Winter 2023 ECSE 331: Electronics

Laboratory 2: Characterization of Basic Op-Amp Circuits

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***Abstract*— The purpose of this laboratory assignment is to conduct measurements using the 741 op-amp and test its behavior in different configurations on NI-ElvisII+ prototyping board. These configurations are: comparator, voltage follower, non-inverting amplifier, inverting amplifier, differentiator, integrator and digital to analog converter. In addition, while conducting the experiment we were also introduced 741 op-amp pins. The results we obtained were compared with LT Spice simulations and are referred to as theory throughout the report. These spice simulations can be found in the appendix of the report.**

Keywords- 741 Op-amp, Comparator, Voltage Follower, Non-inverting Amplifier, Inverting Amplifier, Differentiator, Integrator, D/A Converter

I. INTRODUCTION

Operational amplifiers are DC-coupled voltage amplifiers with single input dual output design configuration. Specifically, the 741 op-amp is an analog integrated circuit that has a high voltage gain, a wide range of operating voltage, and a high input impedance. It is affordable and versatile; thus, it can be used in various applications. 741 op-amp has 8 pins in total each having different purposes as seen in figure 1A.

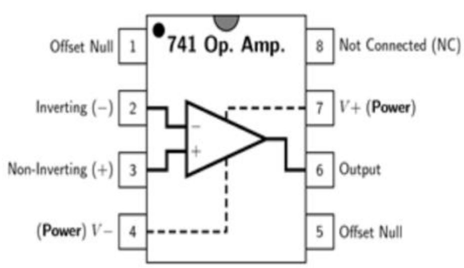

Figure 1A - 741 Op-amp Pin-Out Configuration

The investigation is divided into seven distinguishable parts; each concerned with a specific configuration of the 741 op amp circuit. The parts are labeled according to the configuration; a comparator, a voltage follower, a non-inverting amplifier, an inverting amplifier, a differentiator, an integrator, and a D/A converter.

II. METHODOLOGY AND ANALYSIS

A. The Op-Amp Comparator

The circuit in figure 1B is that of an Op Amp Comparator circuit; a circuit which compares one

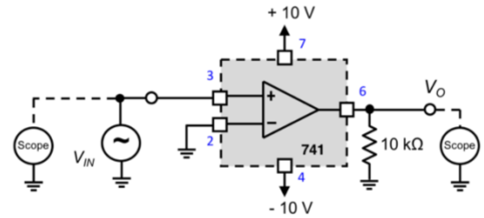

Figure 1B – Op Amp Comparator Circuit

analog voltage level with another voltage level. This deems to be very useful in practical usages of the op amp. The circuit in Figure 1B was built on the Elvis prototyping board and circuit analysis of the circuit commenced. Our input voltage signal was a 1 kHz sine wave with a 1V peak-to-peak voltage. A scope channel was connected to both the input and output signal to inspect both signals at each respective point. The output of the scope can be observed in figure 1C.

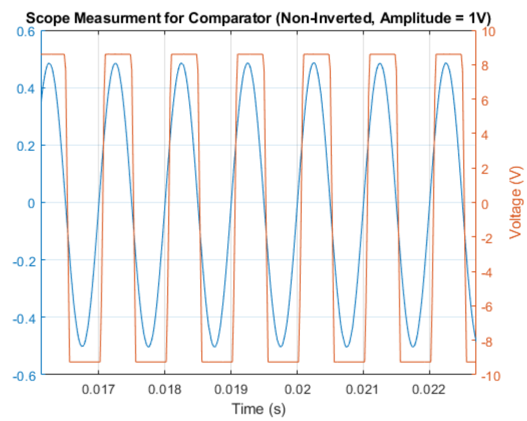

Figure 1C – Scope Plot of Input and Output Signal (Blue Input, Orange Output)

As seen from the plot above; our circuit acts as a comparator between the input voltage V_{IN} (blue) and our grounded, inverting input. And so; we can see from this plot that when our input signal is higher than the ground (in the band of positive voltage), the output becomes high and when it is low, the output becomes low; creating a square wave across the plot. This complies with our theoretical measurements from LTSpice. Furthermore, the RMS value of our output was measured to be 5.121 V. We then reduced the amplitude of the input signal to 0.1 V. After changing the amplitude, we noticed that the output signal is identical to that of figure 1C. This is due to our configuration, which does not consider the input amplitude.

