Introduction to Op-Amps

ECE 10BL Lab 4

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Background

The objective of this lab is to understand the op-amp and analyze the properties of various circuits that can be built using one. Op-amps allow us to transform two small input voltages into a higher output voltage. A unity-gain circuit was first built using two resistors, one at the negative input voltage and one on the negative feedback from the output, as well as a potentiometer at the output. The voltage amplifier was then analyzed by adjusting the potentiometer to achieve certain output voltage gains. To understand how op-amps could be used as adders and subtractors, we built an adder circuit consisting of two inputs in the negative input, and a subtractor circuit consisting of one input voltage in each of the inputs for the op-amp.

Procedure

Op-amps are amplifiers that take in two input voltages (one negative and one positive) and output a voltage with a larger magnitude than the input voltage. Op-amp circuits are primarily built in two ways: open-loop and closed-loop. This is determined by whether there is a feedback loop from the output voltage into the input voltage.

In an open-loop op-amp circuit, there is no feedback to the input voltage from the output voltage. Input voltages tend to be very small in magnitude compared to the output voltage, so the open-loop gain, A, is typically large in magnitude (and infinite in an ideal case). The op-amp used in this lab has an open-loop gain of A = 2 * 10^5. Using this, we can calculate the output voltage using the following equation:

$$v_{out} = A(v^+ - v^-) \qquad (1)$$

where V^+ and V^- are the two input voltages.

However, we are more interested in closed-loop op-amp circuits. These circuits feed the output voltage back into one of the inputs of the op-amp. Figure 1 below shows the closed-loop op-amp circuit for the first and second parts of this lab, which is an inverting voltage amplifier. Since the voltage at the input nodes of the op-amp are no longer small in magnitude in comparison to the output voltage, we can define a new gain, G, the closed-loop gain.

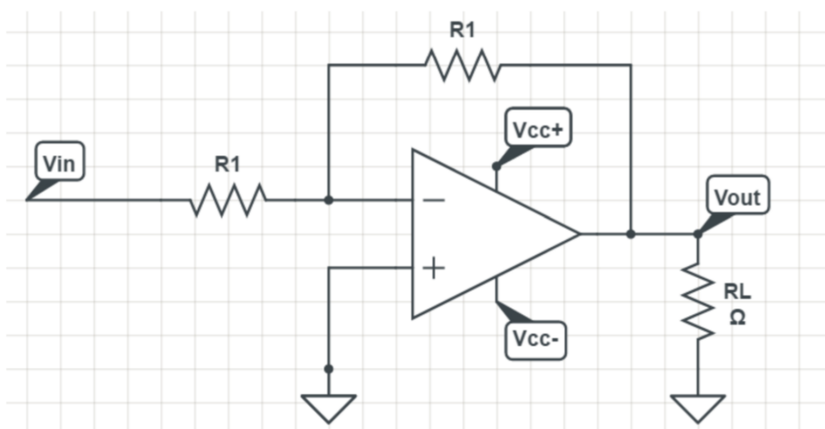

Figure 1: Schematic for Inverting Op-Amp Circuit

We can begin our exploration into the various closed-loop op-amp circuits by starting with an inverter op-amp circuit. By performing nodal analysis on the circuit in Figure 1, we can obtain the following expression for gain for the op-amp:

$$G = \frac{-AR_f}{R_1+R_f+AR_1} \qquad (2)$$

where R_1 is the resistor between V_{IN} and the input node of the op-amp, R_f is the resistor in the feedback loop, and A is the open-loop gain. Since the open-loop gain is typically large in magnitude (and infinite in the ideal case), we can assume:

$$AR_1 \gg R_1 + R_f \qquad (3)$$

and we can assume G is therefore equal to:

$$G = \frac{-AR_f}{AR_1} = -\frac{R_f}{R_1} \qquad (4)$$

In the first scenario, we are looking to achieve unity gain. The term "unity gain" refers to a circuit whose gain is equal to one, meaning the input voltage is equal to the output voltage (in this case, G = -1 since this is an inverting circuit). We can easily see that R_1 and R_f must be equal for this to occur. As a result, we will test this assumption later using equal resistance values of 1 kΩ.

Once we achieve unity gain, we can begin to obtain other values for the gain. We can achieve this by adjusting the resistance value in the feedback loop, R_f. Since R_1 is a fixed value, G and R_f are directly proportional, and to achieve higher gains, we can simply increase the feedback resistance. For example, to achieve a gain of G = 2, we can double the feedback resistance to a value of R_f = 2 kΩ.

The second op-amp circuit that we will explore is the non-inverting op-amp circuit. This is like the inverting op-amp circuit, except V_{IN} is instead applied to the positive terminal of the op-amp instead of the negative terminal. The circuit is shown in Figure 2 below.

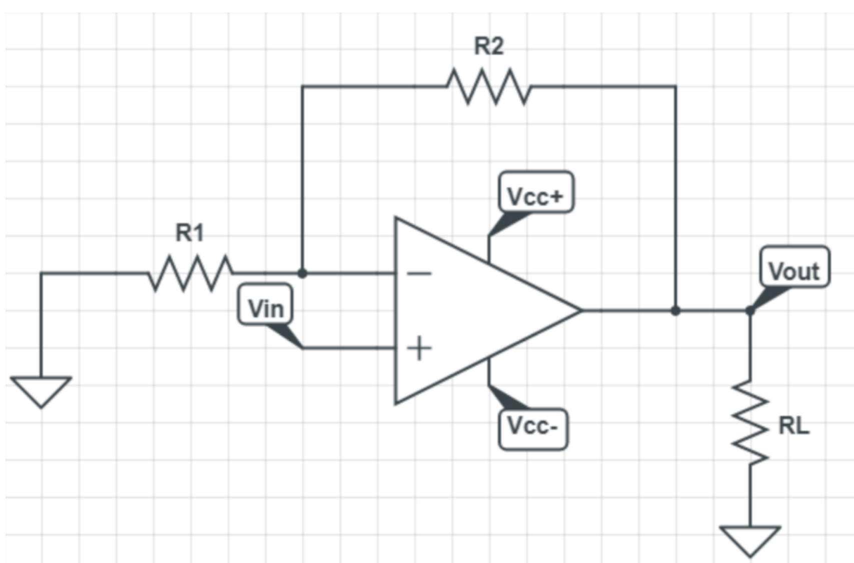

Figure 2: Schematic for Non-Inverting Op-Amp Circuit

We can obtain the following expression for the voltage of the op-amp:

$$v_{out} = \frac{R_1+R_f}{R_1} v_{in} \tag{5}$$

Using this, we can also obtain the gain:

$$G = \frac{R_1+R_f}{R_1} \tag{6}$$

Like the inverting op-amp, we can increase the gain by increasing the feedback resistance. However, the gain and the feedback resistance are no longer directly proportional.

