EE1202
Introduction to Electrical Engineering II

Laboratory 5: Signal Processing with Operational Amplifiers

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Date: April 11, 2023

Abstract

This laboratory exercise aims to observe an operational amplifier's signal-processing ability through an oscilloscope. A 1k and two 2k resistors, a LM741 op-amp chip, BNC connectors and alligator clips, and jumper wires are used to create the inverting and summing operational amplifier configurations. DC power supplies and function generators provided the inputs to the circuit. In addition, the experiment consists of building an active high-pass filter using two inverted voltage inputs. As the experimental output voltages were relatively accurate since they were proximate to the calculated values, the outcomes of this laboratory exercise demonstrated that the output of a summing amplifier is equal to the sum of the two input voltages and is inverted.

Introduction

An operational amplifier, commonly known as an op-amp, is an electronic voltage signal amplifier composed of more than twenty transistors and eleven resistors that process analog signals. The component works through direct coupling, an electrical arrangement that allows alternating and direct current signals to pass through an amplified circuit [2]. It features a differential input, which carries the same signal in two wires but with different polarities, and a single-ended output [5]. Currents into both input terminals are equal to zero, and the voltage across the input terminals is also equal to zero. The ideal characteristics of an op-amp include an infinite open-loop gain, an infinite input resistance, and a zero-output resistance. The idea of negative feedback is significant to the understanding of operational amplifiers. The negative feedback is due to the output terminal being fed back into the inverting terminal of the op-amp, which means that the signal is 180 degrees out of phase with the original input signal [3]. This process allows for a stable circuit and reduces the fluctuations in the output.

As integrated circuits, operational amplifiers perform addition, subtraction, multiplication, and division. The integrated circuit of the operational amplifier has eight pins with five terminals: inverting input, non-inverting input, an output, and two rails to supply the voltage. The components are used in audio, medical equipment, and control systems. For example, operational amplifiers can be used in audio equipment to amplify and process audio signals. In medical equipment, operational amplifiers can be used in electrocardiogram (ECG) machines to amplify the tiny electrical signals produced by the heart and to filter out interference.

This lab provides a guide to understanding how an operational amplifier operates. In this lab, three configurations of operational amplifiers (an inverting amplifier, a summing amplifier, and a high-pass filter) will be discussed and tested by providing identical input voltages at different frequencies with altered resistances. In addition to the LM741 operational amplifier integrated circuit, other components, including resistors, capacitors, an oscilloscope, an AC signal generator, and a DC power supply, will be used to build the circuits, power the chip, and measure the signals. By the end of this laboratory exercise, we will identify the relationship between inverting and summing amplifiers and the operation of a high-pass filter.

Procedure

Within this lab, a total of five operational amplifier circuits will be used to measure voltage values to find the relationship/characteristics of the circuits. We will be creating two inverting amplifiers, two summing amplifiers, and an active high-pass band filter.

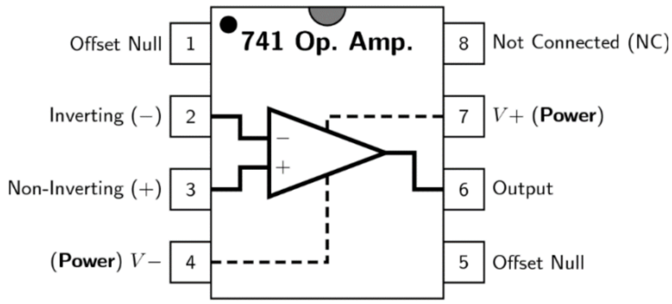

Figure 1. Pin-out information of the op-amp. [1]

As per Figure 1, pins 4 and 7 will be used to supply power to the circuits. To supply the operational amplifier with positive ten volts and negative ten volts, we connect the two pairs of leads from the DC power supply to the multimeter using alligator clips. We manually set the voltage to +10v and -10v on the DC power supply. Next, we connect the +10-volt wire to pin 7 on the operational amplifier integrated circuit and -10v to pin 4. After building the circuit, we use BNC connectors to connect the oscilloscope to the input and output components of each circuit to measure the v_{in} and v_{out} values.

I. Inverting Amplifiers

Figure 2 and Figure 3 are schematics for setting up the inverting amplifiers. They are characterized by a feedback resistor that connects the output back to the inverting input terminal, which creates negative feedback. Hence, the output voltage of an inverting amplifier is defined by the changes in the opposite direction of the input voltage.