Next, we grounded the input of the positive terminal of the op amp and connected our input signal to the negative terminal of the op amp. The scope plot for this configuration can be observed in figure 1D; where we see an output signal that is like that of 1C. However, unlike the non-inverting configuration, we can observe a phase shift resulting in inversion. This follows from general theory as the inverting port inverts the input signal being compared.

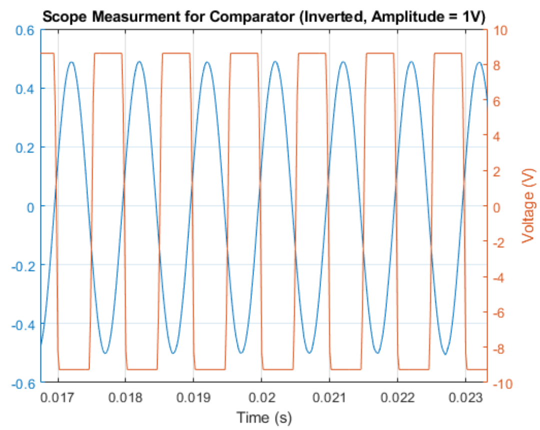

Figure 1D – Scope Plot of Inverting Comparator

B. The Op-Amp Voltage Follower

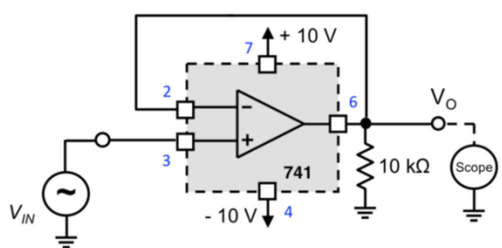

Figure 2A – Closed Loop Op-Amp Voltage Follower Circuit

Within this section we investigate the op-amp voltage follower. We assembled the circuit as seen in figure 2A and applied the same 1 kHz, 1V peak-to-peak sine signal as input to the circuit. We can examine the output to our voltage follower in figure 2B, to recognize an output of a nearly identical plot of our input. The output signal realized an RMS value of 350.02 mV, a frequency of 1 kHz, and a peak-to-peak voltage of 993.96 mV. This follows from theory as a voltage follower produces a signal that is equal in amplitude to the input signal; causing it to act as a buffer. The input impedance was measured by running varying voltages through the circuit and recording the current according to each voltage level. A measurement for 5V and 10V; arriving at a current of 2.75 mA and 2.83 mA. We then took the difference of these two points and arrived at the impedance using the impedance equation of Z = V/I. We arrived at an input impedance of 62500 Ω. This also follows from theory as the input impedance of an ideal op-amp should be infinite; however, we are not working with an ideal op-amp, so, we see that the input impedance has a very high magnitude [1].

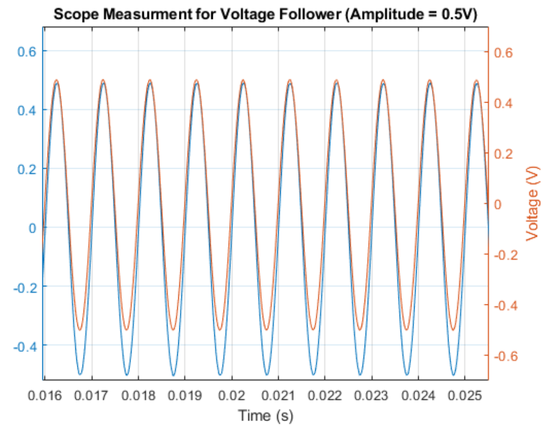

Figure 2B – Scope Plot of Voltage Follower with Sine Input

We then ran a square wave (with the same frequency and amplitude characteristic as our sine wave) through the voltage follower and achieved an output of an identical signal through the output; seen in figure 2C.

