ECSE331 Lab 2

Characterization of Some Basic Op-Amp Circuits

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ECSE331

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ECSE331 Lab-2 Report

***Abstract* — The following report includes measurements with different configurations of the 741 op-amp using NI-Elvis instruments. It also compares the expected output gained from LTSpice with the measured values.**

I. INTRODUCTION

In this lab, students will use a 741 op-amp to build OpAmp circuits with different characterizations. To better understand the dynamic behavior of an operational amplifier, students will measure the input/output gain for each circuit and compare the results with theoretical and simulated values from LTspice. The following seven circuits will be built in this lab and analyzed in this report: comparator, voltage follower, non-inverting amplifier, inverting amplifier, differentiator, integrator, and D/A converter.

II. EXPERIMENT RESULTS

A. (a) Non-Inverting Comparator

In this part, we reproduced the circuit based on Fig.1, and the output signal is observed on the oscilloscope. Theoretically, Comparator will produce +Vcc when the input voltage is positive and -Vcc when the input voltage is negative. As we can observe in Fig.2, when the input voltage is positive, the output is around 9.7V; when the input voltage is negative, the output is -7.9V.

These values are close to but not exactly $\pm 10V$ since the real op-amp may have internal resistance and consume the power.

Figure 3 shows the input and output signal when the amplitude of the input is reduced to 0.1V. We can clearly see that the output signal remains the same.

The simulation results from LTSpice are shown in Figure 4 and Figure 5. For both cases, the output voltage is around 9.7V, which is very close to the expected value.

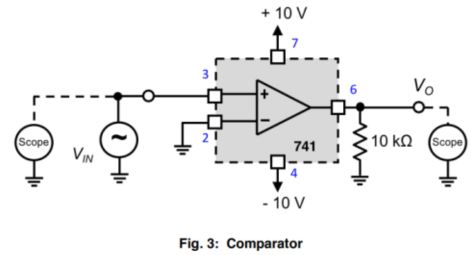

Fig.1.Comparator circuit with a 1kHz sinusoidal input of 1V Vpp

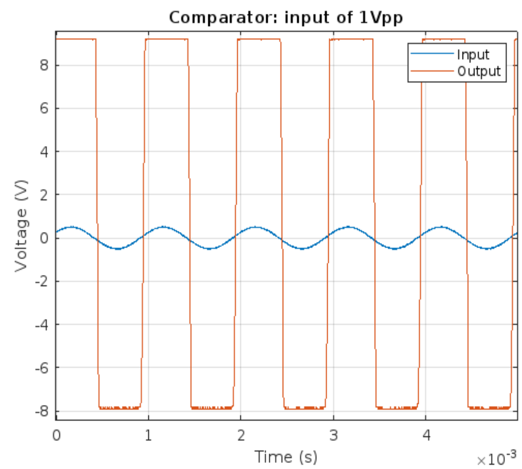

Fig.2. Output voltage plotted by MATLAB when input has 1V peak-to-peak value.

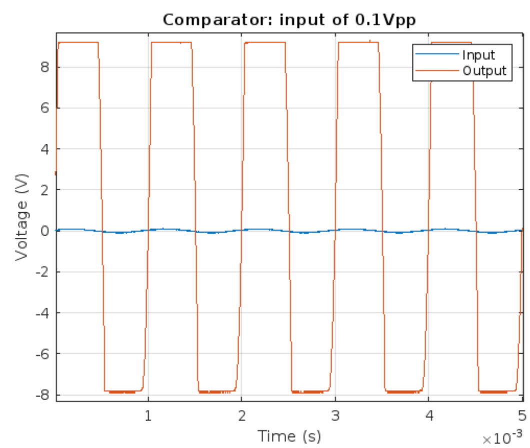

Fig.3. Output voltage plotted by MATLAB when input has 0.1V amplitude.