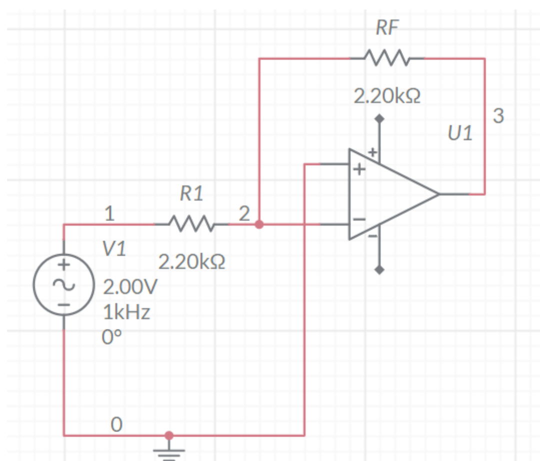

Figure 2. Schematic of inverting operational amplifier circuit with voltage input of 2 volts at 1k Hz, input resistance of 2.2k Ω, and feedback resistance of 2.2k Ω.

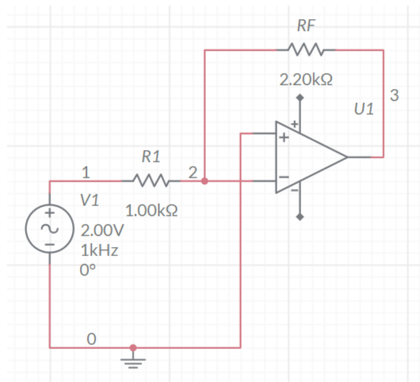

Figure 3. Schematic of inverting operational amplifier with voltage input of 2 volts at 1k Hz, input resistance of 1k *Ω*, and feedback resistance of 2.2k *Ω*.

To find the calculated value of $v_{out\text{-}pp}$ for the inverting amplifier, the following equation is used:

$$V_{out\text{-}pp} = \frac{-R_f}{R_i}(V_{in})$$

II. Summing Amplifier

The summing circuit combines the multiple input voltage into a single voltage output, as shown in Figures 4 and 5. R_f refers to the feedback resistor, which controls the output, thus creating a stable circuit through a negative feedback loop. The voltage output of the summing operational amplifier circuit is calculated through the following equation:

$$v_o = -R_f\left(\frac{v_1}{R_1} + \frac{v_2}{R_2} + \frac{v_3}{R_3} + \ldots + \frac{v_N}{R_N}\right)$$

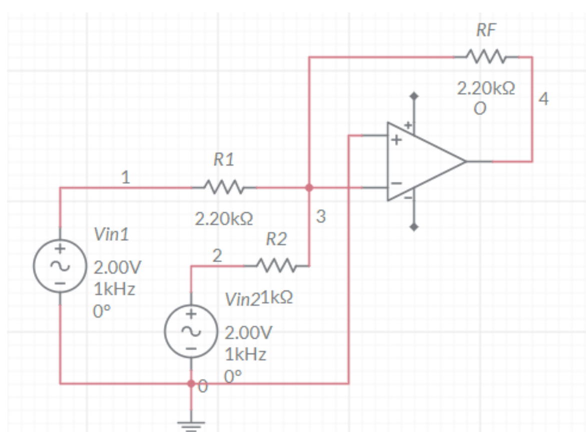

Figure 4. Schematic of summing operational amplifier with voltage inputs of 2 volts at 1k Hz.

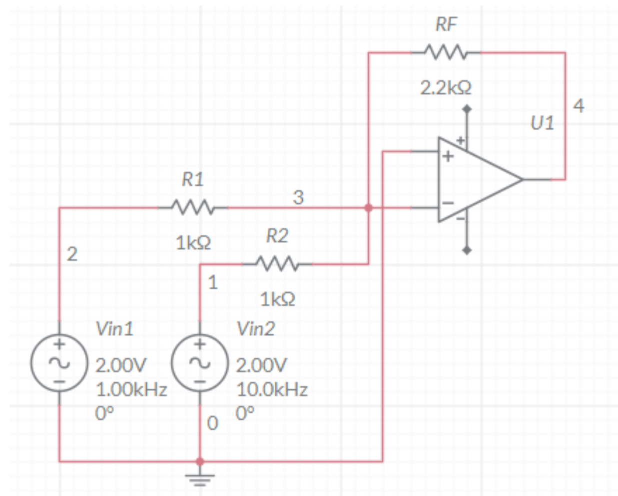

Figure 5. Schematic of summing operational amplifier with voltage inputs of 2 volts at 1k Hz and 10kHz.