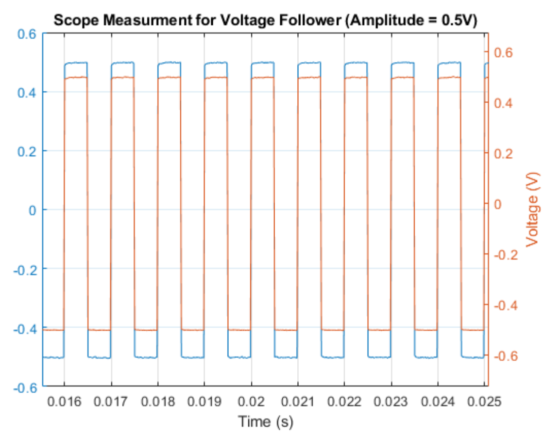

Figure 2C – Scope Plot of Voltage Follower with Square Input

C. The Op-Amp Non-Inverting Amplifier

Within this section of the investigation, we took on a closed loop non-inverting amplifier configuration as seen in figure 3A. We applied an input of a 1 kHz sine wave with a 1V peak-to-peak voltage and commenced circuit analysis on the configuration. As seen in figure 3B, our output is also a sine wave; however, with a higher amplitude. Further, after examining the input to the inverting terminal of the op-amp, we find that it has the same form and characteristics as our input signal.

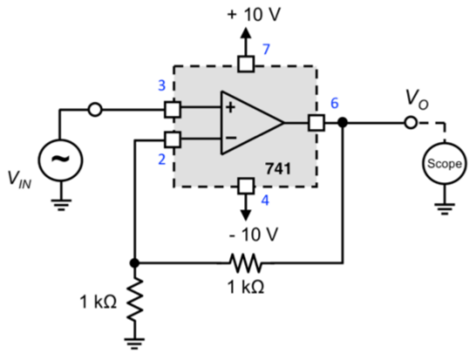

Figure 3A – Non-Inverting Op-Amp Amplifier Circuit

To find the gain of this amplifier, we first found the theoretical value by using the equation below [1] and validating using LTSpice. It should be noted that R_f corresponds to the feedback resistor seen in the above circuit, while R_g is the grounded resistor. We infer that the gain of our amplifier should be around 2 V/V, according to the equation below. Then, through our measurements with this specific input signal we receive an RMS reading for V_{In} of 350.19 mV, while our V_{Out} had a reading of 696.51 mV, giving us a gain of approximately 1.99 V/V. We then tested this configuration of the circuit across varying input signal amplitudes to arrive at the table seen in figure 3C. From this table we can further confirm experimentally that the gain of this configuration and op-amp are indeed of a magnitude of ≈ 2 V/V. Figure 3C also confirms that the gain of the circuit does not change across varying input signal amplitudes; the signals are proportionately scaled by a factor of 2.

$$Gain = \frac{V_{Out}}{V_{In}} = 1 + \frac{R_f}{R_g}$$

Equation 1 – Gain of Closed Loop Op-Amp Amplifier

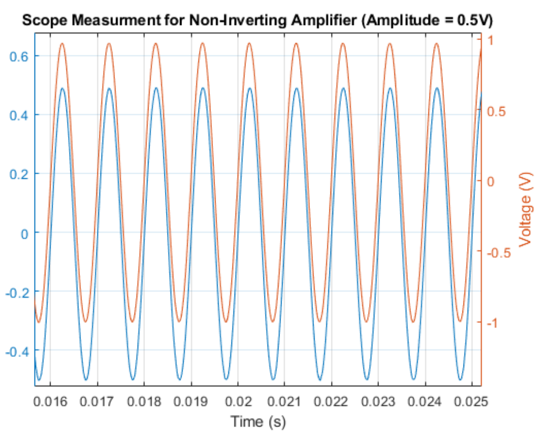

Figure 3B – Scope Plot of Non-Inverting Amplifier

Amplitude of Input (V_{PP})	V_{In} (V)	V_{Out} (V)	Gain (V/V)
1	0.35019	0.69651	1.989
2	0.70923	1.41300	1.992
4	1.41500	2.81900	1.992
6	2.12800	4.23900	1.992

Figure 3C – Table of Gain Against Varying Frequencies

We then tested this configuration against a square wave input with a V_{PP} value of 1 V to arrive at the scope plot in figure 3D. Again, the signal was simply amplified through our configuration where the input signal RMS value is 499.12 mV and the output signal RMS is 994.4 mV; again realizing a gain of 2 V/V.