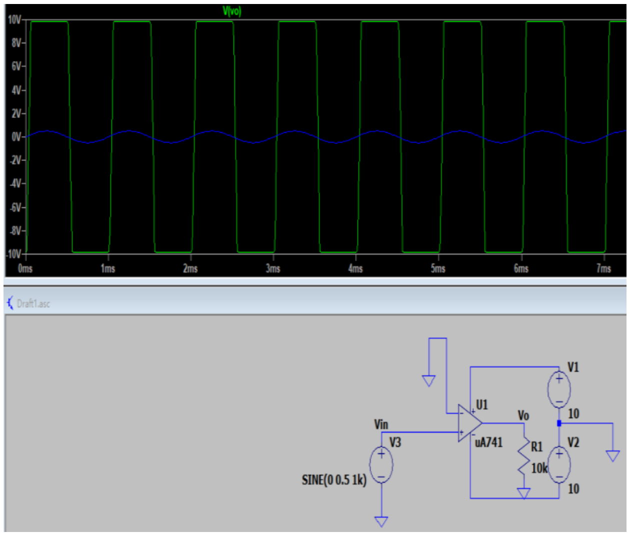

Fig.4. LTspice simulation plot of non-inverting comparator when input has 1V Vpp.

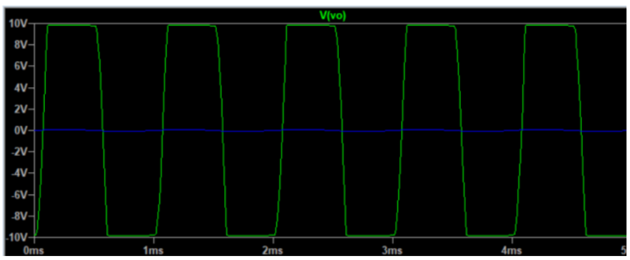

Fig.5. LTspice simulation plot of non-inverting comparator when input has 0.1V amplitude.

A. (b) Inverting Comparator

If we ground the + input terminal and connect the signal to the **-** input terminal, the comparator will be inverted as shown in figure 6. When the input is negative, the output is close to +Vdd. When the input is positive, the output is close to -Vdd. This is opposite to what we observe with the non-inverting comparator. Figure 7 also shows the simulation result from LTspice, which is consistent with our measurement.

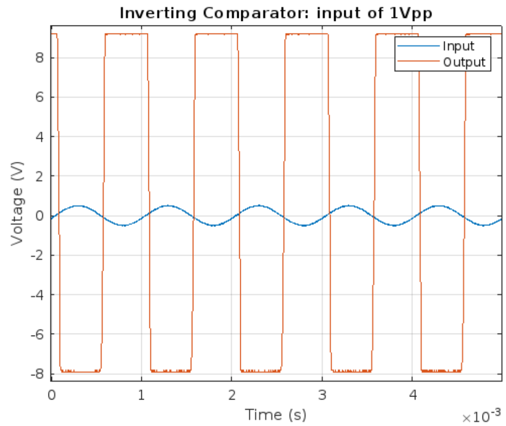

Fig.6. Output voltage plotted by MATLAB when input has 1V peak-to-peak value.

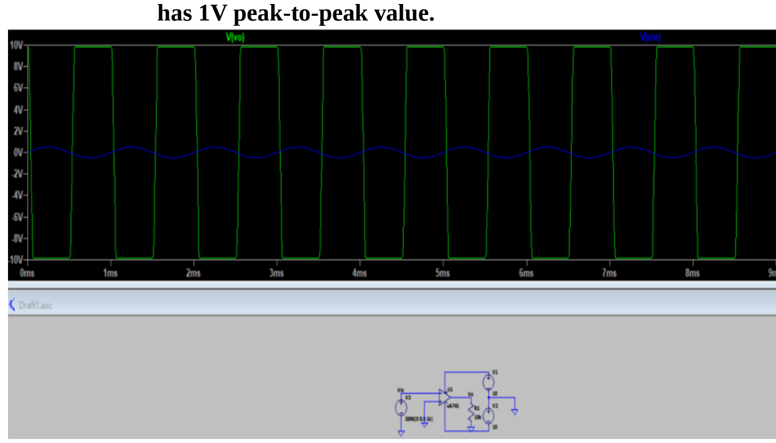

Fig.7. LTspice simulation plot of inverting comparator when input has 1V Vpp

B. Voltage follower

We reproduced the circuit based on figure 8. In theory, the output voltage should be close to the input voltage due to the effect of negative feedback. Figure 9 shows the output voltage when the inputs are sine signals with 1V Vpp. To get the input impedance of the circuit, we make use of a 1MΩ test resistor. We connected the resistor in the non-inverting terminal of the op-amp and measured the voltage Vin at the non-inverting terminal. The measured result is shown in figure 10. We can then compute the input impedance as follow: $I = \frac{Vtest - Vin}{Rtest} = \frac{0.5-0.21}{1M} = 2.9 * 10^{-7} A.$

$\boldsymbol{Rin = \frac{Vin}{I} = \frac{0.21}{2.9*10^{-7}} = 724\ K\Omega}$. In theory, there will be almost no current flowing into the terminal, and input impedance should be very high, which is consistent with our measurement.