In addition to building amplifier circuits, we can also use closed-loop op-amps to build adders and subtractors. The circuits are like the amplifier circuits above, but we now have two inputs that we wish to compute with. To achieve an adder circuit, we can tie both input voltages to the negative op-amp input node, and to achieve a subtractor circuit, we can tie one input voltage to each op-amp input node. Figures 3 and 4 below show an adder circuit and subtractor circuit, respectively.

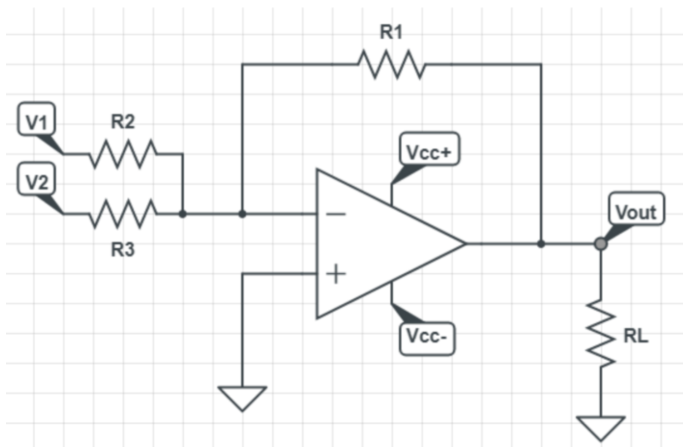

Figure 3: Schematic for Op-Amp Adder Circuit

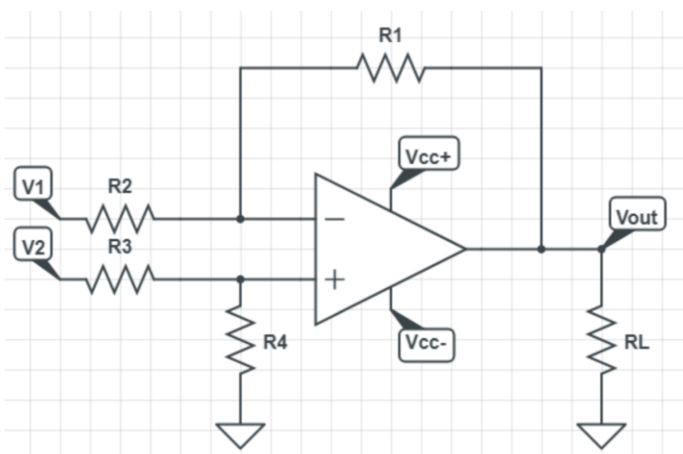

Figure 4: Schematic for Op-Amp Subtractor Circuit

We can solve for the output voltage for each circuit above as a function of the input voltages and resistances. For an adder circuit:

$$v_{out} = -R_1\left(\frac{v_1}{R_2} + \frac{v_2}{R_3}\right) \tag{7}$$

For a subtractor circuit:

$$v_{out} = \frac{R_4(R_1+R_2)}{R_2(R_3+R_4)}v_2 - \frac{R_1}{R_2}v_1 \tag{8}$$

We can clearly observe that, for the adder circuit, increasing V_1 or V_2 will increase the (inverted) output voltage, and for the subtractor circuit, V_1 is subtracted from V_2, making it a subtractor.

Analysis

Throughout the analysis, I denoted the various closed-loop gains with A_V. These are the closed-loop gains that were used to provide each output and is **not** the open-loop gain (the open-loop gain is also much larger in value).

Figure 5 below is a plot of input voltage and output voltage versus time for an op-amp in unity gain. The resistances R_1 and R_f were both equal to 1 kΩ, matching our prediction that equal resistances would produce a unity gain.