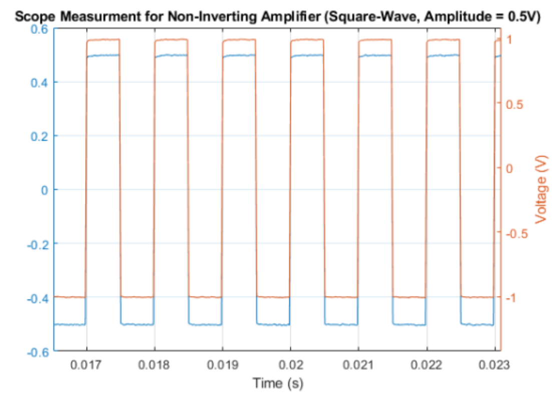

Figure 3D – Scope Plot for Square Wave Input in Non-Inverting Amplifier

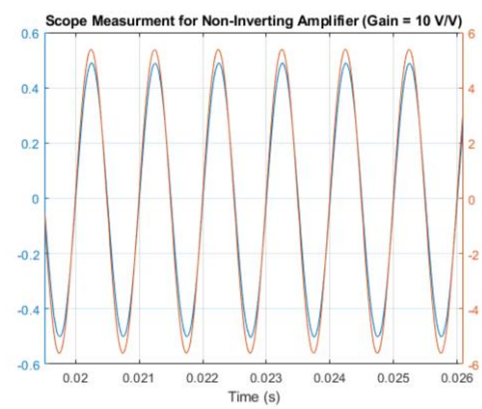

Figure 3E – Scope Plot for a Gain of 11 V/V

In order to realize a gain of 10 V/V we must change the ratio of the feedback resistor with the grounded resistor to a magnitude of 9. This could be done by replacing the feedback resistor by a 9 kΩ resistor. However, due to a limited supply of resistors; we opted to replace it with a 10 kΩ resistor to theoretically arrive at a gain of ≈ 11 V/V. We then ran a 1 kHz, 1 V_{PP} sinusoidal input through the circuit. By doing this, we arrive at a scope plot seen in figure 3E. We can see that the input signal has an RMS value of 350.19 mV and the output signal has a value of 3.887 V. By using equation 1, we arrive at a gain of 11.09 V/V.

D. The Op-Amp Inverting Amplifier

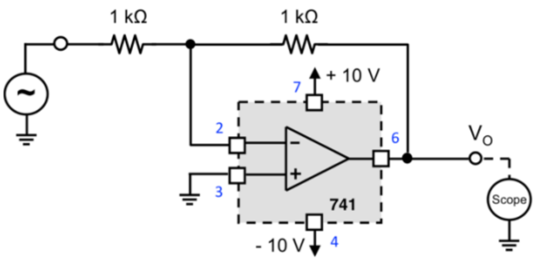

Figure 4A – Closed Loop Inverting Op-Amp Circuit

Within this section of the investigation, we take on the closed loop op-amp inverting amplifier circuit seen in figure 4A. Before we commenced circuit analysis on this configuration, we measured the voltage at the inverting input terminal of the op-amp. We measured a value of 1.578 mV; a tiny magnitude of voltage which follows through from theory and our LTSpice simulations. Then, by applying the 1 kHz, 1 V_{PP} sine wave input we arrive at the plot in figure 4B. We can realize the gain of this circuit theoretically by way of equation 2 as -1 V/V (with R_f being the feedback resistor and R_s, our source resistor). We can observe from our plot in figure 4B that the input signal has an RMS value of 331.15 mV, while our output has an RMS value of 328.90 mV; giving us a gain of 0.99 V/V, and by observing that our output signal has a phase shift of around π; we can realize that this output RMS is inverted to give us a gain of -0.99 V/V; which follows from our theoretical predictions [1].