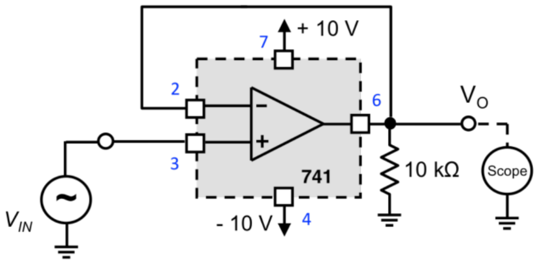

Fig.8.Voltage follower circuit with a 1kHz sinusoidal input of 1V Vpp

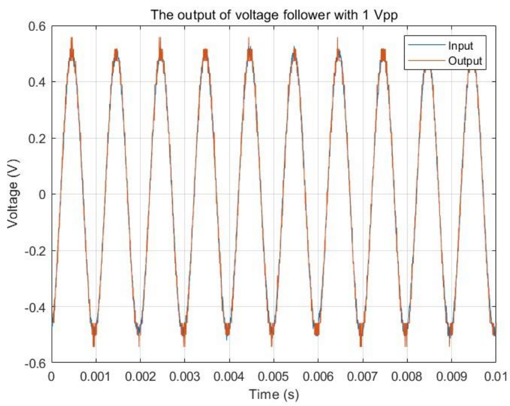

Fig. 9. Output voltage plotted by MATLAB when input has a 1V peak-to-peak value.

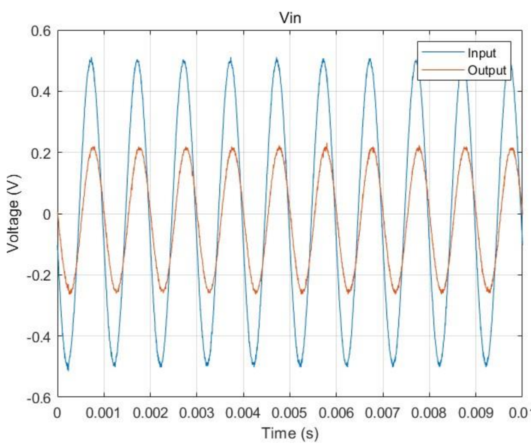

Fig. 10. Vin plotted by MATLAB when input has a 1V peak-to-peak value.

We then changed the input to the square wave input and output also has the same behavior as shown in figure 11.

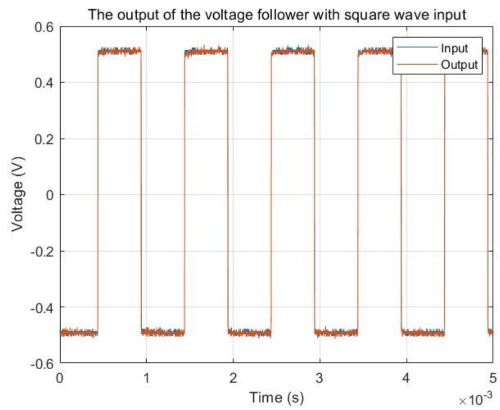

Fig. 11. Output voltage plotted by MATLAB when input is square wave.

C. Noninverting Amplifier

We built the non-inverting amplifier circuit, as shown in Fig. 12, and applied the same signal as in part 1 to its input. The expected peak-to-peak voltage of the output signal should be around 2*V*, and in practice, we got a 2.077 peak-to-peak voltage. We applied 1kHz frequency and 1Vpp signal to its inverting terminal. With formula *(1)*, we calculated the gain, A, of the amplifier,

$$A = 1 + \frac{R_2}{R_1} = 2 \ (1)$$

Our measured gain is $\frac{Vout}{Vin} = \frac{2.077V}{1V} = 2.077$, which agrees with the theoretical value.