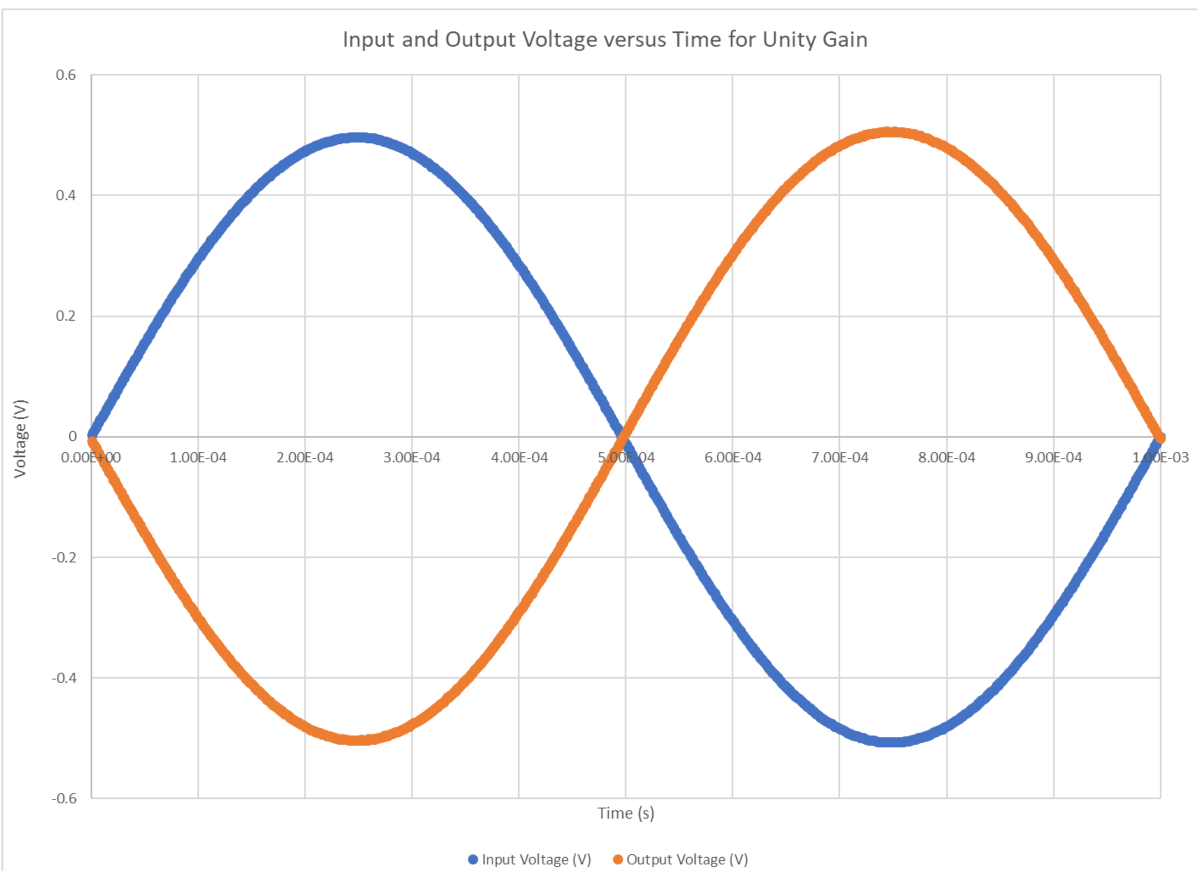

Figure 5: Input and Output Voltage versus Time for Unity Gain

The following five figures show the input voltage and output voltage versus time for an inverting op-amp with gains of A_V = 2, 4, 6, 8, 10, along with the feedback resistance value used to achieve it. All trials contained a maximum V_{IN} amplitude of 0.25 V and used R_1 = 1 kΩ.