$$Gain = \frac{V_{Out}}{V_{In}} = -\frac{R_f}{R_s}$$

Equation 2 – Gain in a Closed Loop Inverting Amplifier

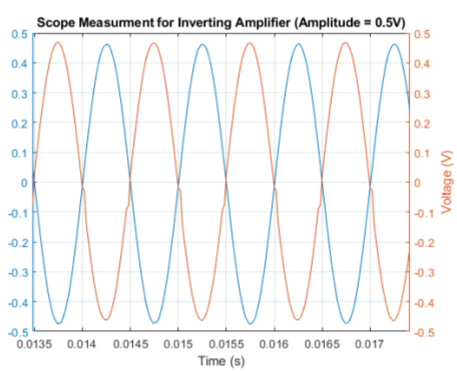

Figure 4B – Scope Plot of Closed Loop Inverting Amplifier

We then connected the inverting terminal to the op-amp to the ‘real ground’ of the circuit opposed to the virtual ground created by the connection between the resistors. The same input signal was then run through the circuit to arrive at an output signal seen in figure 4C. From this plot we observe that the output signal has an RMS value of 9.039 V, while the input has a value of 434.06 mV. This follows from theoretical analysis in LTSpice and is justifiable by the inverting terminal acting as a ‘virtual ground’ to the rest of the circuit, hence also why the readings of the output span negative values. We also notice a slight distortion in the signal which is assumed to be electrical noise created within the internal circuitry of our configuration.

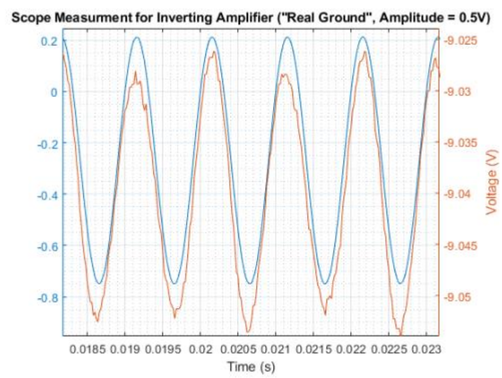

Figure 4C – Plot of Output when Inverting Terminal is Grounded

In order to change the magnitude of the gain of this circuit to 10 V/V, we would have to swap out the feedback resistor R_f for a resistor with a resistance of 10 kΩ, this is to achieve a ratio of magnitude 10 according to equation 2. So, we swapped the 1 kΩ resistor for a 10 kΩ resistor to arrive at the output seen in figure 4D. We can see from this plot that the gain is indeed at a magnitude of 10 with our input RMS being 331.67 mV and our output RMS being 3.349 V; giving us a gain of -10.097 V/V.

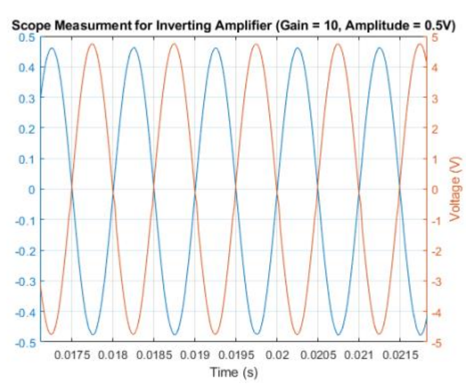

Figure 4D – Scope Output of Inverting Amplifier with Gain of 10

We then measured the input impedance of the circuit in a similar fashion to that of part B; across the 1 kΩ source resistor R_S. We measured the current caused by a 5 V_{PP} and a 10 V_{PP} input and arrived at the respective measurements of 147.33 mA and 152.03 mA. Then, by using the impedance formula mentioned in part B, and taking the difference in measurements, we arrive at an input impedance of 1063.83 Ω. This value follows from theoretical and LTSpice analysis; as the resistor is connected directly to the voltage, the input impedance of the circuit is caused by this very resistor, and hence it follows that since the resistor has a resistance of 1 kΩ, that our overall input impedance of the circuit is close to this resistance.

