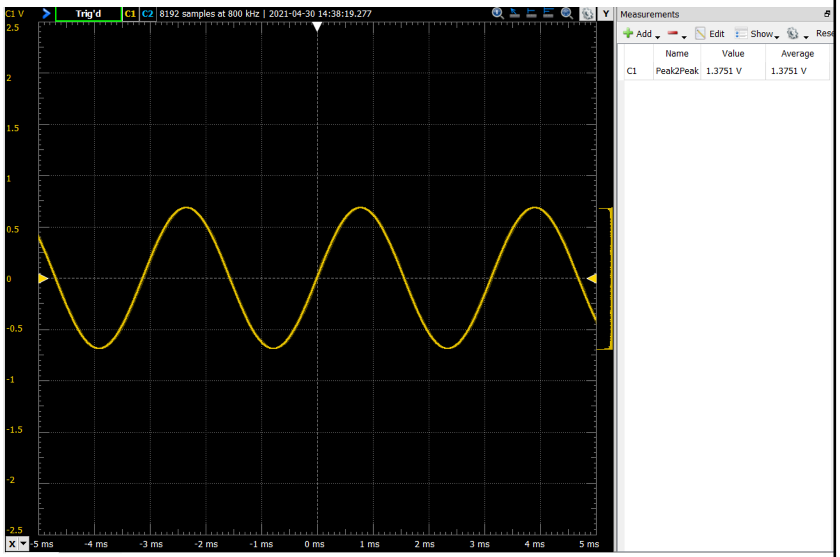
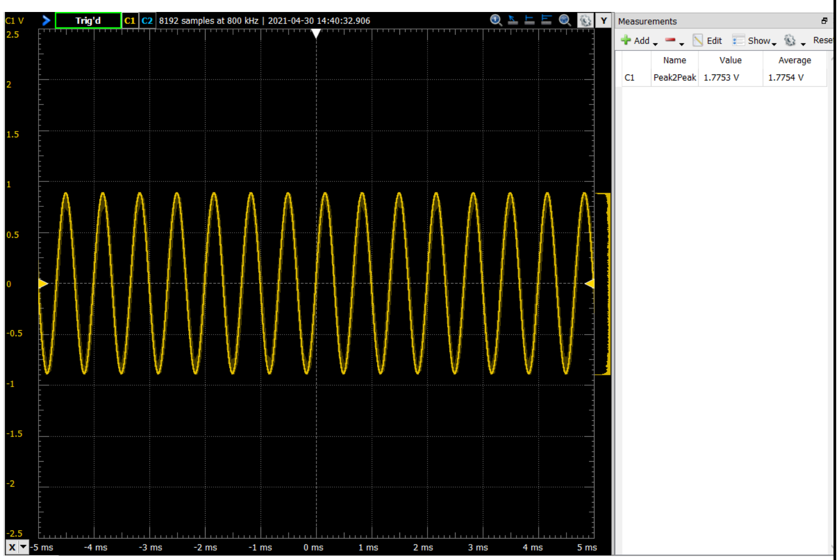
High pass filter result evaluation:
Expected Vout/Vin = 0.707 V/V
Actual Vout/Vin = 0.696 V/V

$$\%Error = |0.696 - 0.707| / 0.707 * 100\% = 1.55\%$$

Since the %Error is within the specified range, the high pass filter passes the test.

Band Pass filter: (Passing between 320 to 3200 Hz frequency signals):

Input Voltage	Output voltage	Vout/Vin
Testing for frequencies below 320 Hz Input voltage: Peak to peak amplitude: 2 V Frequency: 100 Hz Offset: 0 V	 Output peak to peak measured: 0.575 V	0.288 V/V

Testing for frequency AT 320 Hz (-3 dB) Expected VOut/Vin = 0.707 Input voltage: Peak to peak amplitude: 2 V Frequency: 320 Hz Offset: 0 V	 Output peak to peak measured: 1.375 V	0.688 V/V
Testing for frequencies in the pass band Input voltage: Peak to peak amplitude: 2 V Frequency: 1500 Hz Offset: 0 V	 Output peak to peak measured: 1.775 V	0.888 V/V

<table>
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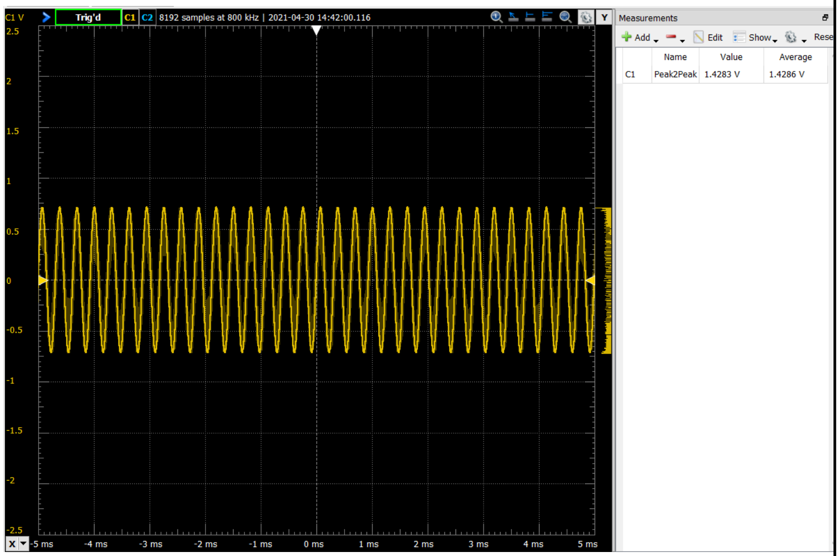
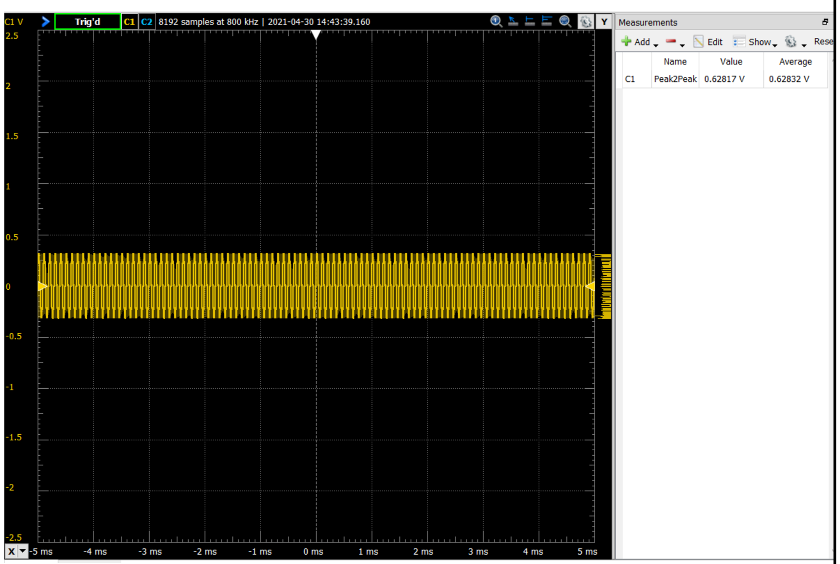
<td>Testing for frequency AT 3200 Hz (-3 dB) Expected VOut/Vin = 0.707
Input voltage:
Peak to peak amplitude: 2 V
Frequency: 1k Hz
Offset: 0 V</td>
<td>

Output peak to peak measured: 1.428 V</td>
<td>0.714 V/V</td>
</tr>
<tr>
<td>Testing for frequencies above 3200 Hz
Input voltage:
Peak to peak amplitude: 2 V
Frequency: 10k Hz
Offset: 0 V</td>
<td>

Output peak to peak measured: 0.628 V</td>
<td>0.314 V/V</td>
</tr>
</table>

Table 4: Testing procedure and data on band pass filter

Band pass filter result evaluation:
First cut off frequency:
Expected Vout/Vin = 0.707 V/V
Actual Vout/Vin = 0.688 V/V

$$\%Error = |0.688 - 0.707| / 0.707 * 100\% = 2.68\%$$

Since the %Error is within the specified range, the high pass filter passes the test.
Second cut off frequency:
Expected Vout/Vin = 0.707 V/V

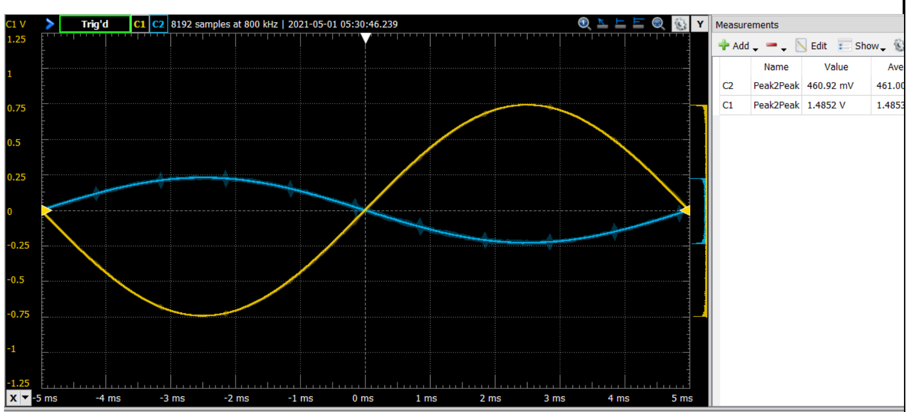
Actual Vout/Vin = 0.688 V/V

$$\%Error = |0.714 - 0.707| / 0.707 * 100\% = 0.99\%$$

Since the %Error is within the specified range, the high pass filter passes the test.