III. High-Pass Filter

Figure 6 depicts a high-pass filter circuit, which lets higher frequencies through while attenuating lower frequencies. Through lower feedback impedance and higher input impedance that attenuate lower frequencies, there is little to no effect on frequencies that pass the cutoff frequency. In this lab, we will supply the power and voltage to the high-pass filter by connecting the high-pass filter circuit to the previous summing amplifier circuit.

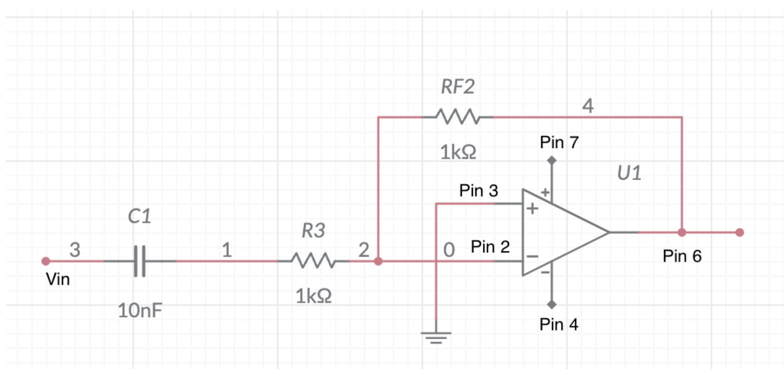

Figure 6. Schematic of High-Pass Filter with the pins labeled, which is connected to the summing amplifier.

The cutoff frequency, in Hertz, of the high pass filter is calculated by the following equation:

$$f_c = \frac{1}{2\pi R_i C_i}$$

Using the impedance values of the input branches and the feedback components, the gain of the high-pass filter (in decibels) can be obtained through the following equation:

$$|G| = \left|\frac{Z_f}{Z_i}\right| = 20log10\left[\frac{\frac{f}{f_c}}{\sqrt{1+\left(\frac{f}{f_c}\right)^2}}\right]$$

If the inputs of the summing amplifier are both at $2v_{pp}$ at 15k Hz the magnitude of v_{out} from the filter should be $|V_{out}| = V_{in}|G|$.

Results

I. Inverting Amplifiers

The output voltage for the circuit in Figure 2 with an input resistance of 2.2k Ω and a feedback resistance of 2.2k Ω was calculated as $V_{out\text{-}pp} = \frac{-R_f}{R_i}(V_{in}) = -2v$. Using the oscilloscope, the v_{in} and v_{out} values were determined as $V_{in\text{-}pp}$ = 2.03v and $V_{out\text{-}pp}$ = 2.01v.

The output volage for the circuit in Figure 3 with an input resistance of 1k Ω and a feedback resistance of 2.2k Ω was calculated as $V_{out\text{-}pp} = \frac{-R_f}{R_i}(V_{in}) = -4.4v$. Using the oscilloscope, the v_{in} and v_{out} values are as follows: $V_{in\text{-}pp}$ = 1.99v and $V_{out\text{-}pp}$ = 4.24v.

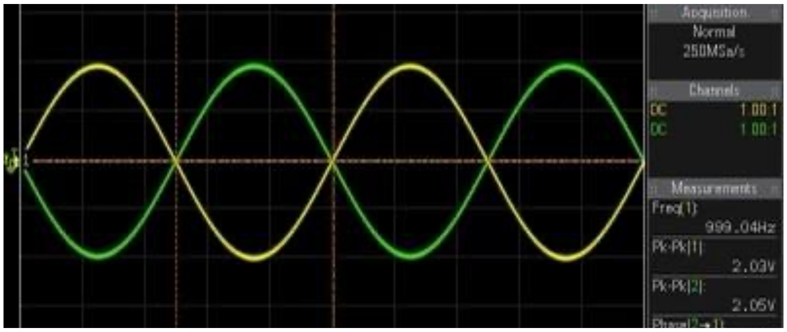

Figure 7. Oscilloscope image displaying the input and output voltages of the inverting amplifier circuit when the input resistance is 2.2k Ω and the feedback resistance is 2.2k Ω.

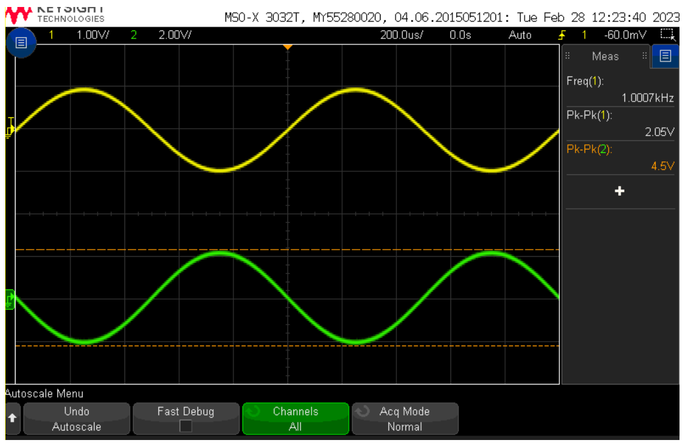

Figure 8. Oscilloscope image displaying the input and output voltages of the inverting amplifier circuit when the input resistance is 1k Ω and the feedback resistance is 2.2k Ω.