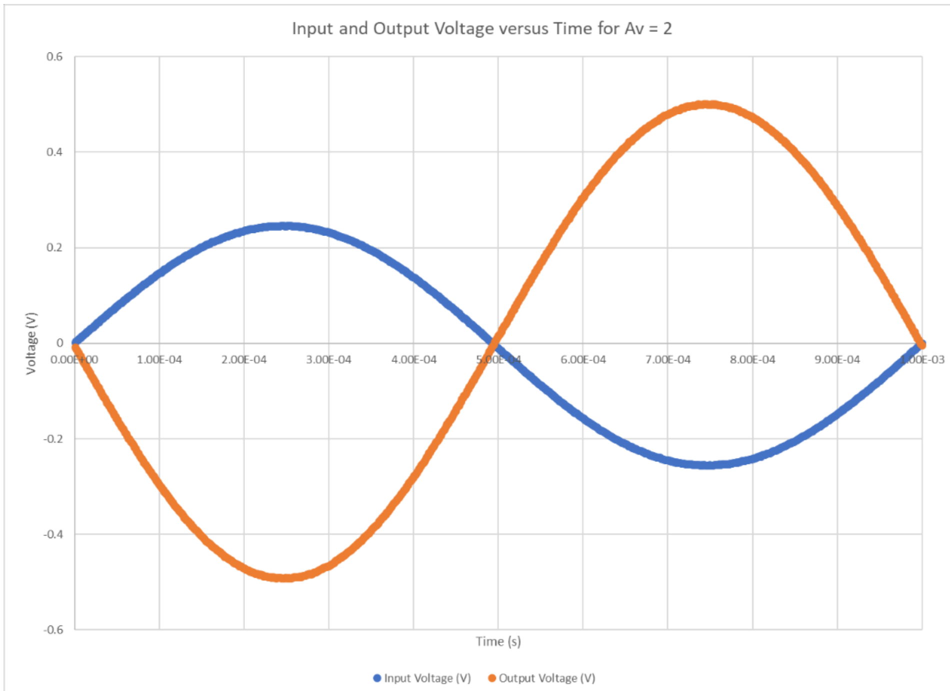

Figure 6: Input and Output Voltage versus Time for A_V = 2 and R_f = 1.98 kΩ

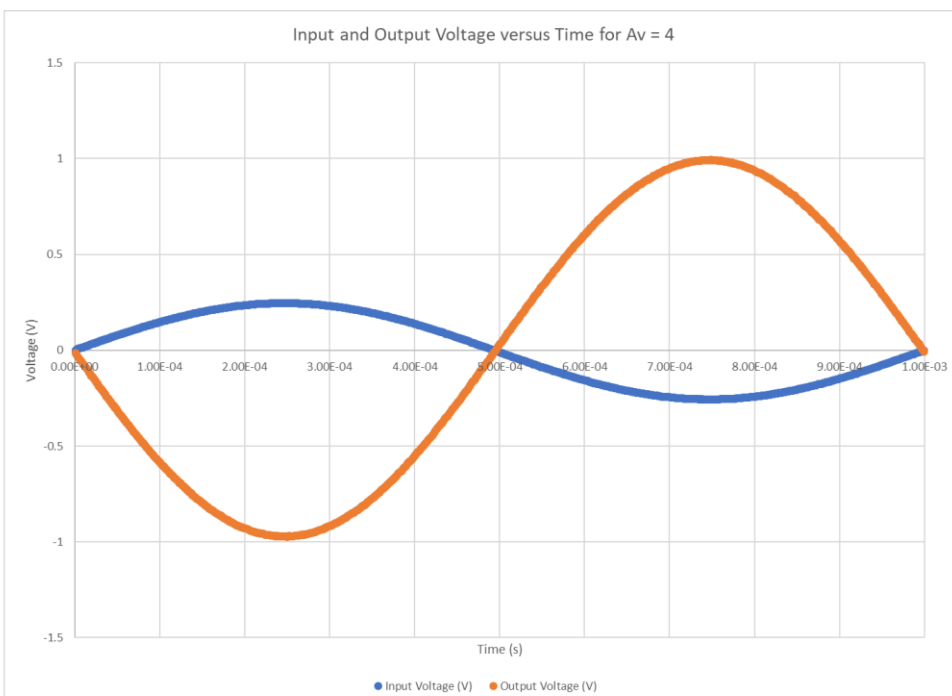

Figure 7: Input and Output Voltage versus Time for A_V = 4 and R_f = 3.91 kΩ

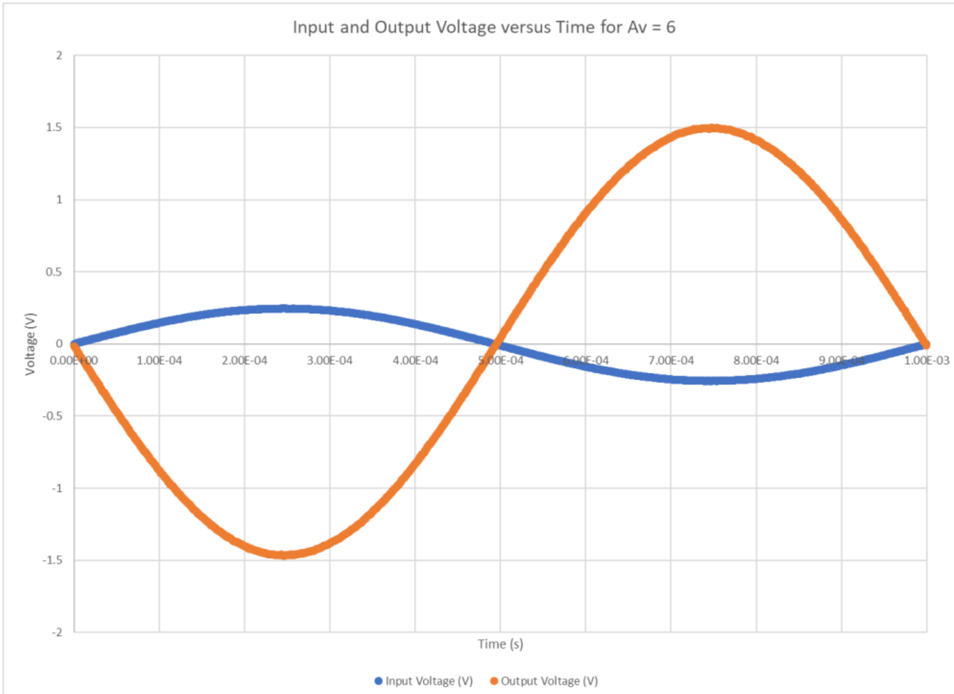

Figure 8: Input and Output Voltage versus Time for $A_V = 6$ and $R_f = 5.91\ k\Omega$

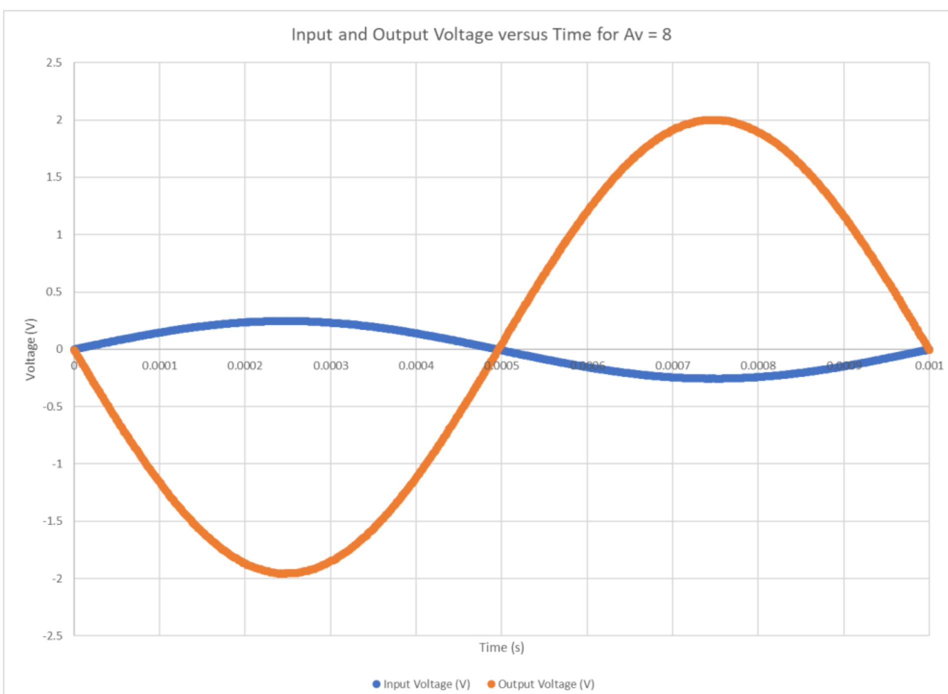

Figure 9: Input and Output Voltage versus Time for $A_V = 8$ and $R_f = 7.89\ k\Omega$