Now that the filters are tested, we will be testing the operational amplifiers together with it. We will send a signal through the filters. The output voltage from the filters will then be considered as the input voltage into the inverting amplifiers. In order to verify that we got the desired gain, we will measure the output of the inverting amplifiers compared with the input and check that it agrees with the numbers.

Low Pass filter: (Passing 320 Hz frequency signals or less):

Rf and Ri Value	Output voltage (signal coming out from inverting amplifier) vs Input voltage (signal coming out from filters)	Magnitude of Gain
Rf = 10kΩ Ri = 33kΩ	 Measured Vout peak to peak: 461 mV Measured Vin peak to peak: 1.4853 V	0.31

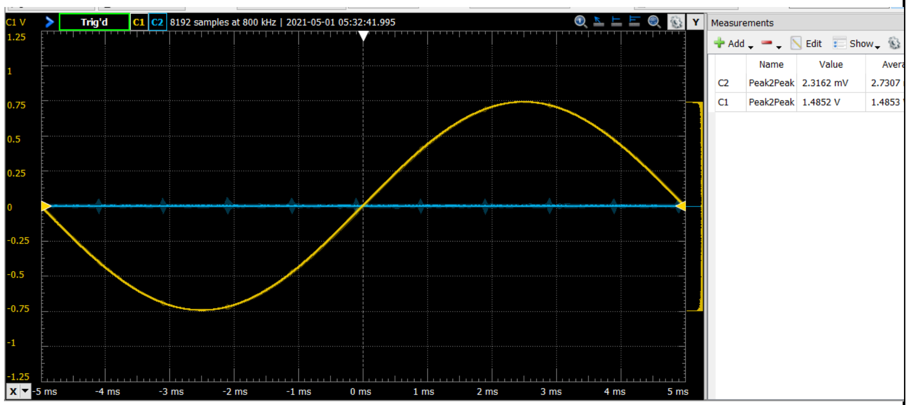
Rf = 0Ω Ri = 33kΩ	 Measured Vout peak to peak: 2.73 mV Measured Vin peak to peak: 1.4853 V	0.001

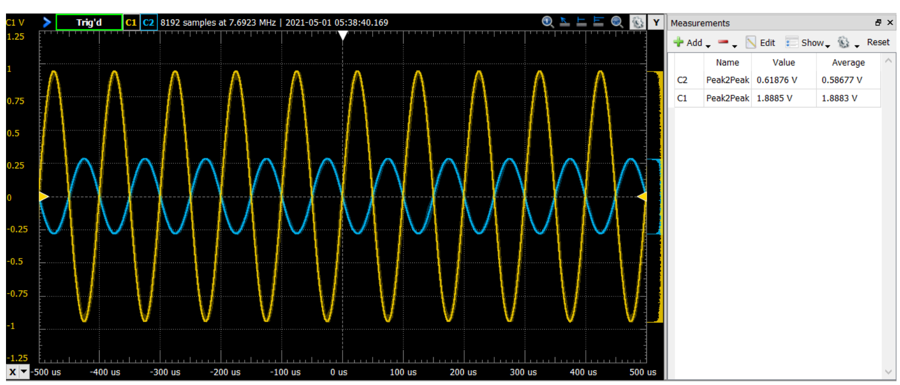
Table 5: Testing procedure and data on Bass EQ

Bass EQ result evaluation:
At maximum gain, expected magnitude of gain: $10k/33k = 0.303$
Actual magnitude of gain: 0.31

$$\%Error = |0.31 - 0.303| / 0.303 * 100\% = 2.31\%$$

At maximum gain, expected magnitude of gain: $0/33k = 0$
Actual magnitude of gain: 0.001
Since we cannot divide by 0, %Error cannot be calculated but the results can be seen as reasonably close to the desired value.

High Pass filter: (Passing 3200 Hz frequency signals or above):

Rf and Ri Value	Output voltage (signal coming out from inverting amplifier) vs Input voltage (signal coming out from filters)	Magnitude Of Gain
Rf = 10kΩ Ri = 33kΩ	 Measured Vout peak to peak: 0.5868 V Measured Vin peak to peak: 1.8883 V	0.311

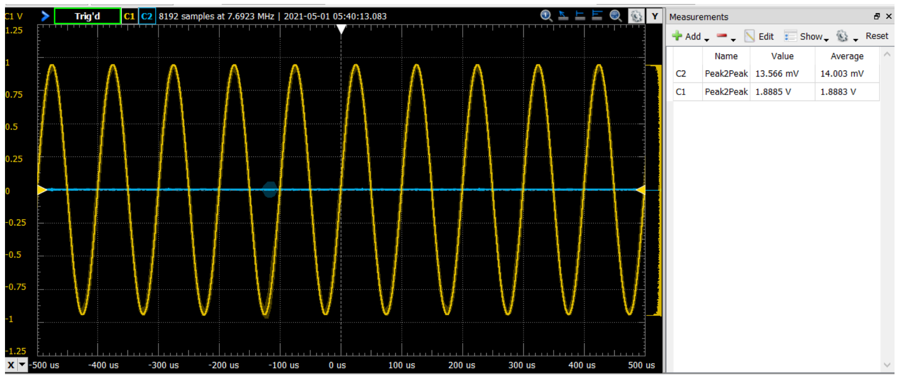
Rf = 0Ω Ri = 33kΩ	 Measured Vout peak to peak: 14.003 mV Measured Vin peak to peak: 1.8883 V	0.0074

Table 6: Testing procedure and data on Treble EQ

Treble EQ result evaluation:

At maximum gain, expected magnitude of gain: $10k/33k = 0.303$

Actual magnitude of gain: 0.311

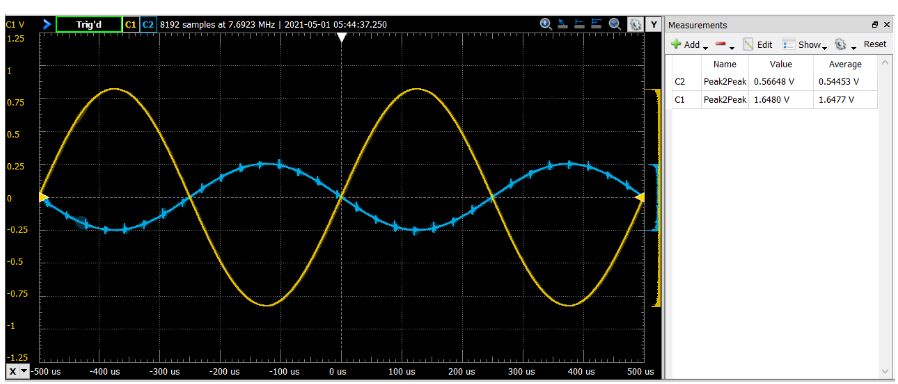
$$\%Error = |0.311 - 0.303| / 0.303 * 100\% = 2.64\%$$

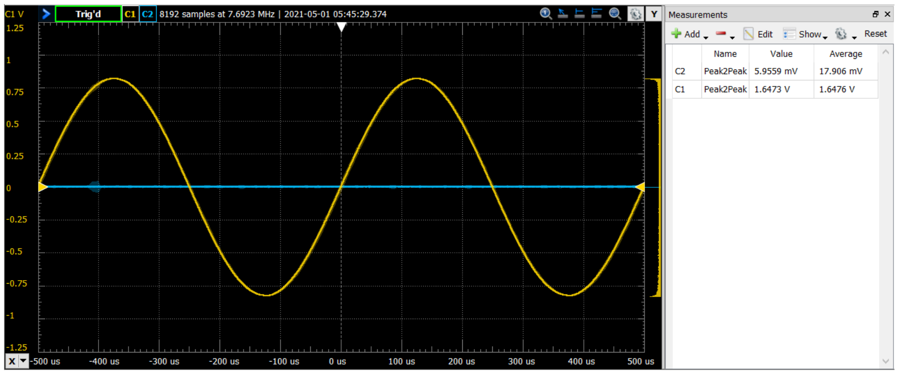
At maximum gain, expected magnitude of gain: $0/33k = 0$

Actual magnitude of gain: 0.0074

Since we cannot divide by 0, %Error cannot be calculated but the results can be seen as reasonably close to the desired value.

Band Pass filter: (Passing between 320Hz to 3200Hz frequency signals):

Rf and Ri Value	Output voltage (signal coming out from inverting amplifier) vs Input voltage (signal coming out from filters)	Magnitude Of Gain
Rf = 10kΩ Ri = 33kΩ	 Measured Vout peak to peak: 0.5445 V	0.33

<table>
<tr><td></td><td>Measured Vin peak to peak: 1.6477 V</td><td></td></tr>
<tr><td>Rf = 0Ω
Ri = 33kΩ</td><td>

Measured Vout peak to peak: 17.906 mV
Measured Vin peak to peak: 1.6476 V</td><td>0.0109</td></tr>
</table>

Table 7: Testing procedure and data on Mid EQ

Mid EQ result evaluation:
At maximum gain, expected magnitude of gain: $10k/33k = 0.303$
Actual magnitude of gain: 0.311

$$\%Error = |0.33 - 0.303| / 0.303 * 100\% = 8.91\%$$

At maximum gain, expected magnitude of gain: $0/33k = 0$
Actual magnitude of gain: 0.0074
Since we cannot divide by 0, %Error cannot be calculated but the results can be seen as reasonably close to the desired value.