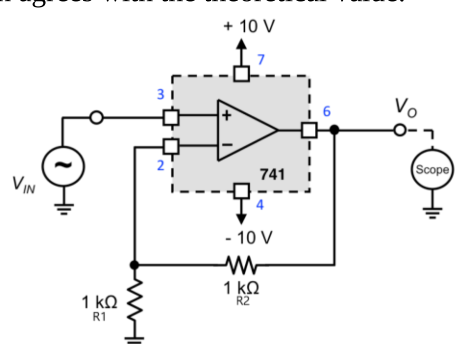

Fig. 12. Non-inverting Amplifier with a 1kHz sinusoidal input of 1V Vpp

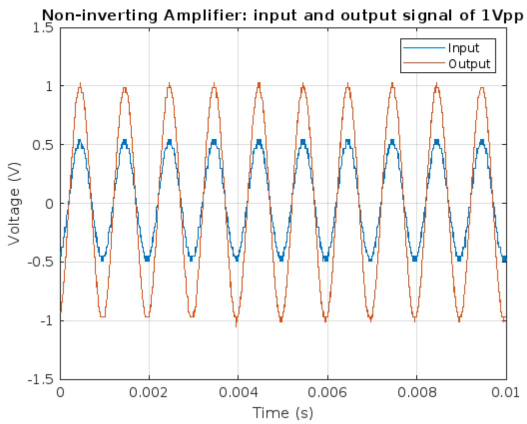

Fig. 13. Output voltage plotted by MATLAB when input has a 1V peak-to-peak value.

We then increased the peak-to-peak voltage of the input signal to 2*V* with 1kHz frequency, and the peak-to-peak voltage of the output signal we got was 4.026*V*. We can see the gain is maintained consistent around 2*V/V*.

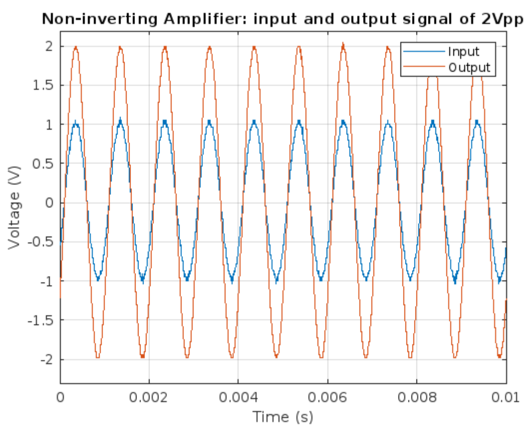

Fig. 14. Output voltage plotted by MATLAB when input has a 2V peak-to-peak value.

When applying a 1Vpp square wave input signal with 1kHz frequency to the non-inverting amplifier, we got an output square wave signal with 2Vpp (Fig. 15.). Hence, we concluded that the amplifier would not change the frequency or the waveform. Still, it will scale up the input signal by a factor of around 2, which is the gain of the circuit.

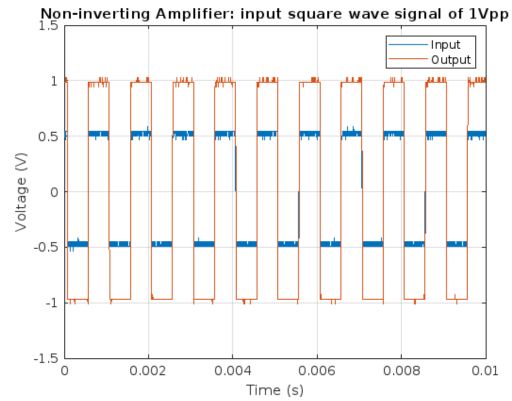

Fig. 15. The output voltage plotted by MATLAB when the square wave input has a 1V peak-to-peak value.

To change the gain of this non-inverting amplifier circuit to 10*V/V*, we did the circuit analysis, by which we noticed 10*V/V* gain could be achieved by increasing R_2 to 9kΩ. To do this, we decided to add an 8kΩ resistor in series with a 1kΩ resistor. However, we did not have an exact 8kΩ resistor; thus, we used a 10kΩ resistor instead to replace R_2. In this case, the expected voltage gain should be around 11. After changing the circuit, we got an output signal with a 10.980 peak-to-peak voltage, which indicated that the gain was approximately 11*V/V*. Hence, our circuits operated correctly and will achieve a gain of 10V/V if we have exactly 9kΩ resistor.