After analyzing the similar calculated and measured the v_{in} and v_{out} values, we determined no error in the voltage input and output values for the inverting operational amplifier circuits.

II. Week 1 Summing Amplifier

Given that both v_{in1} and v_{in2} are 2_{vpp}, the output of the circuit is -6.4 volts as per the calculation below. The resistance values are given in kilo-ohms, while the output voltage is in volts.

$$v_o = -2.2(\frac{2}{1} + \frac{2}{2.2}) = -6.4\ v$$

After physically building the summing amplifier circuit in the laboratory (using a breadboard, two 2.20k Hz resistors, one 1k Hz resistor, jumper wires, and the LM741 operational amplifier integrated circuit), as depicted in Figure 2, the DC power supply and function generator leads are connected. The frequency at which the summing amplifier operated was 1k Hz. While the function generator supplies a $2V_{pp}$ sinusoidal input, the oscilloscope measured the magnitudes of $v_{in\text{-}pp}$ as 2.05 volts and $v_{out\text{-}pp}$ as 6.3 volts. Figure 9 shows the oscilloscope output derived from the experiment. As per the calculations shown above, the magnitude of the expected voltage output was 6.4 volts.

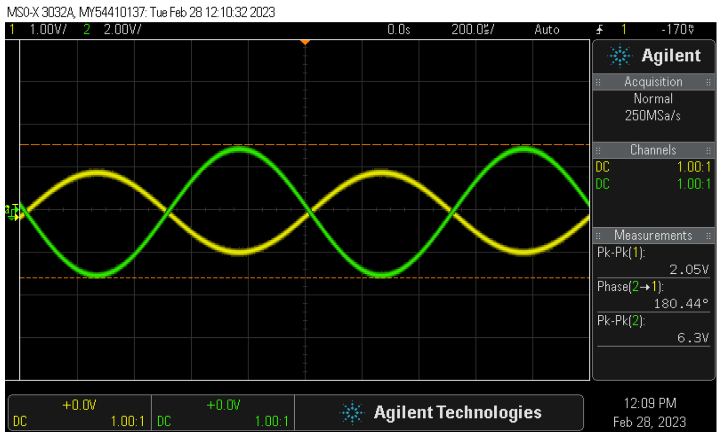

Figure 9. Oscilloscope image illustrating the output of the summing operational amplifier when both inputs v_{in1} and v_{in2} are $2v_{pp}$.

In addition, a MATLAB simulation of the voltage input and calculated voltage outputs supported the experimental values obtained, demonstrated in Figure 10. As per the circuit schematic, an input voltage of 2 volts would be provided to the inverting terminal of the operational amplifier, meaning that the voltage outputs should be inverted. This characteristic of the summing amplifier's output voltage was shown in the calculation above, as it was determined to be -6.4 volts. The negative sign indicates that the signal is inverted.

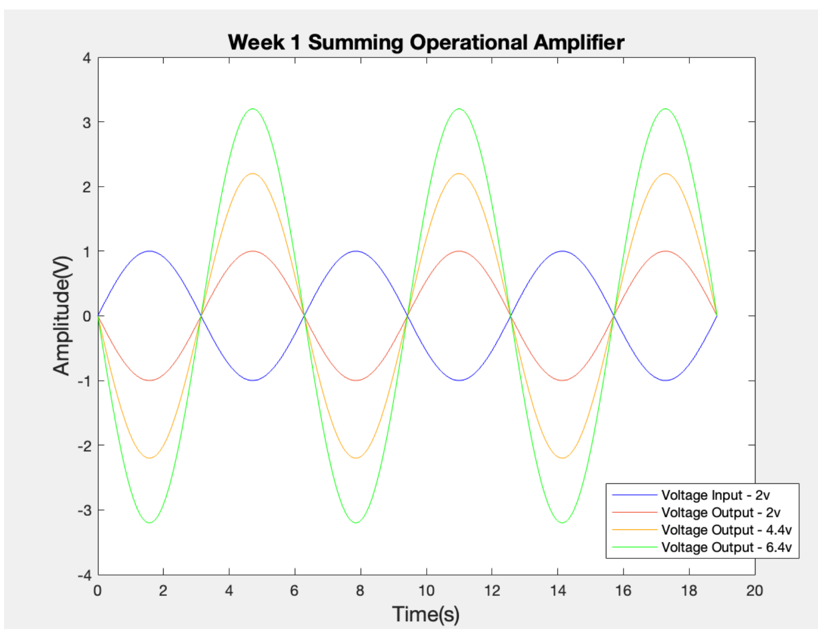

Figure 10. MATLAB simulation of the voltage input and output waveforms for the summing operational amplifier circuit.