Finally, testing will be performed on the summing amplifier in order to confirm that it is indeed summing up the signals together. Each of the signals from the individual filters will be measured. Then the final summed up signal will be measured to evaluate whether or not it is a correct representation of the sum of the signals. The gain through the final amplifier will also be taken into consideration given that there is a potentiometer put in place, the potentiometer will be adjusted to 10kΩ in order to see the full gain. The measurements below assume that all "knobs"-potentiometers are adjusted to 10kΩ.

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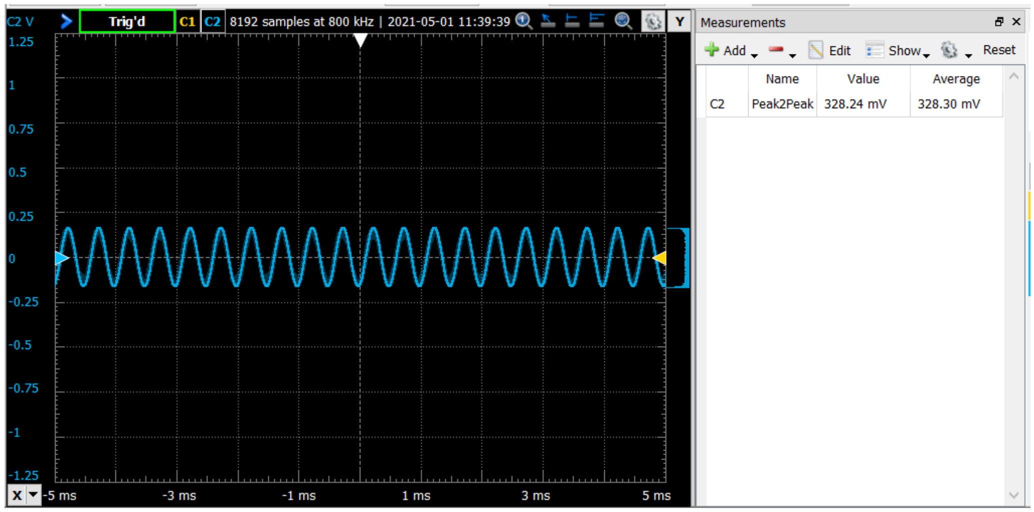
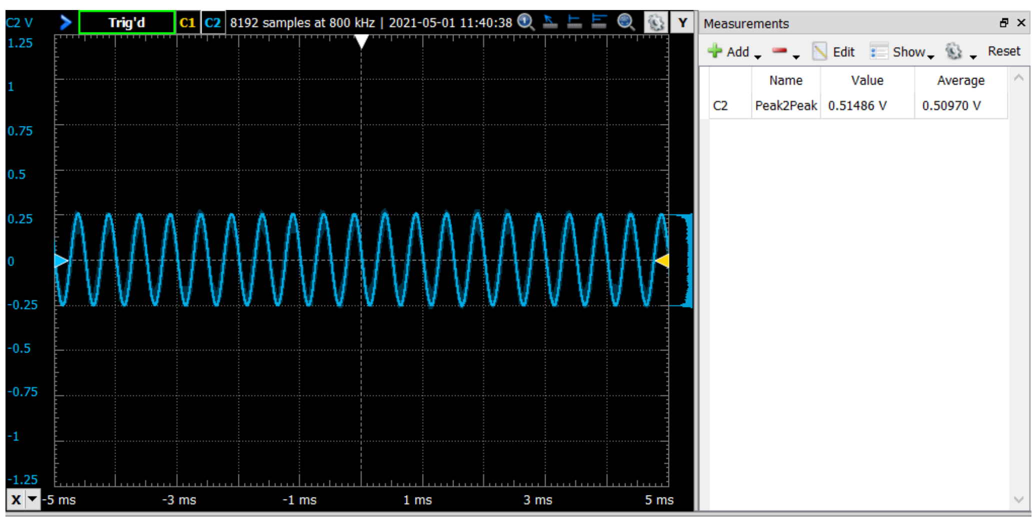
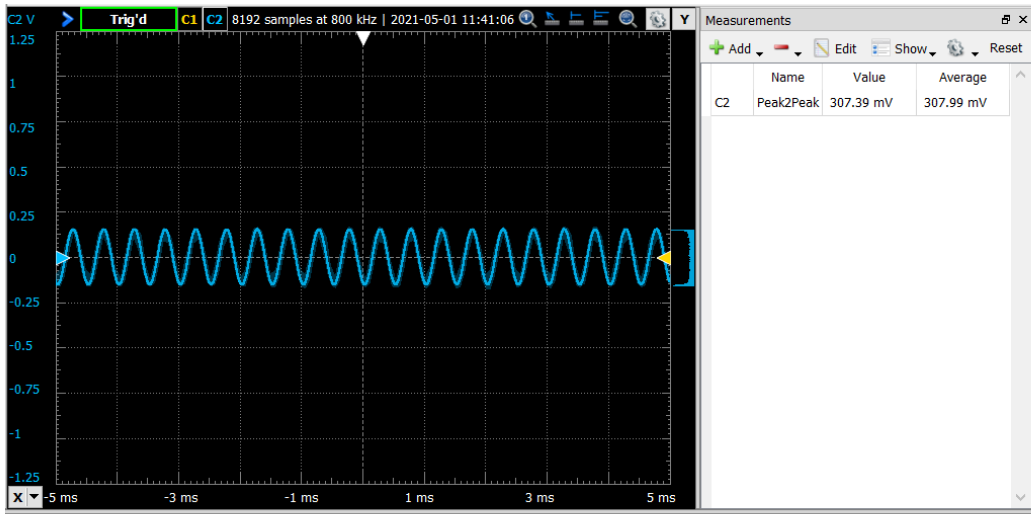
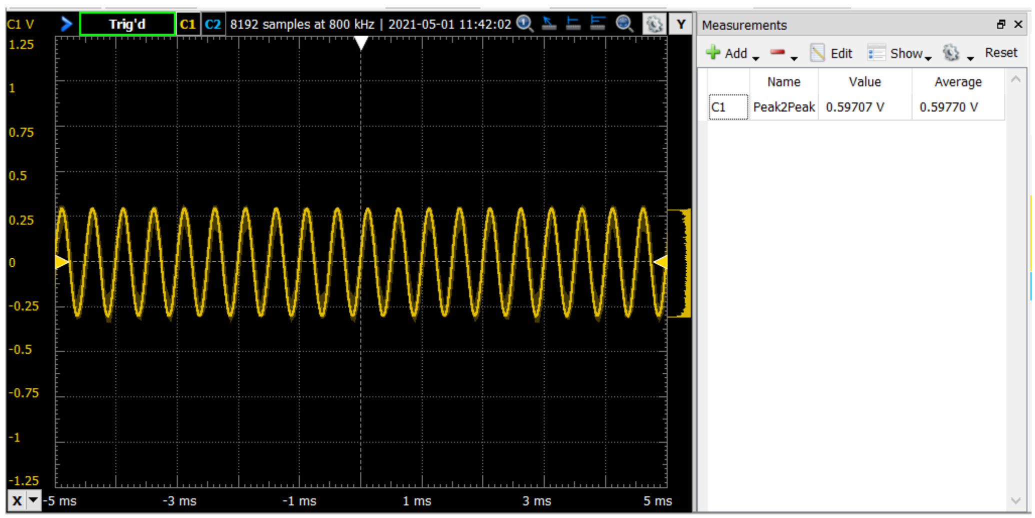
Experiment 14

<table>
<tr>
<td>Signal 1:
Bass filter</td>
<td>


Measured Vpeak to peak: 328.24 mV
</td>
</tr>
<tr>
<td>Signal 2:
Mid filter</td>
<td>


Measured Vpeak to peak: 0.50970 V
</td>
</tr>
</table>

<table>
<tr><td>Signal 3:
Treble filter</td><td>

Measured Vpeak to peak: 326.12 mV</td></tr>
<tr><td>Signal 4:
Vamp- Sum of signals w/
Rf = 10kΩ
Ri = 11kΩ</td><td>

Measured Vpeak to peak: 0.5977 V</td></tr>
</table>

Table 8: Testing procedure and data on summing amplifier

Summing amplifier result evaluation:
The expected peak to peak amplitude at VAMP can be written as the magnitude of the sum of the first three signals:

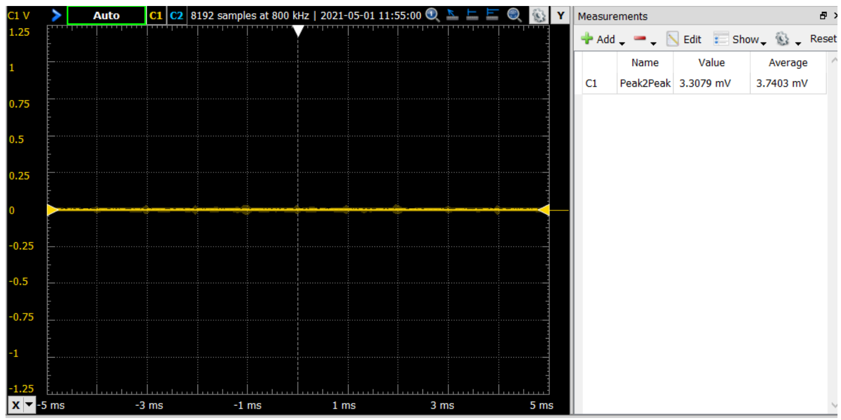
$$\sqrt{(0.32824^2 + 0.50970^2 + 0.32612^2} = 0.688\,V$$