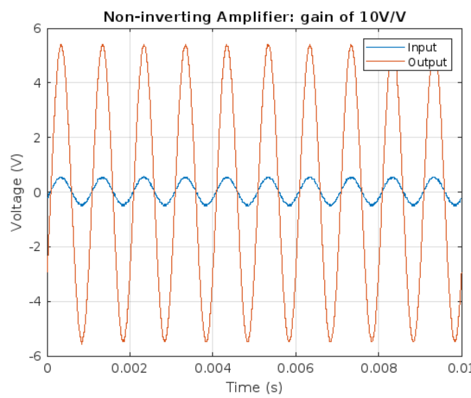

Fig. 16. Output voltage plotted by MATLAB when input has a 1V peak-to-peak value with R_2 replaced by an 8.2kΩ resistor in series with a 1kΩ resistor

D. Inverting Amplifier

We built the inverting amplifier as shown in Fig. 14, and connected the inverting input terminal to the virtual ground. We applied a 1Vpp signal with

1kHz frequency to its input. The expected peak-to-peak voltage of its output signal should be approximately 1, and our measured output signal had a 1.102 peak-to-peak voltage. With formula *(2)*, we calculated the gain, *A*, which is:

$$A = -\frac{R_2}{R_1} = -1 \; (2)$$

The magnitude of *A* is 1.

The magnitude of our measured gain is $\frac{Vout}{Vin} = \frac{1.102V}{1V} = 1.102$, which agrees with the theoretical value.

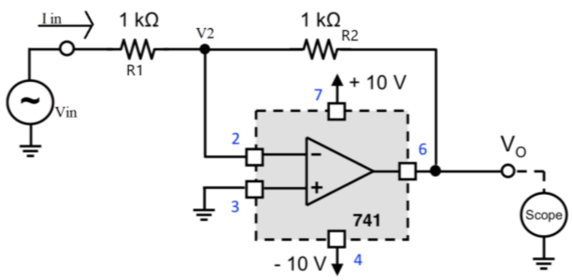

Fig. 17. Inverting Amplifier

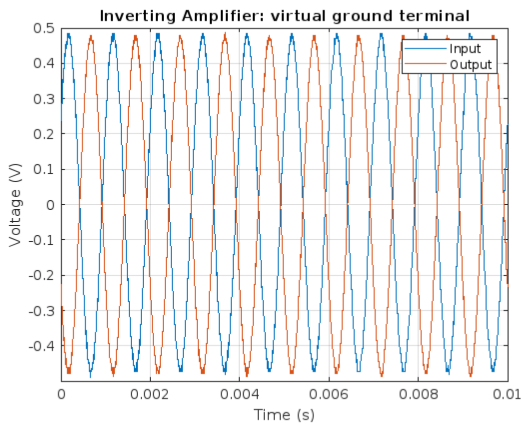

Fig. 18. Output voltage plotted by MATLAB when connecting the inverting input terminal to the virtual ground

If we connected the inverting input to the op-amp to the real ground, the expected voltage at the output should be 0 as the current will flow directly to the real ground. However, in practice, we noticed there was a sinusoidal output signal, as shown in Fig. 19, with a negative offset. This is probably because the op-amp we used in practice is not an ideal op-amp and there is an input bias current flowing the terminal. After the differential amplification, this current is detected by the oscilloscope.

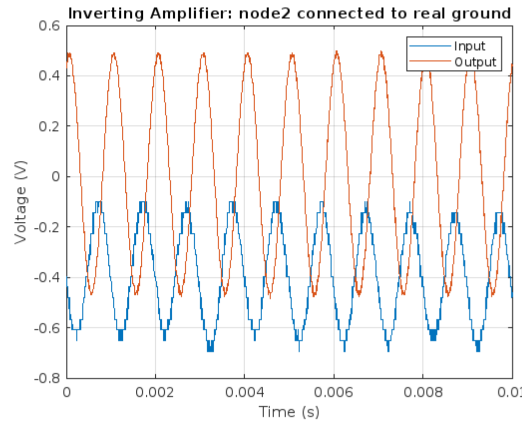

Fig. 19. Output voltage plotted by MATLAB when connecting the inverting input terminal to the real ground

To have a gain of $10V/V$ of the inverting amplifier circuit, we did circuit analysis and found out this could be done by replacing R_2 with a 10kΩ resistor. After changing the circuit, the expected voltage at the output should be around $10V$, and in practice, we got an output signal with a 9.653 peak-to-peak voltage. This indicated that we designed and built the circuit correctly.