The input signal is the blue waveform in Figure 4, which has an amplitude of one volt, given that the peak-to-peak voltage is $2_{v\text{-}pp}$. The red- and orange-colored waveforms represent the outputs of the inverting amplifiers since the summing amplifier combines both inverting voltage sources. The red waveform was determined to have a $v_{out\text{-}pp}$ of -2V, while the orange waveform had a $v_{out\text{-}pp}$ of -4.4V. Thus, the red waveform graph had an amplitude of -1 volts, and the orange waveform had an amplitude of -2.2 volts. Lastly, the green waveform is the final voltage output from the summing amplifier itself, calculated to be -6.4V, allowing the summing voltage output to have an amplitude of -3.2 volts. The MATLAB simulation shows similar results to the experimental values obtained during the laboratory exercise: a summing voltage output close to 6.3 volts that is inverted. It matches the prediction made in the pre-laboratory exercise that the output of the summing amplifier will be inverted since the input voltages are connected to the inverting input terminal. Minor differences in the output voltage are due to interference in the circuit. From this portion of the laboratory exercise, the relationship between inverting and summing amplifiers is that a summing amplifier is composed of multiple inverting inputs, which are added together.

III. Week 2 Summing Amplifier

Given that both v_{in1} and v_{in2} are 2_{vpp}, the voltage output was calculated as per the calculations below. The resistance values are given in kilo-ohms, while the output voltage is in volts.

$$v_o = -2.2(\frac{2}{1} + \frac{2}{1}) = -8.8\, v$$

After building the summing amplifier circuit in the laboratory, using a breadboard, two 1k Hz resistors, one 2.2k Hz resistor, jumper wires, and the LM741 operational amplifier integrated circuit, the DC power supply and function generator leads (from two separate function generators to provide the one kilohertz and ten kilo-hertz inputs) were connected to the circuit. The oscilloscope measured the v_{in}1k-pp as 2.05 volts, the v_{in}10k-pp as 2.09 volts, and the $v_{out\text{-}pp}$ as 8.8 volts. Figure 9 shows the oscilloscope output derived from the laboratory exercise.

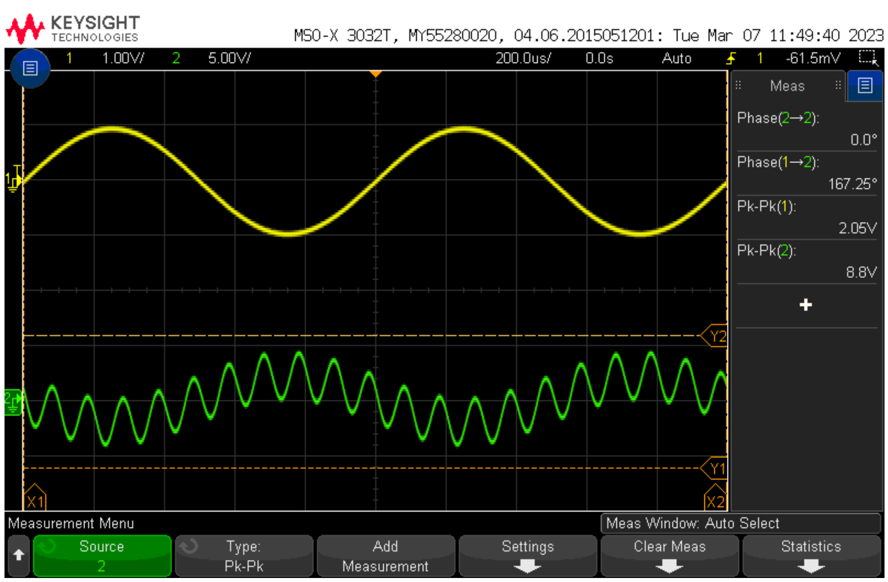

Figure 11. Oscilloscope image illustrating the output of the summing operational amplifier when both inputs v_{in1} and v_{in2} are $2v_{pp}$ at 1k Hz and 10k Hz, respectively.