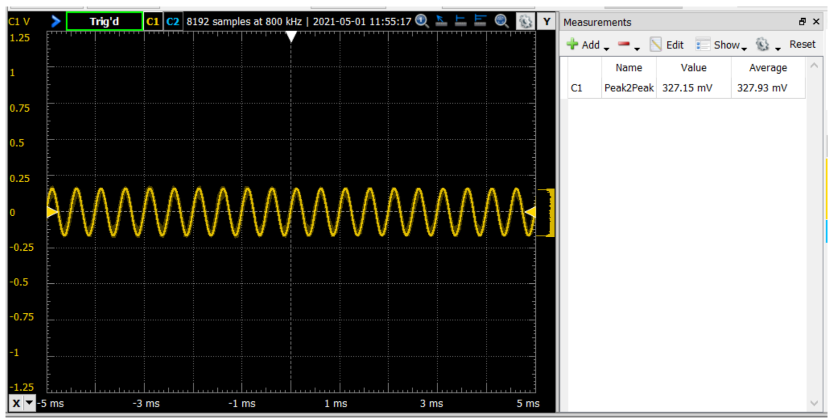
The gain of the signal will be Rf/Ri which is (10kΩ/11kΩ)*0.688V =0.625 V

$$\%Error = |0.5977 - 0.625|\,/\,0.625 * 100\% = 4.368\%$$

The volume control is tested with the previous VAMP signal with a peak to peak of 0.5977 V The knob at the summing amplifier will be adjusted and the resulting signal will be observed and evaluated to see whether or not the volume control works properly. Note that the only adjustment made between the following three graphs is the adjustment of the potentiometer (knob) at the summing amplifier.

<table>
<tr><td>Knob-potentiometer -adjustment

0Ω</td><td>
</td></tr>
<tr><td>Knob-potentiometer -adjustment

Halfway- approx 5kΩ</td><td>
</td></tr>
<tr><td>Knob-potentiometer -adjustment

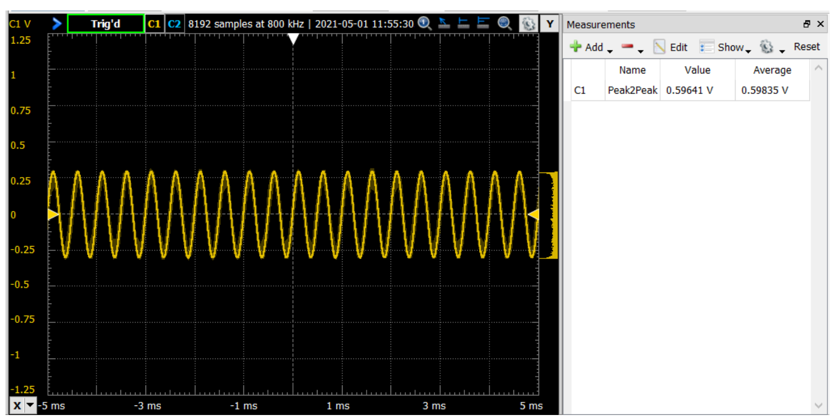
fullway- approx 10kΩ</td><td>
</td></tr>
</table>

Table 9: Testing procedure and data on volume control

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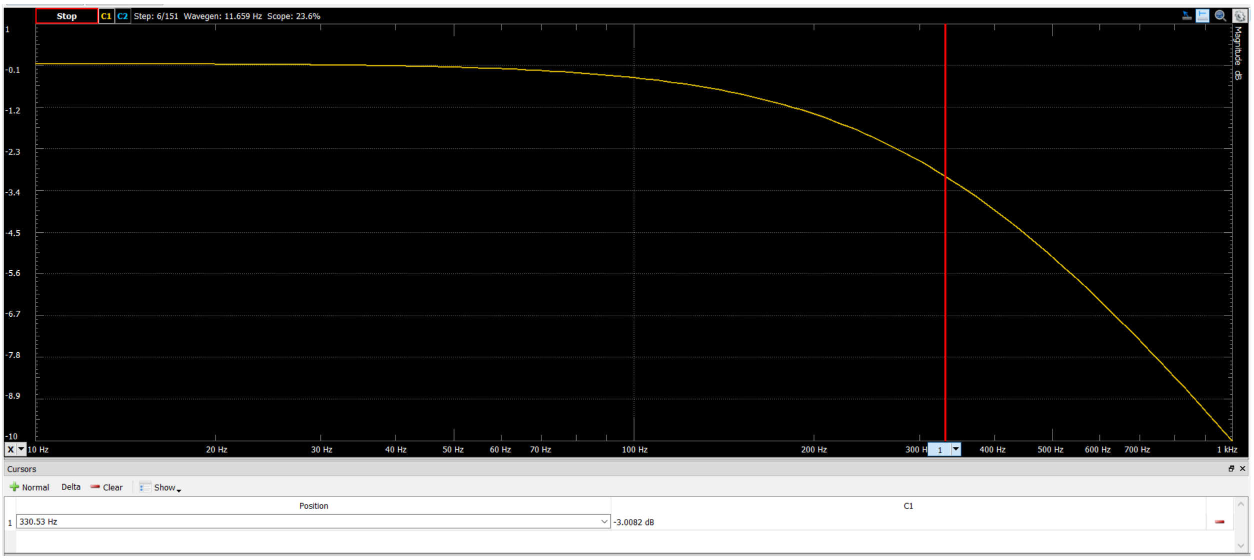
Experiment 14

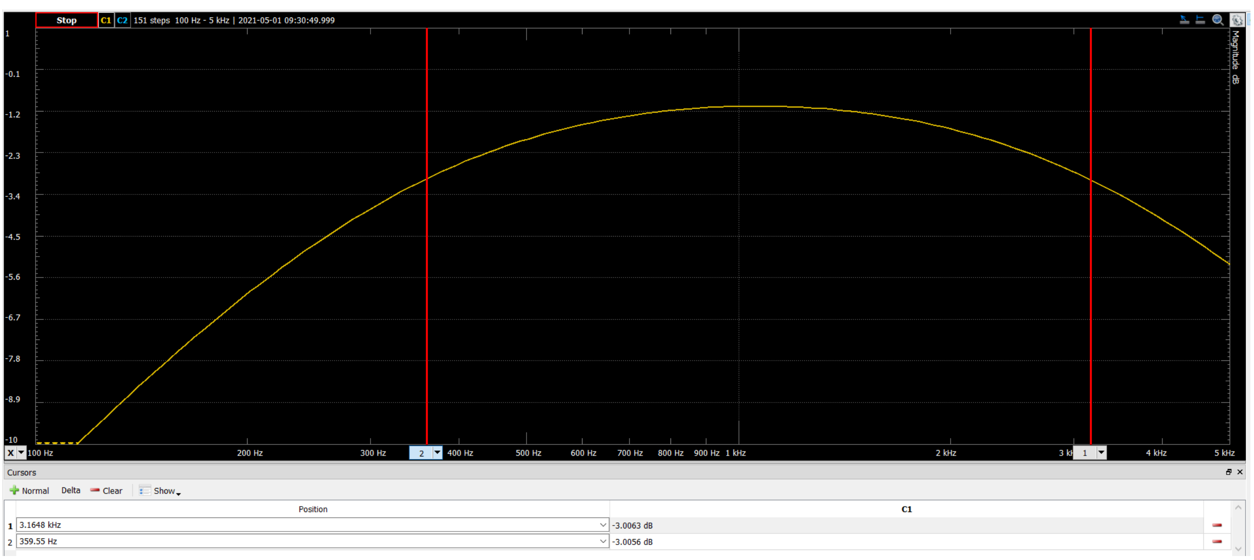
Results

FILTERS

The frequency response was measured and graphed for each filter. The cutoff frequency which is found at -3dB was measured using cursors and will be further evaluated.