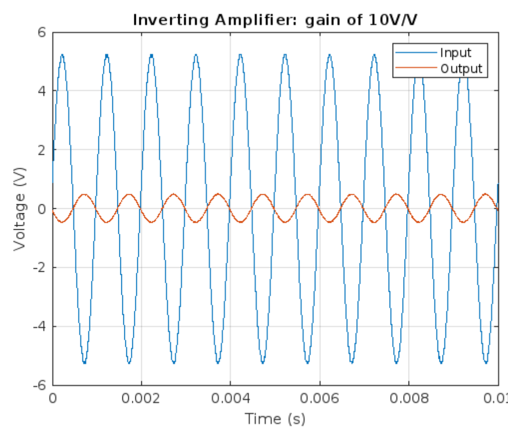

Fig. 20. Output voltage plotted by MATLAB when input has a 1V peak-to-peak value with R_2 being replaced by a 10kΩ resistor

We then changed the input voltage to 5Vpp. To compute the current flowing through the 1kΩ resistor, we measured the voltage at the output which was 4.76mV. Hence, with the 5Vpp input voltage, we got $\cdot V_{in} = \frac{5V}{2} = 2.5V$. The input current, I_{in}, was thus:

$$I_{in} = \frac{V_{in} - V_2}{R_1} = \frac{2.5V - 4.76 \times 10^{-3}V}{1k\Omega}$$
$$= 2.49524 \times 10^{-3}A$$

Thus, with a $5V$ input voltage, the input impedance was:

$$\frac{V_{in}}{I_{in}} = \frac{2.5V}{2.49524 \times 10^{-3}A} = 1001.907632\Omega$$

E. Differentiator

We reproduced the circuit as shown in figure 21. Theoretically, the output voltage of the differentiator is $Vo = -RC\frac{dVin}{dt}$.If we plug in the values and $Vin = 0.5Vsin(2000\pi Hz * t)$, we will get the expected output voltage should be $(-)0.69cos(2000\pi Hz * t)$. As shown in figure 22, measured output is in the form of negative cosine wave and have an amplitude of around 0.7V.

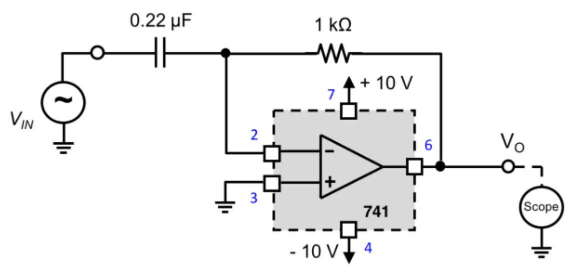

Fig. 21. Differentiator circuit.

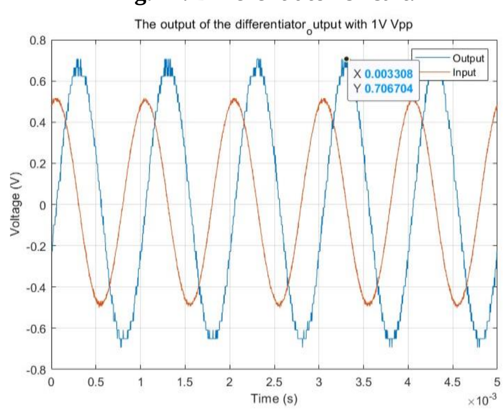

Fig. 22. Output voltage of the differentiator plotted by MATLAB

We then changed the input to a triangular wave. The slope of the triangular wave with 1V Vpp and 1k Hz should be 2000V/s and -2000V/s in one period. The expected output is thus $Vo = \pm RC(2000) = \pm 0.44V$. Our measured result is shown in figure 23 and the peak values agree with our calculation.