As per the circuit schematic, input voltages of 2V at 1k Hz and 10k Hz would be provided to the inverting terminal of the operational amplifier, meaning that the voltage outputs should be inverted. This characteristic of the summing amplifier's output voltage was shown in the calculation above, as it was determined to be -6.4 volts. The negative sign indicates that the signal is inverted. Hence, the experimental output voltage, shown in Figure 11, exactly matches the value obtained through the calculations and shows that the voltage is inverted. In addition, a MATLAB simulation of the voltage input and calculated voltage outputs supported the experimental values obtained, demonstrated in Figure 10.

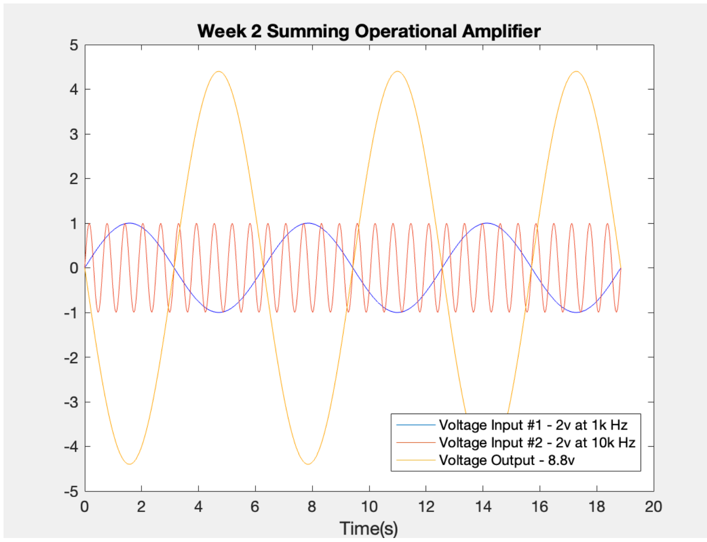

Figure 12. MATLAB simulation of the voltage input and output waveforms for the Week 2 summing operational amplifier circuit.

The MATLAB simulation was created using the calculated voltage output value. As displayed in the MATLAB simulation (Figure 12), the blue waveform represents the 2V input at 1k Hz, while the red waveform presents the other 2V input at 10k Hz. The orange waveform represents the output voltage with a magnitude of 8.8 volts. The sinusoids were graphed using a 1V amplitude for the red and blue waveforms and a -4.4 volts amplitude for the orange waveform. The negative sign was included with the orange waveform's amplitude to indicate that the voltage output was inverted. Overall, the MATLAB simulation and calculations show similar results to the experimental values obtained in the laboratory through the oscilloscope. All three methods produced an output voltage of exactly -8.8 volts, thus confirming that the output should be an inverted voltage with a magnitude of 8.8 volts. This exact measurement can be attributed to the fact that there was a trivial amount of noise when capturing the data from the oscilloscope. This matches the prediction made in the pre-laboratory exercise, as the output voltage was simply the inverted sum of the two input voltages.

IV. High-Pass Filter

The cutoff frequency, in Hertz, of the high pass filter is calculated by the following equation:

$$f_c = \frac{1}{2\pi R_i C_i} = 15.915\ kHz$$

Using the impedance values of the input branches and the feedback components, the gain of the high-pass filter (in decibels) can be obtained through the following equation:

$$|G| = \left|\frac{Z_f}{Z_i}\right| = 20log10\left[\frac{\frac{f}{f_c}}{\sqrt{1+\left(\frac{f}{f_c}\right)^2}}\right] = 0.707\ v/v$$

When the inputs of the summing amplifier were both at $2v_{pp}$ at 15k Hz, the magnitude of v_{out} from the high pass filter is $|V_{out}| = V_{in}|G| = 6.2$ V. The oscilloscope is set up to observe the filter's input and output values. Power is supplied to the summing amplifier and the values of the $v_{in\text{-}pp}$ and $v_{out\text{-}pp}$ were measured as $V_{in\text{-}pp} = 8.8$ V and $V_{out\text{-}pp} = 2.61$ V. While measuring the peak-to-peak value of the 1k Hz components, the input and outputs were determined as: $V_{in\text{-}1k\text{-}pp} = 4.25$ V and $V_{out\text{-}1k\text{-}pp} = 0.237$ V. While measuring the peak-to-peak value of the 10k Hz components, the input and outputs were determined as: $V_{in\text{-}10k\text{-}pp} = 4.55$ V and $V_{out\text{-}10k\text{-}pp} = 2.37$ V.