Plot 1: Low pass frequency Response



Plot 2: Band pass frequency response

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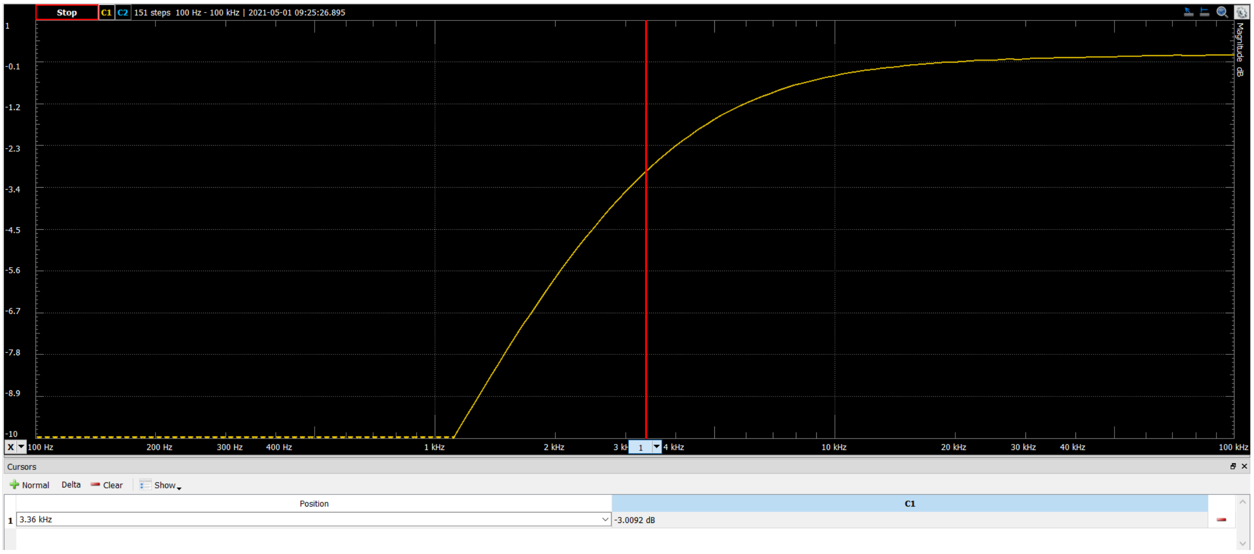
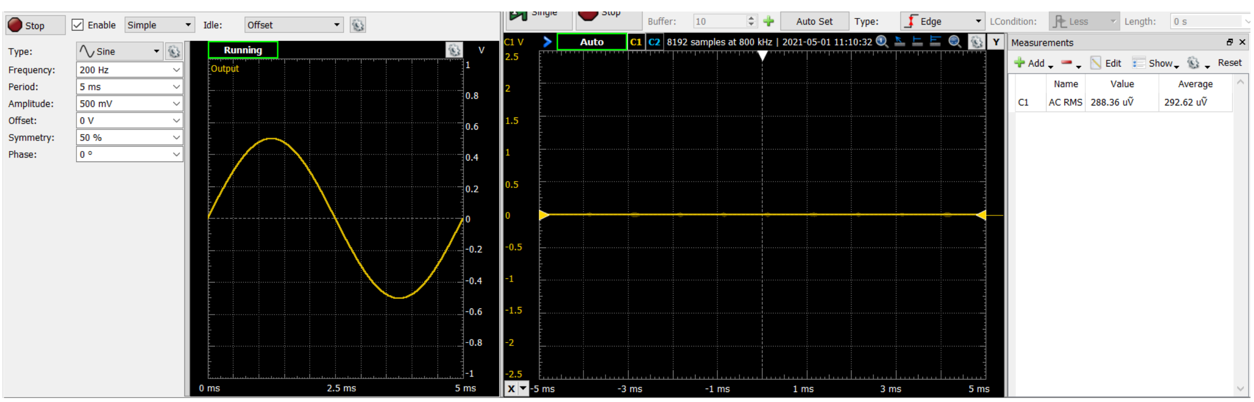
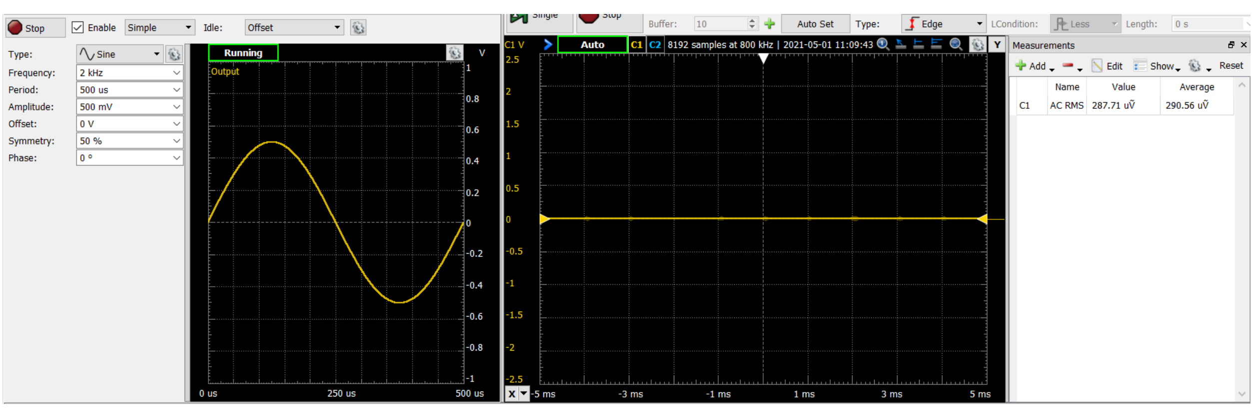


Plot 3: High pass frequency response

VAMP



Plot 4: VAMP with all EQ set to minimum @ 200 Hz



Plot 5: VAMP with all EQ set to minimum @ 2k Hz

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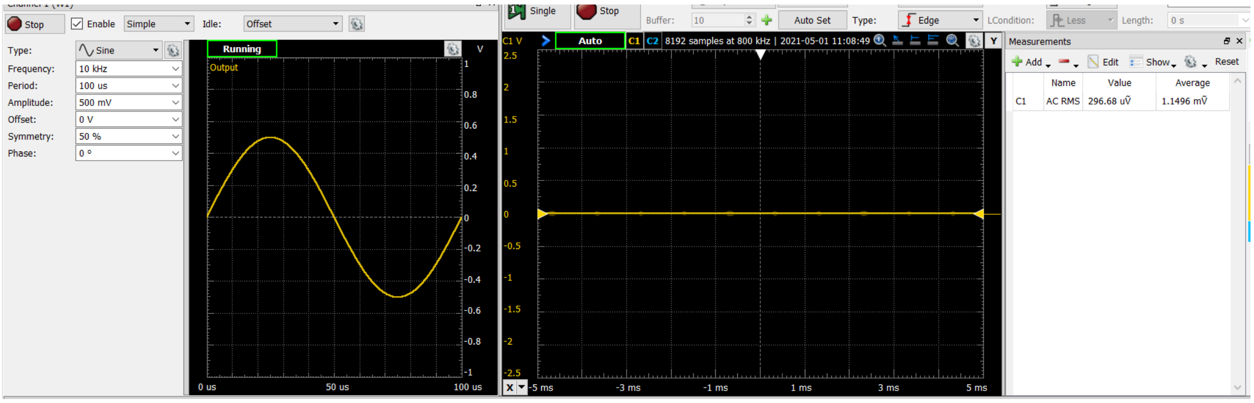
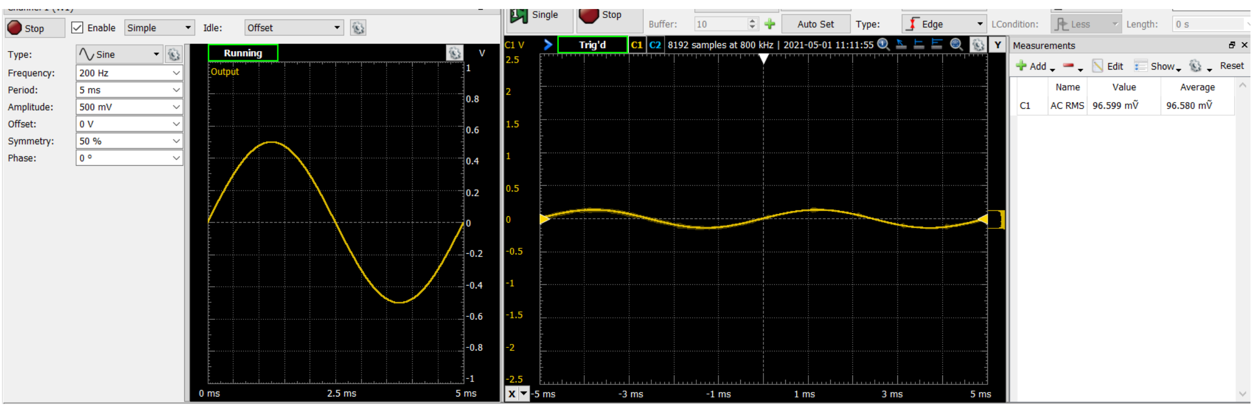
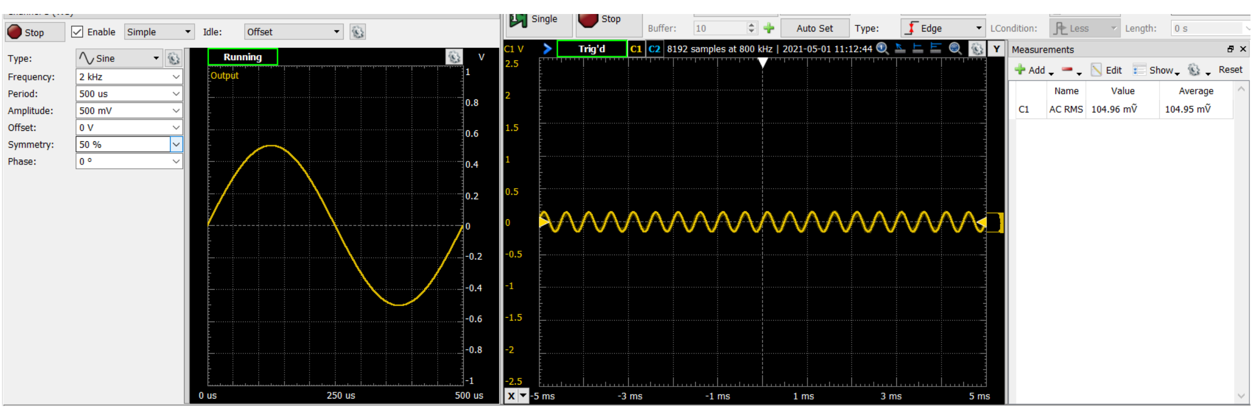