E. The Op-Amp Differentiator

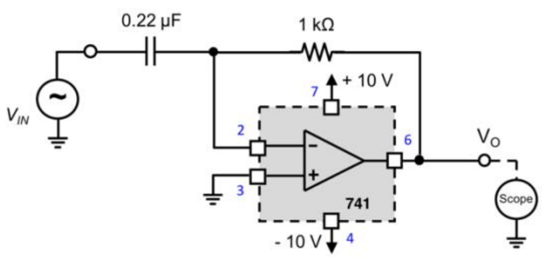

Figure 5A – Op-Amp Differentiator Circuit

We then reconfigured our circuit to match that of an op-amp differentiator circuit seen in figure 5A. Then, we ran an input of a 1 kHz sine wave with a 1V peak-to-peak voltage and commenced circuit analysis on the configuration. The scope plot of our circuit can be found in figure 5B. We notice that this plot showcases our output signal as a shifted version of our input signal, with a shift of about π/2. This follows from theoretical analysis as this circuit is intended to act as a differentiator; and since the differentiation of a sine wave is a cosine wave, it follows that there would be a phase shift of about π/2. Furthermore, our circuit amplified the input signal by a factor of 1.33 V/V.

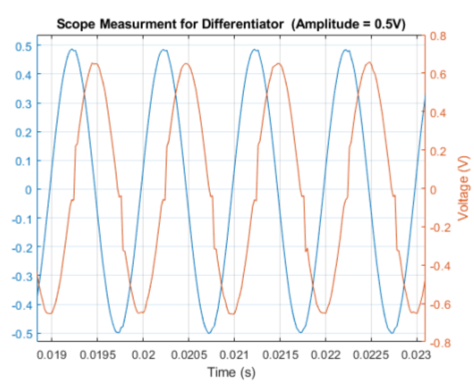

Figure 5B – Scope Output of Op-Amp Differentiator

A similar result was achieved when we substituted our input signal for a triangular signal with the same characteristics. As seen in figure 5B, the signal was differentiated and amplified by a factor of 1.43 V/V.

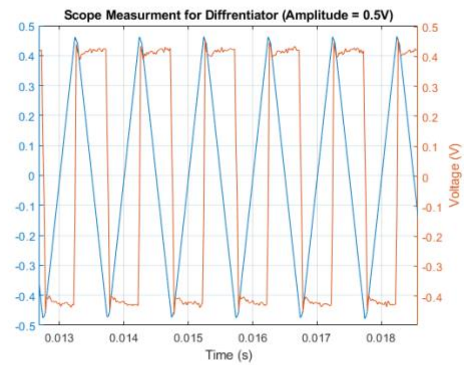

Figure 5C – Scope Plot of Op-Amp Differentiator (Triangular Wave Input)

F. The Op-Amp Integrator

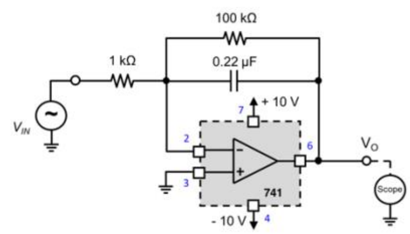

Figure 6A – Op-Amp Integrator Circuit

The circuit was reconfigured to create an op-amp integrator seen in figure 6A. Then, we ran the same input of a 1 kHz sine wave with a 1V peak-to-peak voltage and commenced circuit analysis on the configuration to arrive at the plot in figure 6B. As seen from the plot we can infer that the output signal resembles that of the input with a phase change of about 3π/2, which also corresponds to an inverted cos signal. Again, this result follows from theory as the integration of a sine wave is an inverted cos wave. Further it is noted that the output signal experiences a gain of about 1.53 V/V.

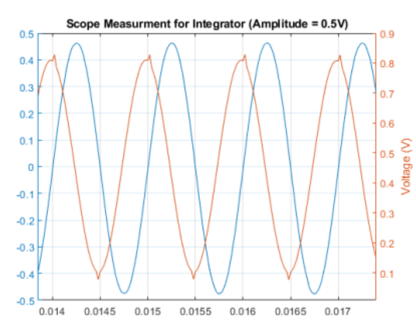

Figure 6B – Scope Plot of Op-Amp Integrator

This analysis was completed on a square wave input with the same characteristics of our sine wave. As seen in figure 6C, the input signal was integrated to create a triangular wave output; the inverse operation that was done in part E. It is noted that noise appears to disturb the signals, and this could be due to parasitic impedance within the internal circuitry of the op amp.