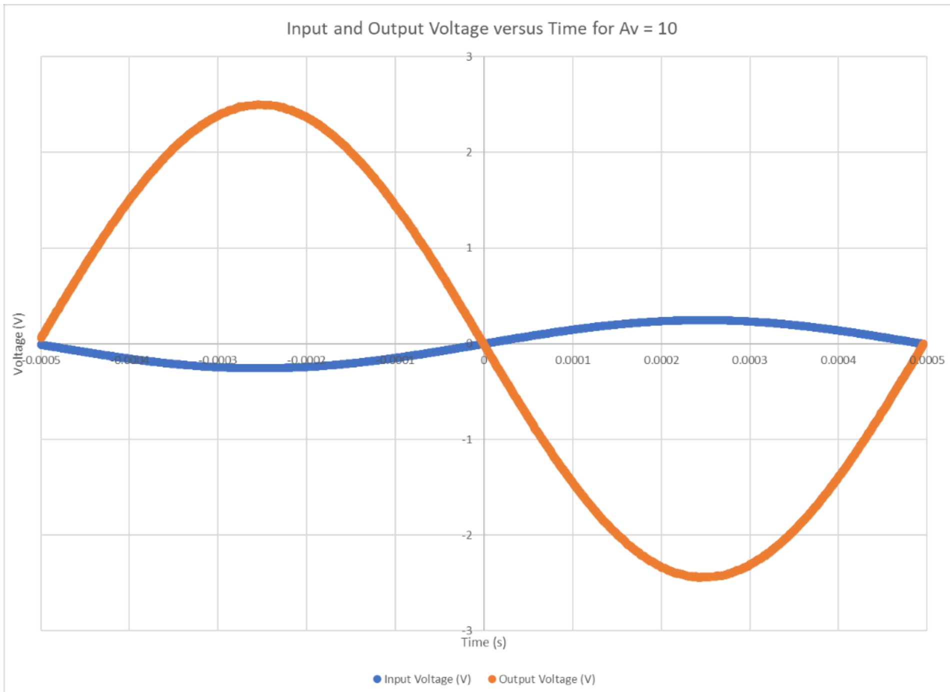

Figure 10: Input and Output Voltage versus Time for A_V = 10 and R_f = 9.82 kΩ

The theoretical and actual feedback resistance values are tabulated below in Table 1:

Table 1: Feedback Resistances for Various Inverted Op-Amp Gains

Theoretical Gain A_V	R_f Theoretical (Ω)	R_f Actual (Ω)	Actual Gain A_V
2	2 kΩ	1.98 kΩ	1.98
4	4 kΩ	3.91 kΩ	3.91
6	6 kΩ	5.91 kΩ	5.91
8	8 kΩ	7.89 kΩ	7.89
10	10 kΩ	9.82 kΩ	9.82

We can observe that the actual values for the feedback resistance are relatively close to the theoretical values for each case, producing a gain that is also close to the theoretical value. This confirms the observations we made from equation 4.

The following five figures show the input voltage and output voltage versus time for a non-inverting op-amp with gains of A_V = 2, 4, 6, 8, 10, along with the feedback resistance value used to achieve it. All trials contained a maximum V_{IN} amplitude of 0.25 V and used R_1 = 1 kΩ.