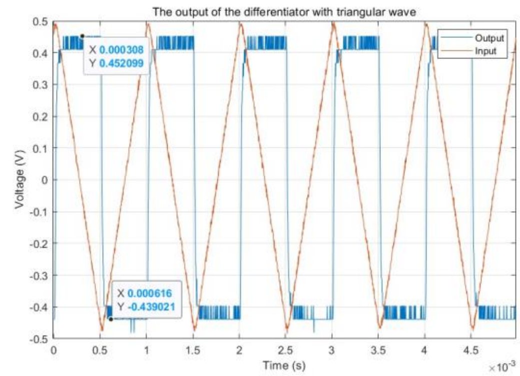

Fig. 23. Output voltage of the differentiator with triangular input plotted by MATLAB

F. Integrator

Similar to what we have done in differentiator, the expected output voltage should be $\frac{-1}{RC}\int_0^t V_{in}(\tau)d\tau = -5000\int_0^t V_{in}(\tau)d\tau$.
Then we changed the output to the square wave. Figure 24 and 25 show our results.

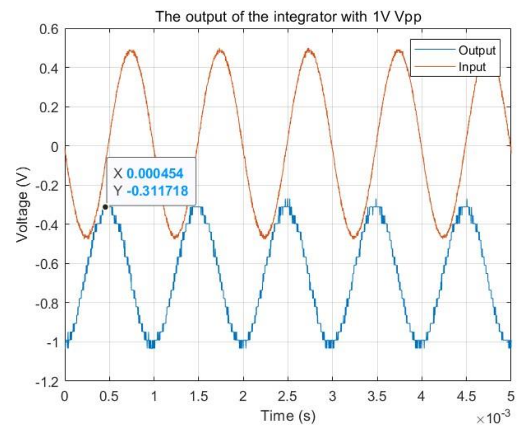

Fig. 24. Output voltage of the integrator with 1V Vpp input plotted by MATLAB

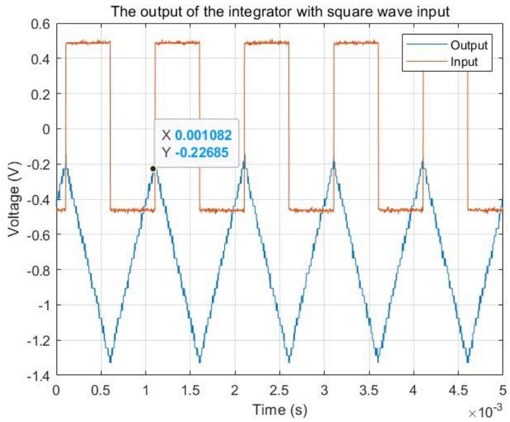

Fig. 25. Output voltage of the integrator with square wave input plotted by MATLAB

F. D/A Converter

We built the D/A converter circuit as shown in Fig. 26. With a D/A converter, we can convert digital signals into analog signals. We used four resistors, each of which represents one bit (0 or 1), to represent 16 digital signals in binary. These four resistors were connected in parallel to the input of the amplifier. When a switch is closed, the resistor controlled by this switch will be connected to the circuit, and the bit represented by this resistor will become one. This way, we could represent digital signals from 0000 to 1111.

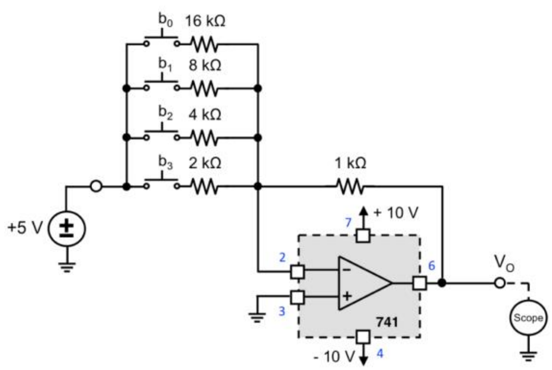

Fig. 26. D/A Converter

This is an inverting amplifier; thus, we calculated the expected output of 16 signals respectively with the formula

$$V_{out} = V_{in} \times A \ (3)$$

where A is the circuit gain and can be calculated through formula *(2)*. We used LTspice to simulate the D/A converter and recorded the simulated output result. We put our measured output, the calculated outputs, and the simulated outputs in a table (Fig. 27).