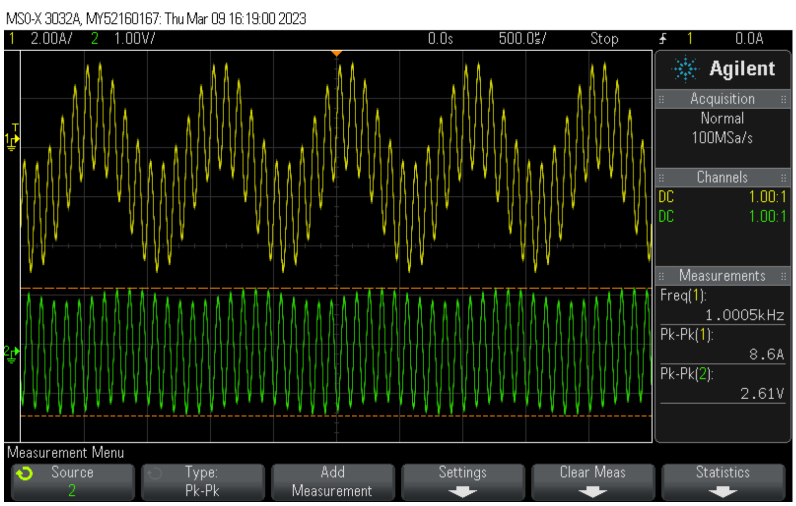

Figure 13. Oscilloscope screenshot displaying the filter's input and output values. Since the filter used is a High Pass Filter, frequencies lower than the cutoff frequency will be attenuated as shown when measuring the peak-to-peak value of the 1k Hz component.

Comparing the calculations with the measurements found using the oscilloscope, the output voltage from the summing amplifier that would supply the voltage to the high-pass filter is 8.8 V. The v_{out} from the filter when the inputs of the summing amplifier are both $2v_{pp}$ at 15k Hz are the same when calculated and measured with a value of 6.2 V. We determined the measured value by subtracting the $V_{out\text{-}pp}$ (2.61 V) from $V_{in\text{-}pp}$ (8.8 V) to get the value of 6.2 V.

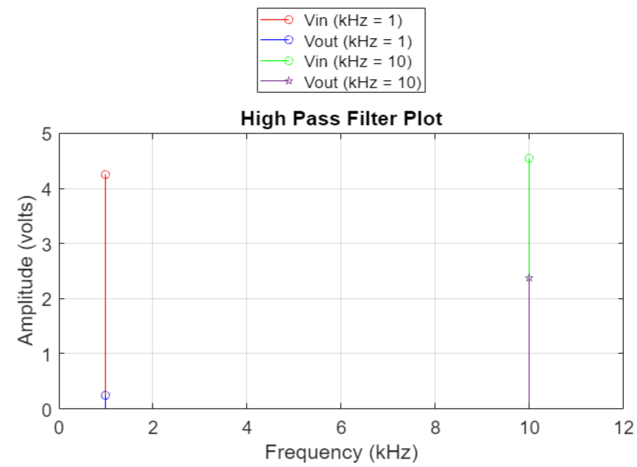

Figure 14. Single frequency graph displaying the v_{in} and v_{out} values for the 1k Hz and the 10k Hz components.

Figure 14 shows the effect on the voltages as the frequency is changed. When the frequency is at 1k Hz, the value of V_{out} is small as compared to its counterpart when the frequency is at 10k Hz. It is a result of the cutoff frequency at 15k Hz since both frequencies are below the cutoff frequency. Thus, the V_{out} at those frequencies will be attenuated. Since the 10k Hz frequency is comparatively close to the cutoff frequency, it will not attenuate as much as the 1k Hz frequency.

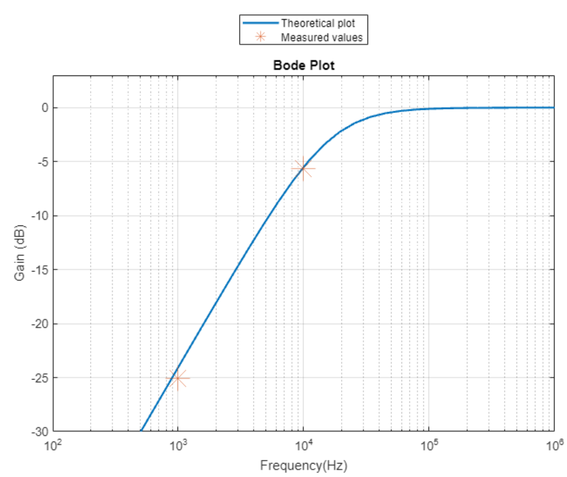

Figure 15. Bode plot of high pass filter displaying the attenuation of the lower frequencies.