Plot 6: VAMP with all EQ set to minimum @ 10k Hz



Plot 7: VAMP with all EQ set to maximum @ 200 Hz



Plot 8: VAMP with all EQ set to maximum @ 2k Hz

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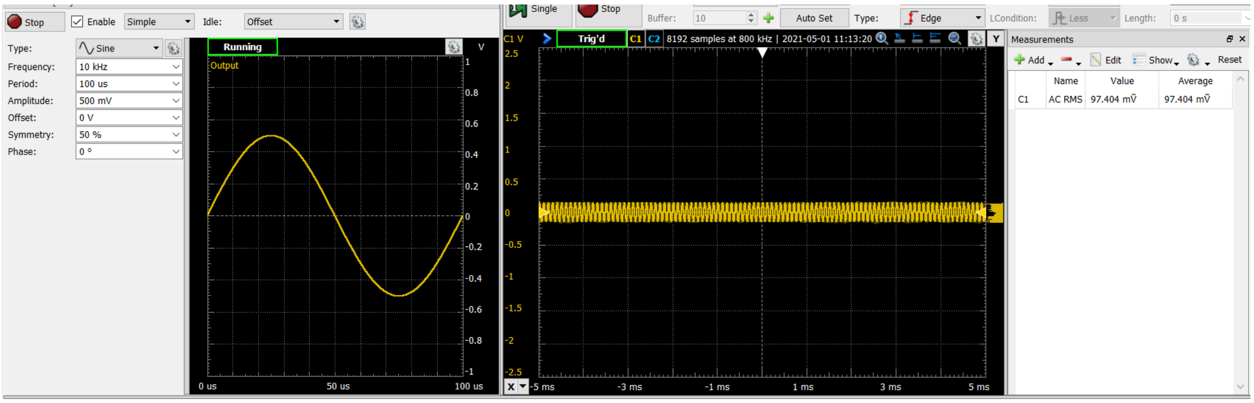
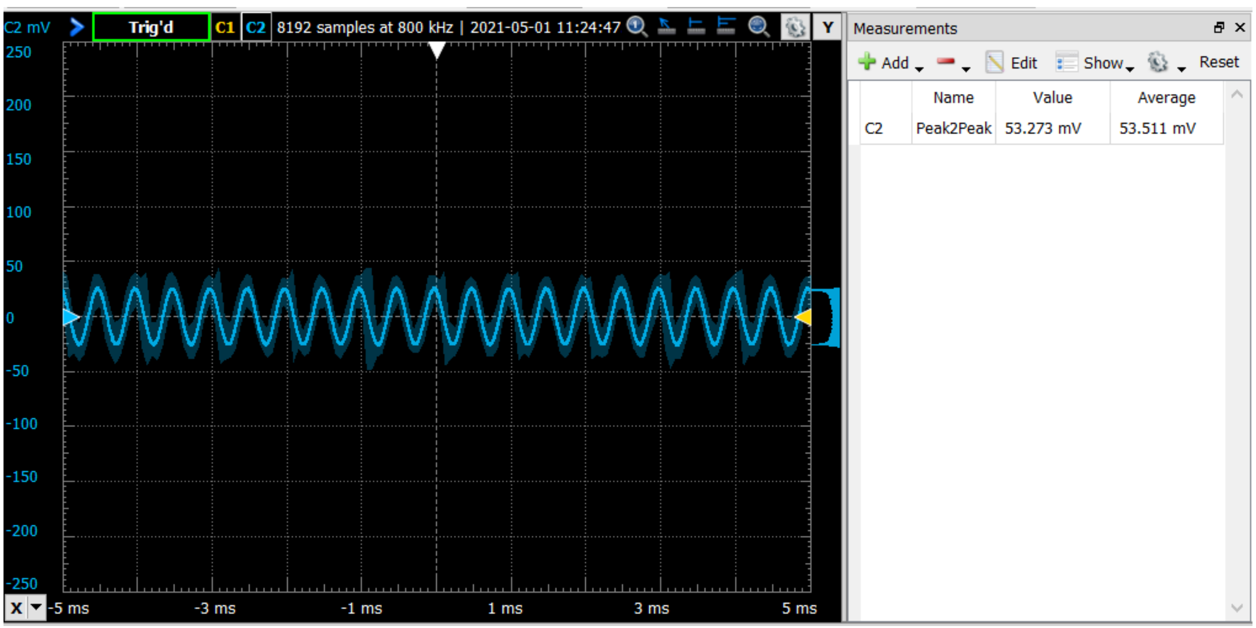


Plot 9: VAMP with all EQ set to maximum @ 10k Hz

ADDER FUNCTIONALITY



Plot 10: Signal 1 from bass filter w/ Vin as 1 volt peak to peak w/ 2kHz frequency

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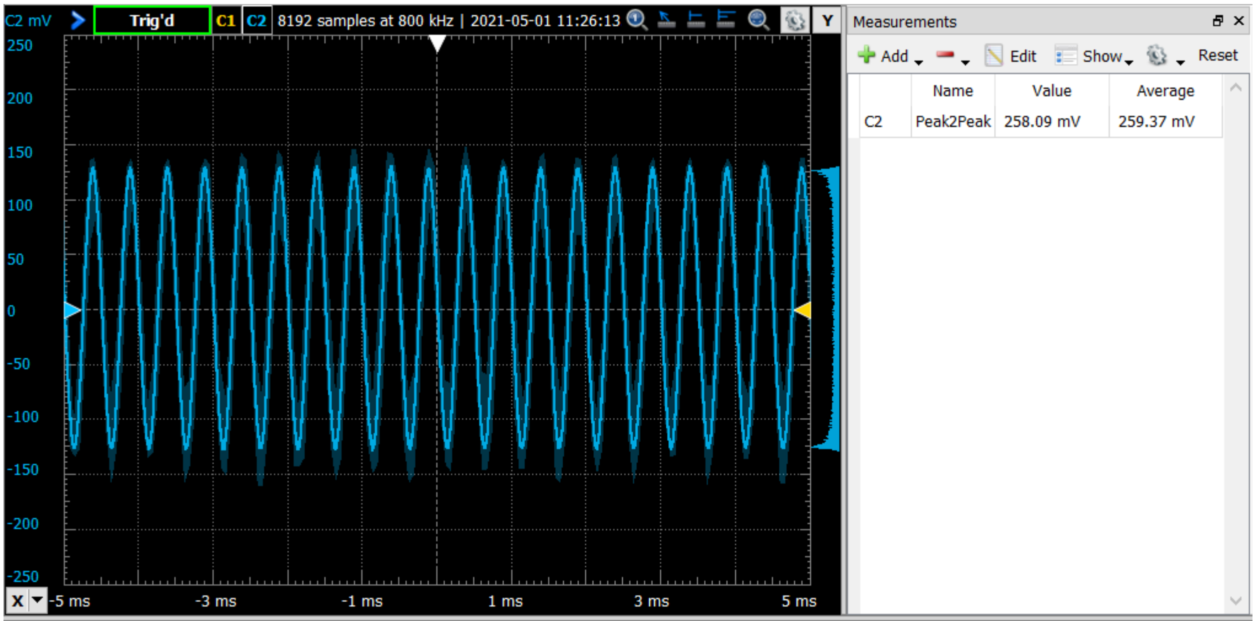
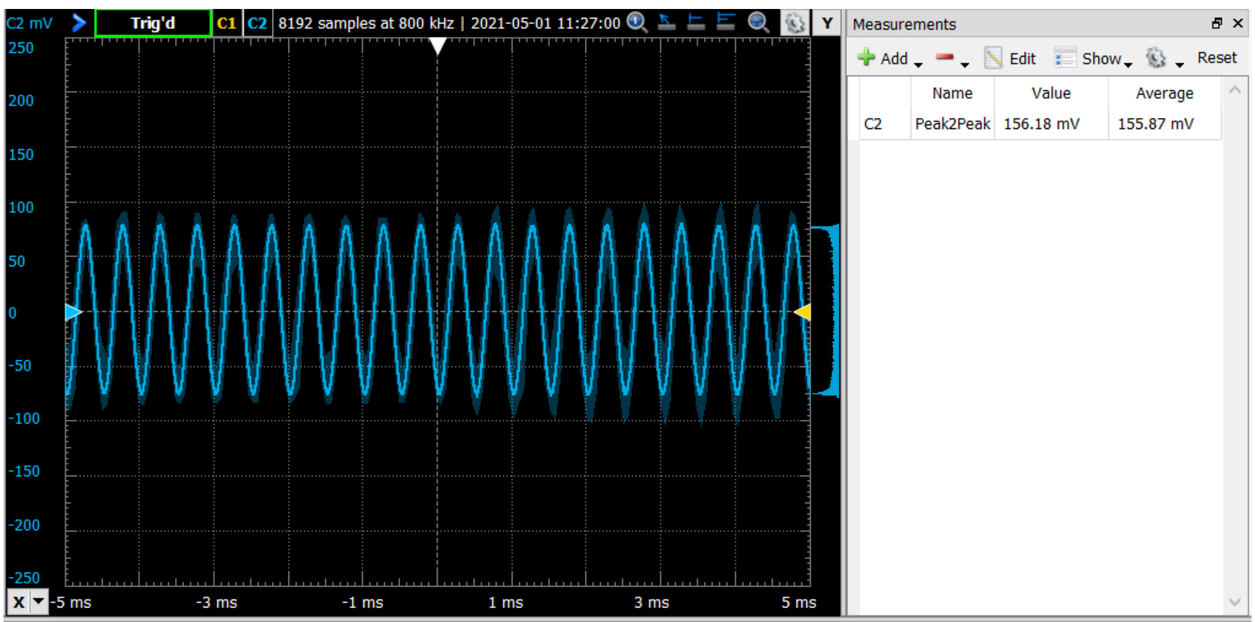
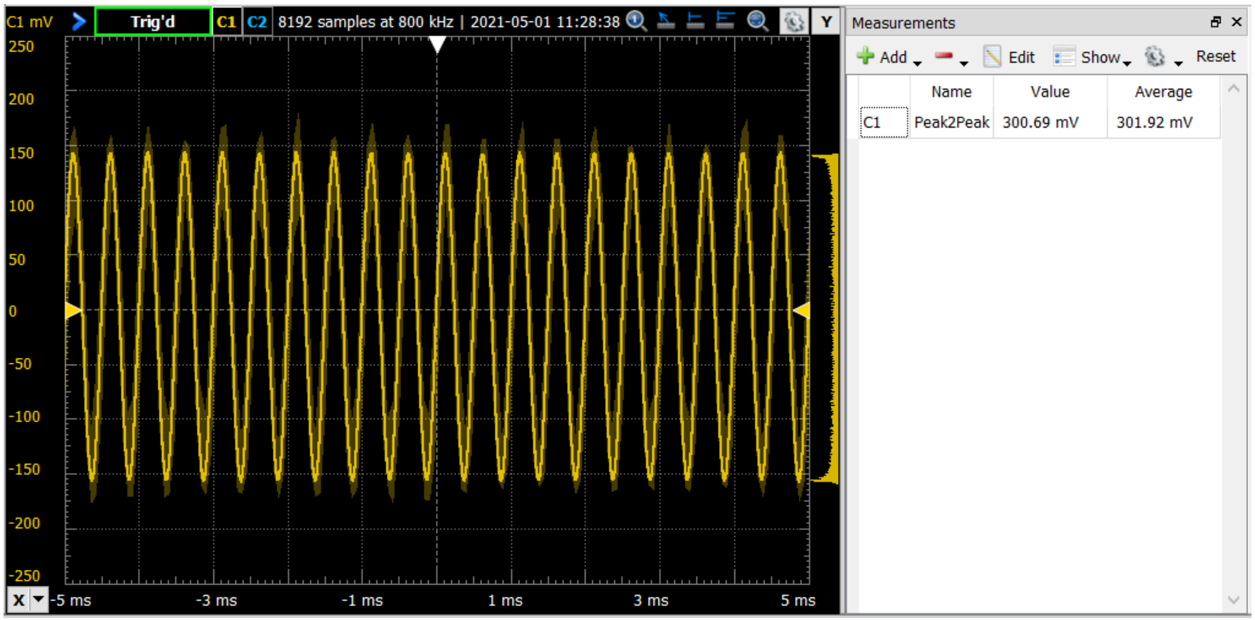