b3b2b1b0	Calcuated Vout (V)	LTspice Simulated Vout (V)	Measured Vout (V)
0000	0.0000	0.000	0.00000
0001	-0.3125	-0.317	-0.31367
0010	-0.6250	-0.631	-0.60667
0011	-0.9375	-0.941	-0.91465
0100	-1.2500	-1.249	-1.267
0101	-1.5625	-1.556	-1.583
0110	-1.8750	-1.874	-1.863
0111	-2.1875	-2.191	-2.172
1000	-2.5000	-2.504	-2.473
1001	-2.8125	-2.803	-2.773
1010	-3.1250	-3.131	-3.091
1011	-3.4375	-3.435	-3.366
1100	-3.7500	-3.743	-3.722
1101	-4.0625	-4.073	-4.018
1110	-4.3750	-4.364	-4.325
1111	-4.6900	-4.690	-4.640

Fig. 27. Calculated V_{out}, Simulated V_{out} by LTspice, and Measure V_{out} for each input digital signal of the D/C converter

We plotted the output voltage of the D/A converter as a function of the digital control signals. Moreover, we joined the two endpoints (0000,0) and (1111, -4.640) with a straight line to observe the maximum distance our measured value deviates from this line (Fig. 28). The maximum deviation of our measured output from the straight line, $y = -0.3093x + 0.3093\ (1 \leq x \leq 16)$, is at point (1011, -3.366). It deviated from the straight line by 0.0363.

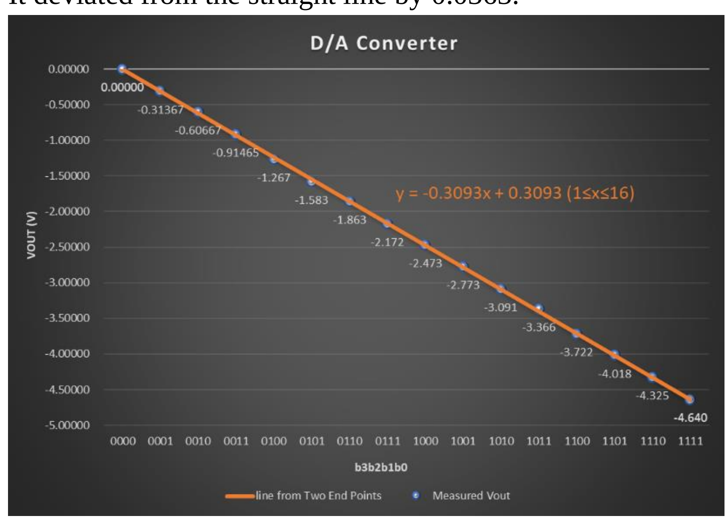

Fig. 28. Plot of the measured output voltage of the 16 input digital signals to the D/A converter

III. CONCLUSION

From this lab, students learned how to build and analyze OpAmp circuits with different characterizations. By implementing these circuits in practice, we consolidated our knowledge, and we learned how the output voltage of each amplifier circuit was produced. After building circuits and designing some simple circuits to get the wanted gain, we have a better understanding of the dynamic behavior of an operational amplifier.

APPENDIX

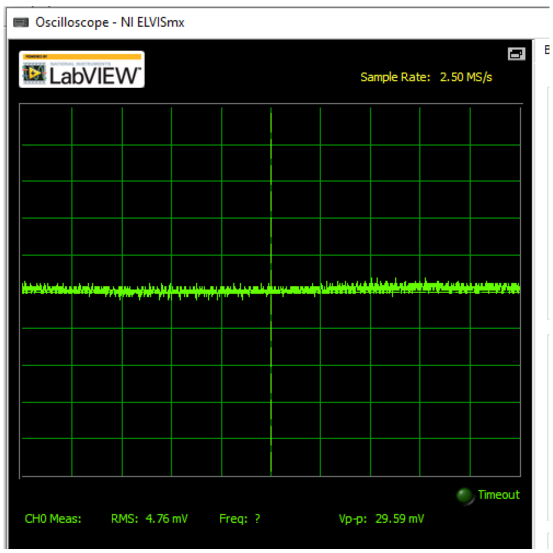

Fig. 29. Voltage measured at the inverting terminal of the inverting amplifier of a 5Vpp input signal