Figure 15 shows the relationship between the frequency and the gain, which highlights the function of the high pass filter. As the frequency decreases below the threshold frequency, the gain also decreases. As the frequency approaches closer to the cutoff frequency, the gain increases in value. Once it passes the threshold frequency, the gain reaches its maximum value.

Discussion and Conclusions

As per our analysis, the data in both laboratory exercises confirmed our earlier calculations and predictions, meaning that the overall experiment was successful. During the first portion, we experienced some interference, which disrupted the oscilloscope's portrayal of the waveforms and provided incorrect values. However, we successfully measured and examined the summation and filtered waveforms from the oscilloscope for the second portion of the laboratory. Overall, this laboratory exercise improved our knowledge of operational amplifiers and helped us to become familiar with the concept of the cutoff frequency in active high-pass filters.

References

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Appendix

1. **MATLAB, Week 1 Summing Code**

```
clc
t=0:pi/100:6*pi;
w=sin(t); %input voltage of 2 volts
x=-sin(t); %output voltage #1 of -2 volts
y=-2.2*sin(t); %output voltage #2 of -4.4 volts
z=-3.2*sin(t); %output voltage of #3 of -6.4 volts
set(gca,'FontSize',12)
inputPlot = plot(t,w);
inputPlot.Color='#0000FF';
hold on
```

```
outputPlot1 = plot(t,x);
outputPlot1.Color='#EE4B2B';
hold on
outputPlot2 = plot(t,y);
outputPlot2.Color='#FFA500';
hold on
outputPlot3 = plot(t,z);
outputPlot3.Color='#00FF00';
hold on
legend('Voltage Input - 2v','Voltage Output - 2v','Voltage Output -
4.4v','Voltage Output - 6.4v');
title('Week 1 Summing Operational Amplifier','fontSize',14)
xlabel('Time(s)','fontSize',14)
ylabel('Amplitude(V)','fontSize',14)
```

2. MATLAB, Week 2 Summing Code

```
clc
t=0:pi/100:6*pi;
w=sin(t); %input voltage of 2 at 1k Hz
x=sin(10*t); %input voltage of 2 at 10k Hz
y=-4.4*sin(t); %output voltage of 8.8
plot(t,w);
hold on
plot(t,x);
hold on
plot (t,y);
set(gca,'FontSize',12)
inputPlot = plot(t,w);
inputPlot.Color='#0000FF';
hold on
outputPlot1 = plot(t,x);
outputPlot1.Color='#EE4B2B';
hold on
outputPlot2 = plot(t,y);
outputPlot2.Color='#FFA500';
hold on
legend('Voltage Input #1 - 2v at 1k Hz','Voltage Input #2 - 2v at 10k
Hz','Voltage Output - 8.8v');
title('Week 2 Summing Operational Amplifier','fontSize',14)
xlabel('Time(s)','fontSize',14)
```

3. MATLAB, High Pass Filter Code

3a. Stem Plot Code

```
clc
hz = [1 10];
vin = [4.25 4.55];
```

```
vout = [0.237 2.37];
stem(1, 4.25, 'r');
hold on
stem(1, 0.237, 'g');
stem(10, 4.55, 'b');
stem(10, 2.37, 'o');
set(gca,'FontSize', 14) % update the font size for both x and y-
axis labels
xlabel('Frequency (kHz)');
ylabel('Amplitude (volts)');
title('High Pass Filter Plot');
xlim([0 12]); % set the x-axis limits to 0 and 12
legend('Vin (kHz = 1)', 'Vout (kHz = 1)','Vin (kHz = 10)', 'Vout
(kHz = 10)', 'Location', 'northoutside')
pbaspect([2 1 1])
grid on
```

3b. Bode Plot

```
clc
x = logspace(0,6);
fc = 15915;
gainTh = 20*log10((x./fc)./sqrt(1 + (x./fc).^2));
vin = [4.25 4.55];
vout = [0.237 2.37];
f = [1000, 10000];
gainCalc = 20*log10(vout./vin);
semilogx(x,gainTh,'LineWidth',1.5);hold on
semilogx(f,gainCalc,'*', 'MarkerSize', 20);
axis([1e2 1e6 -30 3]) % Updated y-axis limits
title('Bode Plot');
xlabel ('Frequency(Hz)')
ylabel('Gain (dB)')
legend('Theoretical plot','Measured values', 'Location',
'northoutside');
grid on
```