Plot 11: Signal 2 from mid filter w/ Vin as 1 volt peak to peak w/ 2kHz frequency

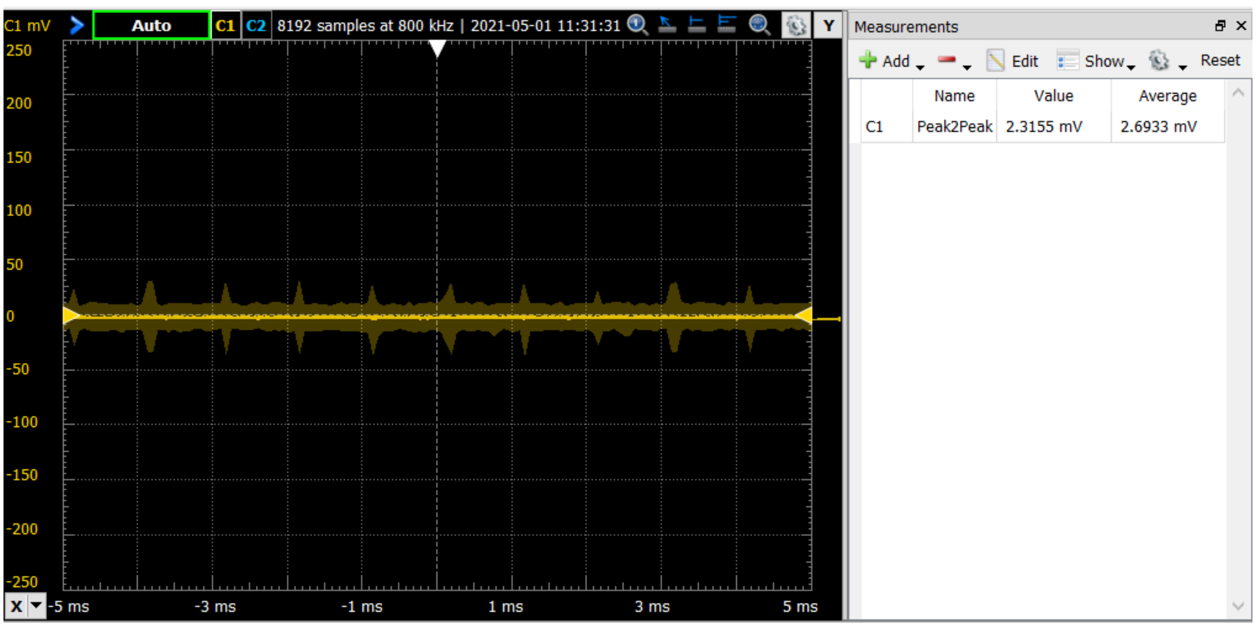


Plot 12: Signal 3 from treble filter w/ Vin as 1 volt peak to peak w/ 2kHz frequency