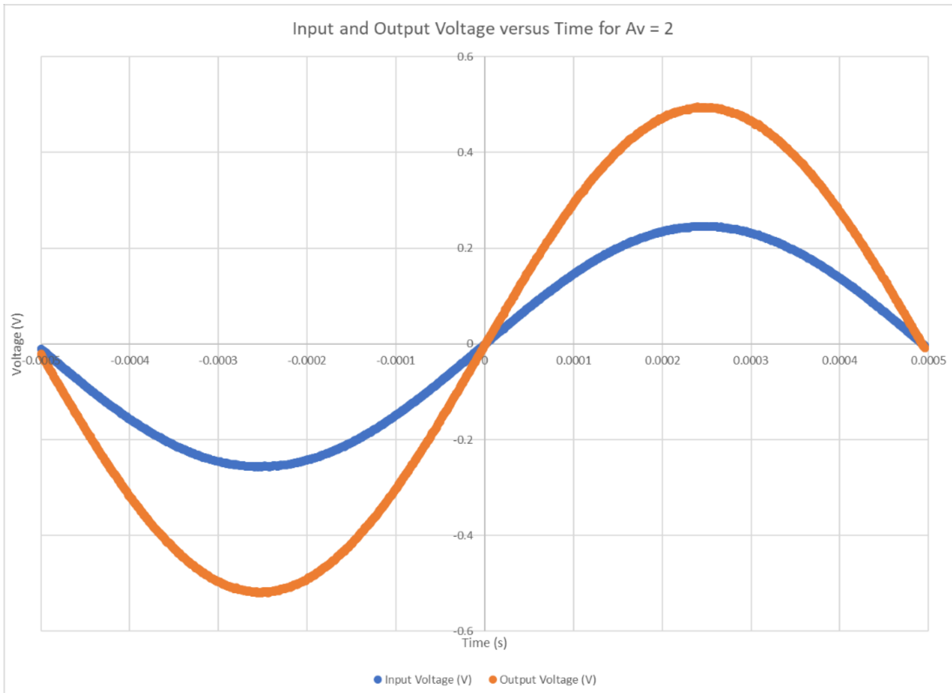

Figure 11: Input and Output Voltage versus Time for A_V = 2 and R_f = 1.01 kΩ

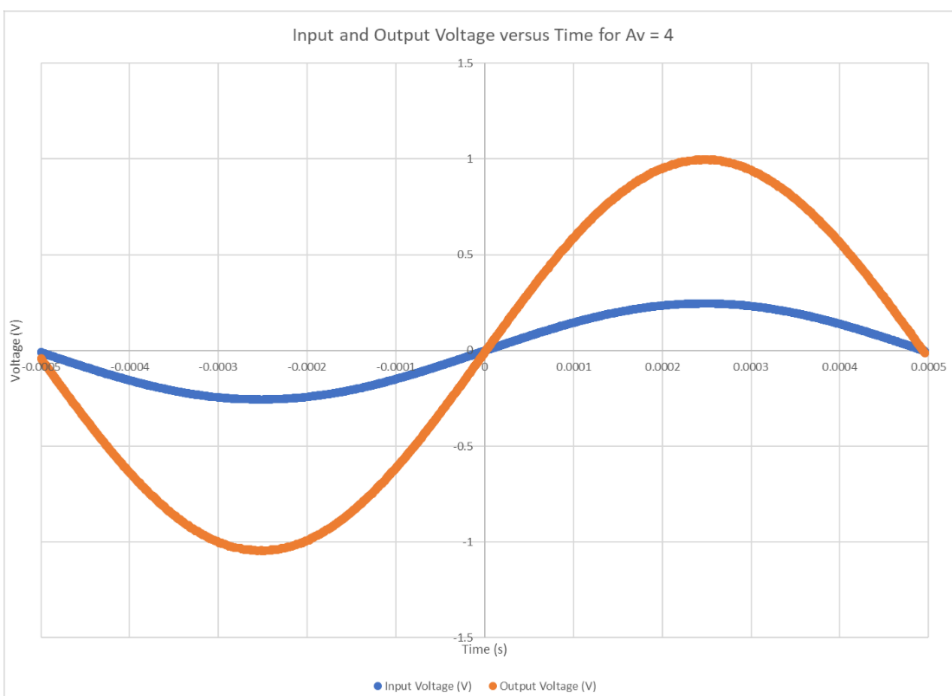

Figure 12: Input and Output Voltage versus Time for A_V = 4 and R_f = 3.07 kΩ

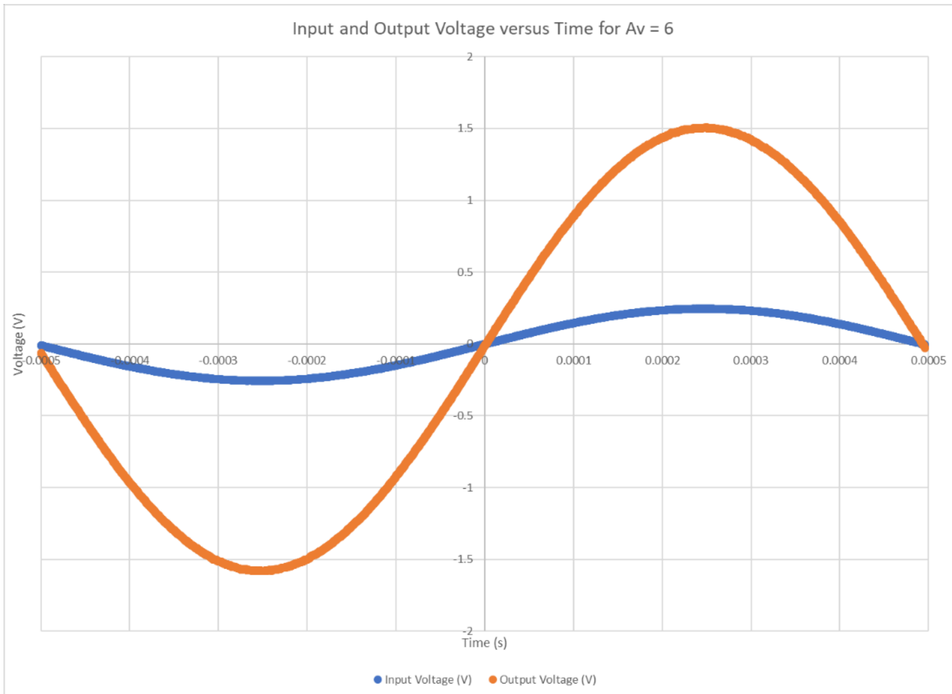

Figure 13: Input and Output Voltage versus Time for A_V = 6 and R_f = 5.15 kΩ

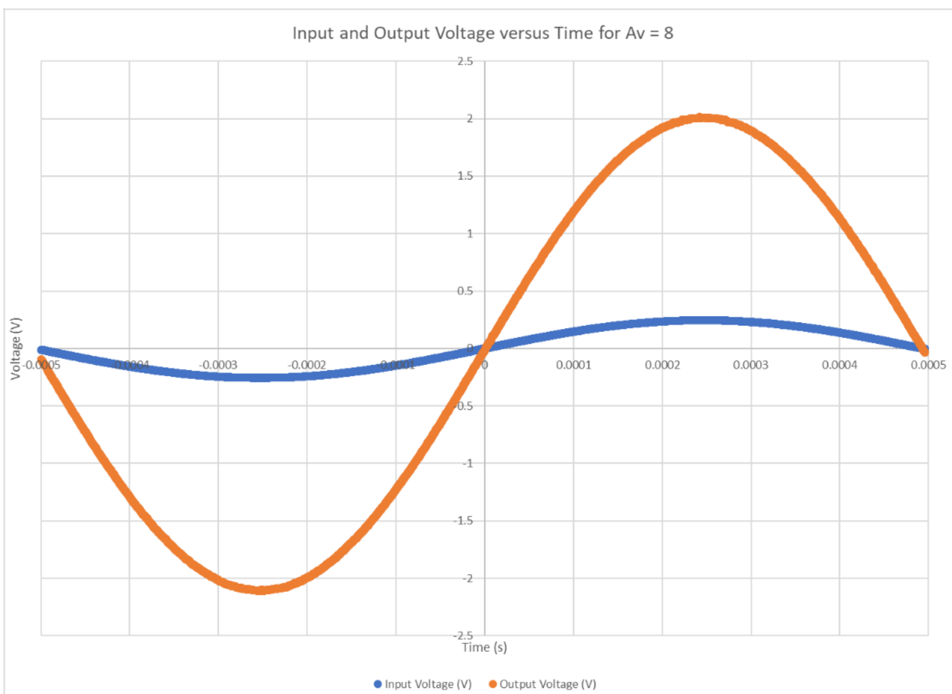

Figure 14: Input and Output Voltage versus Time for A_V = 8 and R_f = 7.21 kΩ

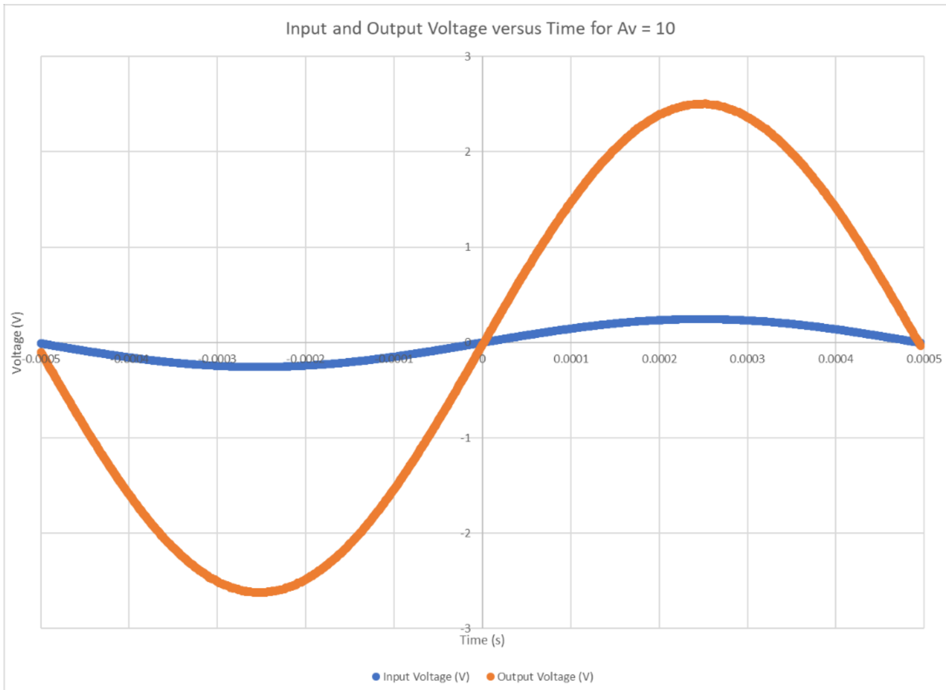

Figure 15: Input and Output Voltage versus Time for A_V = 10 and R_f = 9.21 kΩ

The theoretical and actual feedback resistance values are tabulated below in Table 2:

Table 2: Feedback Resistances for Various Non-Inverted Op-Amp Gains

Theoretical Gain A_V	R_f Theoretical (Ω)	R_f Actual (Ω)	Actual Gain A_V
2	1 kΩ	1.01 kΩ	2.01
4	3 kΩ	3.07 kΩ	4.07
6	5 kΩ	5.15 kΩ	6.15
8	7 kΩ	7.21 kΩ	8.21
10	9 kΩ	9.21 kΩ	10.21

Again, we can observe that the actual values for the feedback resistance are relatively close to the theoretical values for each case, producing a gain that is also close to the theoretical value. This confirms the observations we made from equation 6.

Figure 16 below show the input and output voltages over time for the adder op-amp circuit. In this trial, R_1 = 0.5 kΩ, $R_2 = R_3$ = 1 kΩ, and the amplitude of the trapezoid was 0.25 V.

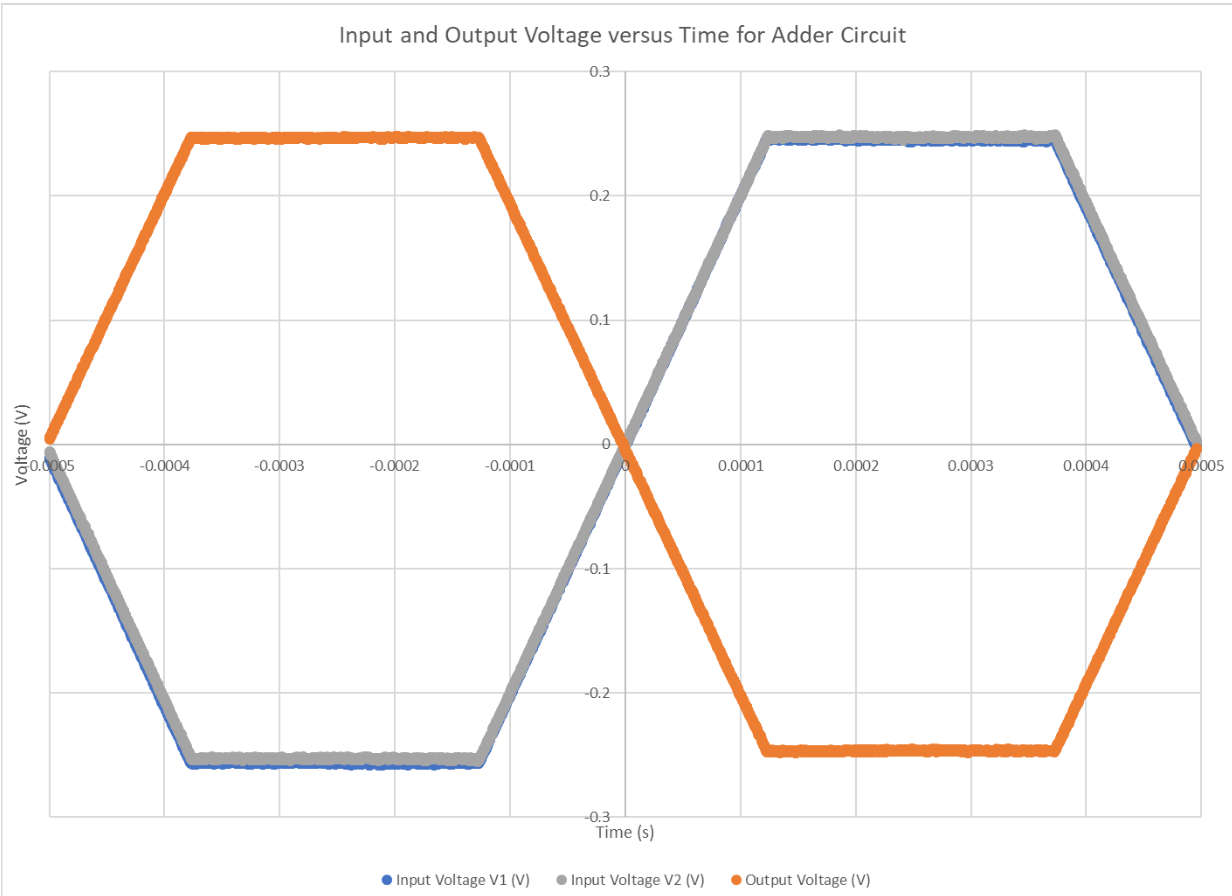

Figure 16: Input and Output Voltage versus Time for Inverted Adder Circuit

We can see that the output voltage is the inverted input voltage, which gives the appearance that the voltage is not being added. However, from equation 7,

$$v_{out} = -R_1(\frac{v_1}{R_2} + \frac{v_2}{R_3}) \qquad (7)$$

we can observe that R_1/R_2 and R_1/R_3 = 0.5, reducing the expression for V_{OUT} to the following:

$$v_{out} = -0.5v_1 - 0.5v_2 \qquad (9)$$

Since V_1 and V_2 are equal, V_{OUT} is in fact the sum of the two input voltages, only halved due to the choice of R_1. If we were to set R_1 to match R_2 and R_3, the coefficients on V_1 and V_2 would simplify to 1, leaving us with an evident inverted adder circuit.