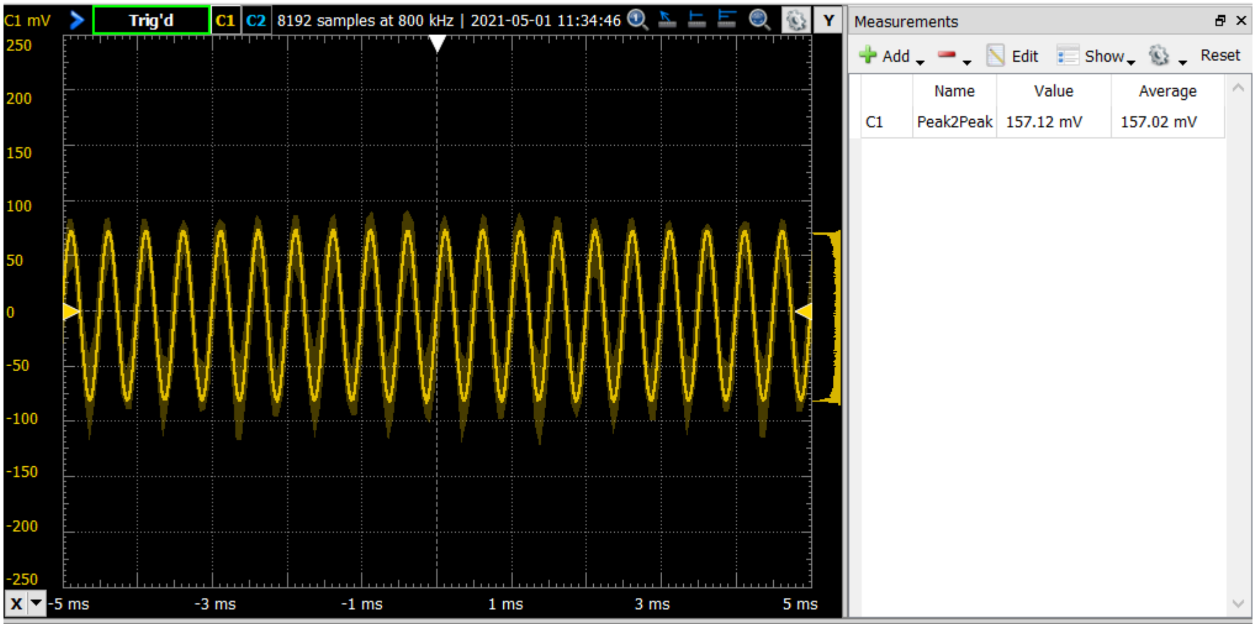


Plot 13: VAMP Signal 4 from Vamp w/ Vin as 1 volt peak to peak w/ 2kHz frequency

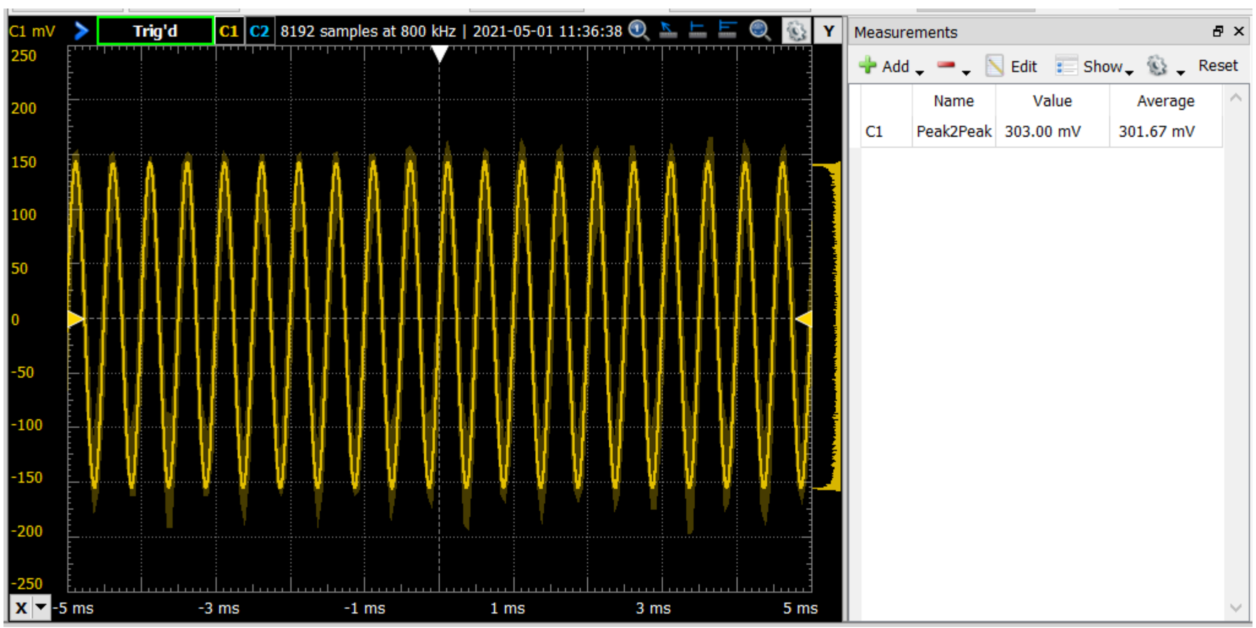
VOLUME CONTROL



Plot 14: VAMP w/ Vin as 1 volt peak to peak w/ 2kHz frequency w/ knob at 0 ohms

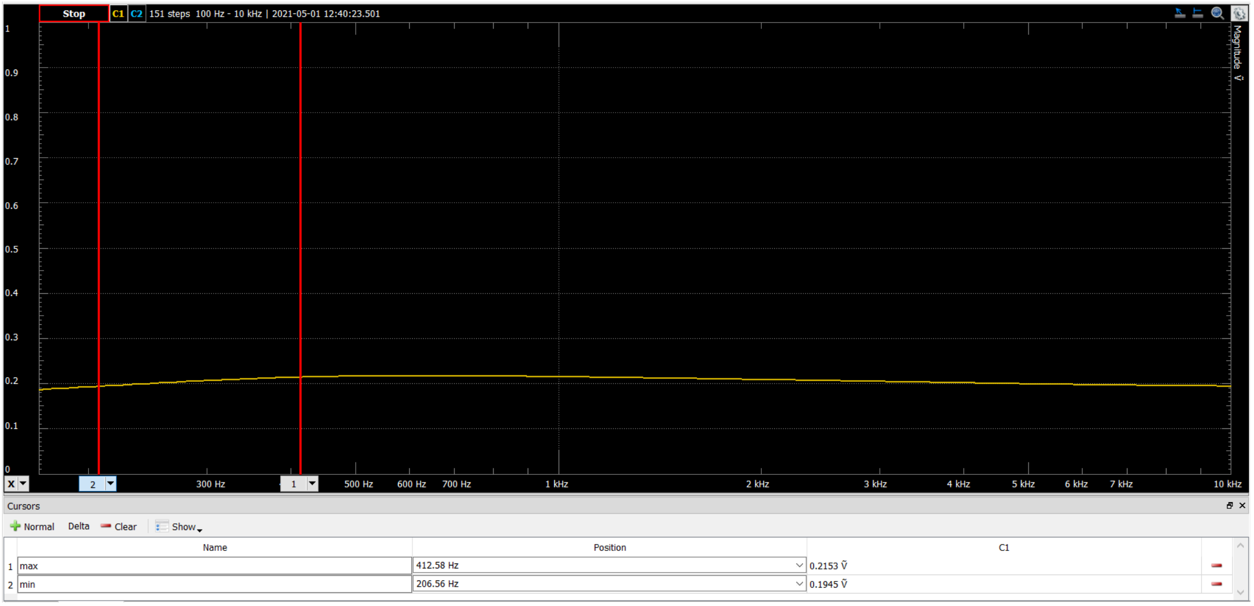


Plot 15: VAMP w/ Vin as 1 volt peak to peak w/ 2kHz frequency w/ knob approx halfway



Plot 16: VAMP w/ Vin as 1 volt peak to peak w/ 2kHz frequency w/ knob at 10k ohms

VAMP RIPPLE



Plot 17: VAMP frequency response- ripple plot

FINAL RESULTS SUMMARIZED

Specification	Required	Measured	Error	Reference
Bass filter -3dB cut-off frequency	320Hz ± 10%	330.53 Hz	3.29%	Plot 1
Mid filter -3dB cut-off frequency (low)	320Hz ± 10%	359.55 Hz	12.36%	Plot 2
Mid filter -3dB cut-off frequency (high)	3.2kHz ± 10%	3.1648k Hz	1.1%	Plot 2
Treble filter -3dB cut-off frequency	3.2kHz ± 10%	3.36k Hz	5%	Plot 3
Vamp w/ all EQ set to MIN @ 200 Hz	< 15 mVRMS	292.6 uVRMS	N/A	Plot 4
Vamp w/ all EQ set to MIN @ 2k Hz	< 15 mVRMS	290.56 uVRMS	N/A	Plot 5

Vamp w/ all EQ set to MIN @ 10k Hz	**< 15 mVRMS**	**1.1496 mVRMS**	**N/A**	**Plot 6**
Vamp w/ all EQ set to MAX @ 200 Hz	**100 mVRMS ± 10%**	**96.58 mV RMS**	**3.42 %**	**Plot 7**
Vamp w/ all EQ set to MAX @ 2k Hz	**100 mVRMS ± 10%**	**104.96 mV RMS**	**4.96%**	**Plot 8**
Vamp w/ all EQ set to MAX @ 2k Hz	**100 mVRMS ± 10%**	**97.404 mV RMS**	**2.6 %**	**Plot 9**
Vamp ripple over freq. band	**< 15 mVRMS**	**20.8 mVRMS**	**N/A**	**Plot 17**

Table 10: Summary of final results

***Not within specs**

Elaboration on additional results

Adder functionality:

Signal 1 Peak to peak (Plot 10): 53.511 mV
Signal 2 Peak to peak (Plot 11): 259.37 mV
Signal 3 Peak to peak (Plot 12): 155.87 mV
VAMP peak to peak (Plot 13): 301.92 mV

Sum of signals $= \sqrt{(53.511\ mV)^2 + (259.37\ mV)^2 + (155.87\ mV)^2} = 307.29\ mV$
$\%Error = |307.29 - 301.92|/307.29 * 100\% = 1.747\%$

Volume control:
Illustration can be found in plots 14, 15 and 16.

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Experiment 14

Conclusion

To summarize, the main focus of the lab was to construct an audio equalizer which allows the user to select certain frequencies to amplify or reduce given an input signal. Although in real life there may be several more different frequencies to isolate, the lab had three main frequencies to isolate namely bass, mid and treble frequencies. The bass frequency was defined as signals below 320 Hz, the mid frequency was defined as signals between 320 Hz and 3.2k Hz and finally the treble frequency was defined as signals above 3.2k Hz. After passing the signals through the filters, each signal of the specified frequency will be passed through an inverting amplifier with controllable gain. The main use of the inverting amplifier is to allow controllable gain through its feedback resistor where a potentiometer is placed. Because the gain is controllable through the feedback resistor, we can amplify or reduce each signal as we would like. Finally, the signals are all summed up into a summing amplifier which is an inverting amplifier with several signals coming in as input. Similarly to the previous inverting amplifiers, the summing amplifier has a potentiometer as its feedback resistor in order to control the final volume of the signal (Vamp). The most important and essential part of the design process in my opinion was the calculations of each value. When calculating values, I aimed for convenience and I kept in mind the number of pieces of each component that were provided to me from the lab kit. I found it useful to combine similar components together to achieve values that were desired such as putting two capacitors in series or resistors in series/parallel. One thing I would do differently next time is that I would plan and layout the circuit ahead of time in order to avoid messiness on the breadboard. I found that resistors or circuit components placed too close together may cause problems such as short circuits if they are in contact too much. Additionally two of the specifications were not met namely the mid filter cutoff frequency and the Vamp ripple effect. The slight off target values could be attributed to estimations and roundings in the calculations as well as minor imperfect resistances within the circuit. I believe that next time I could perform more accurate calculations as possible to avoid getting off the desired value. Overall, I would consider the experiment successful as I learned a lot from the experience which is what matters at the end.