Lastly, Figure 17 below show the input and output voltages over time for the subtractor op-amp circuit. In this trial, all resistances had a value of R = 1 kΩ, $V_{IN,1}$ was driven by a triangle wave, and $V_{IN,2}$ was driven by a square wave, both with amplitude 1. Note that the output is inverted in this graph.

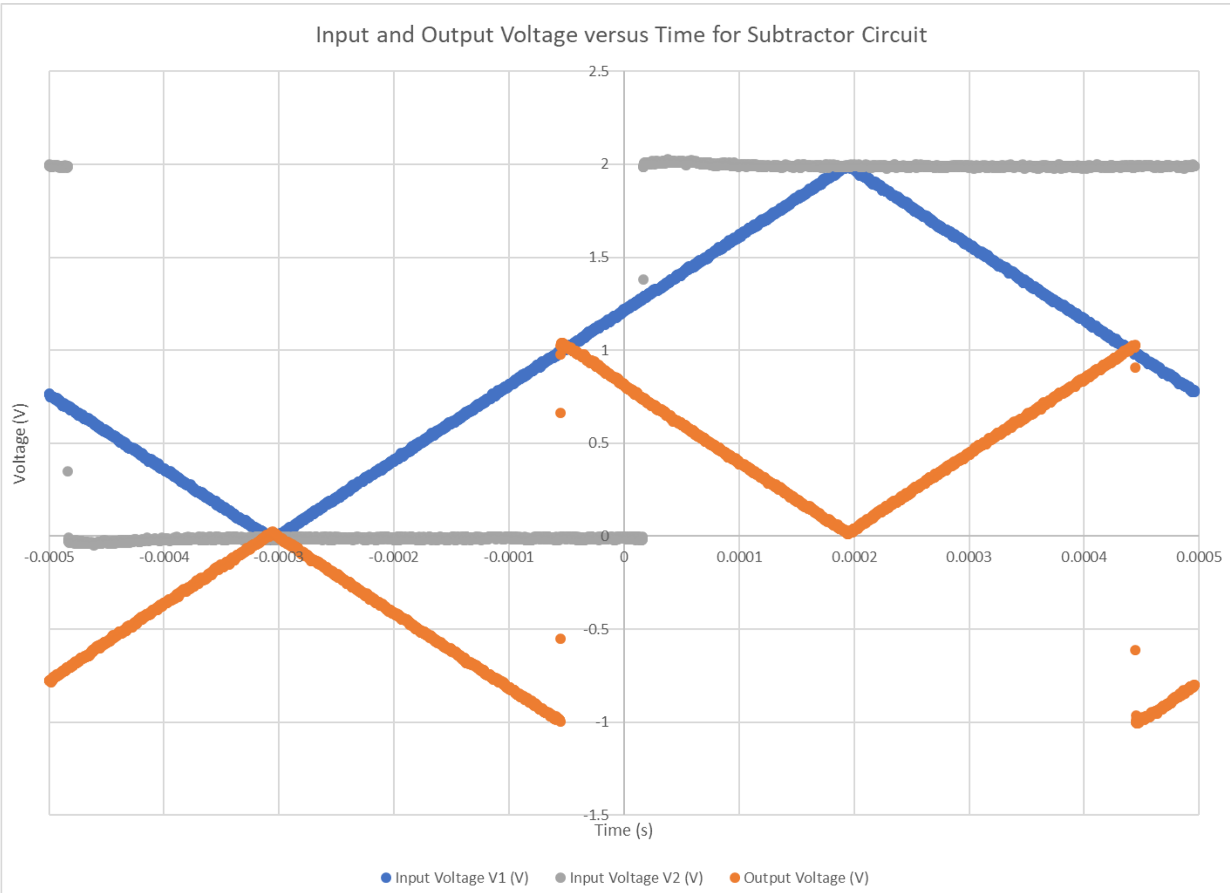

Figure 17: Input and Output Voltage versus Time for Subtractor Circuit

We can observe that the output voltage at all points is the difference between the input voltages V_1 and V_2. This can be further confirmed via equation 8 from above:

$$v_{out} = \frac{R_4(R_1+R_2)}{R_2(R_3+R_4)} v_2 - \frac{R_1}{R_2} v_1 \qquad (8)$$

In this trial, all resistors had a resistance value of R = 1 kΩ. As a result, the coefficient for each of the input voltages V_1 and V_2 in equation 8 simplify to 1, leaving us with the following expression:

$$v_{out} = v_2 - v_1 \qquad (10)$$

This confirms the trends shown in Figure 17 above.

Conclusion

In this lab, we built four different op-amp circuits to understand the operation of an op-amp, vary the circuit's gain, and perform addition and subtraction of input voltages. Using an inverted amplifier circuit, we were able to conclude that a matching V_{IN} resistance and feedback resistance resulted in unity gain, and increasing gain could be achieved by increasing the feedback resistance due to its direct proportionality with the gain. Using a non-inverted amplifier circuit, we were also able to conclude that you could increase gain by increasing feedback resistance, although not directly proportional in this instance. The objective of the last two circuits were to show that op-amps could be used to add and subtract voltages. We were able to conclude that an adder circuit did, in fact, add the two input voltages, due to our choice of resistance values. If all resistance values were equal, then the coefficient terms would drop, and the adder would clearly be evident in the output graph. The same applies for our subtractor circuit.

My group incurred no problems during this lab, and we were able to successfully build all the circuits needed for this lab. However, we did not realize that the outputs for the last two circuits (adder and subtractor) needed to be inverted to clearly show the output in the graph of voltage versus time, which initially confused us. I would note this in future iterations of this lab.

In addition, a reminder to reduce the sample rate of the WaveForms software would be appreciated.