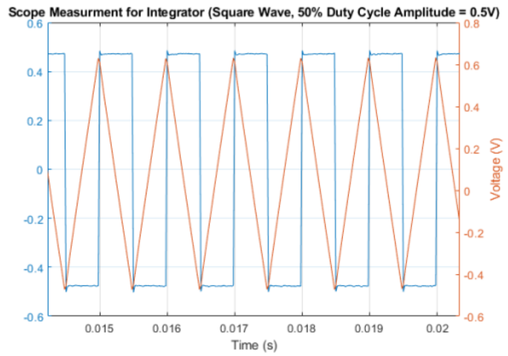

Figure 6C – Scope Plot for Op-Amp Integrator (Square Wave)

G. *The Op-Amp D/A Converter*

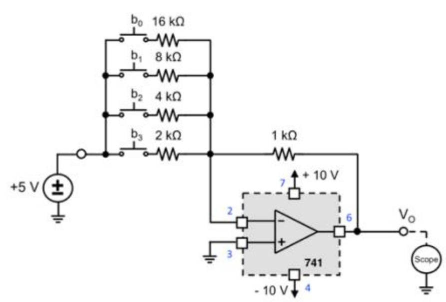

Figure 7A – D/A Converter Op-Amp Circuit

Within this section, we arranged the op-amp circuit in a configuration that allows for the circuit to act as a digital to analog converter. This configuration can be observed in figure 7A. This works by recognizing different configurations of the four switches to match a specific voltage representing 16 different 'states'. These states are dictated by the four switches where each state represents a binary number where b_0 is the least significant bit and b_3 is the most significant bit. Hence, these numbers are placed in the column of the table in figure 7B. This data was then plotted to arrive at the plot in figure 7C. From this plot we see a linear relationship with a maximum deviation of around 0.01 V at the integer 8 configuration point.

Binary Number by Switch	Output Voltage (V)
0	0.0027
1	0.3125
2	0.6216
3	0.9304
4	1.2490
5	1.5550
6	1.8620
7	2.1750
8	2.4940
9	2.8030
10	3.1120
11	3.4120
12	3.7230
13	4.0310
14	4.3380
15	4.6460

Figure 7B – Table of Results for D/A Converter

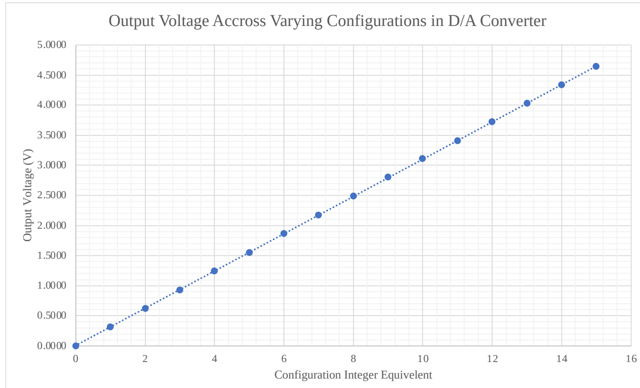

Figure 7C – Plot of Configuration Against Output Voltage

III. CONCLUSION

In conclusion, operational amplifiers, or op-amps, are highly versatile components that can produce a range of outcomes by simply altering their configurations. During this laboratory session, we used a 741 op-amp and explored its several configurations, including comparator, voltage follower, non-inverting amplifier, inverting amplifier, differentiator, integrator, and D/A converter. Our data was compared with the results from LT Spice simulations. It was found that our measured results were mostly consistent with the simulated results from LT Spice. To further improve accuracy and minimize errors, it is recommended to increase the number of trials for each experiment.

IV. REFERENCES

[1] A. S. Sedra and Kenneth Carless Smith, Microelectronic circuits. New York: Oxford University Press, 2010.

V. APPENDIX

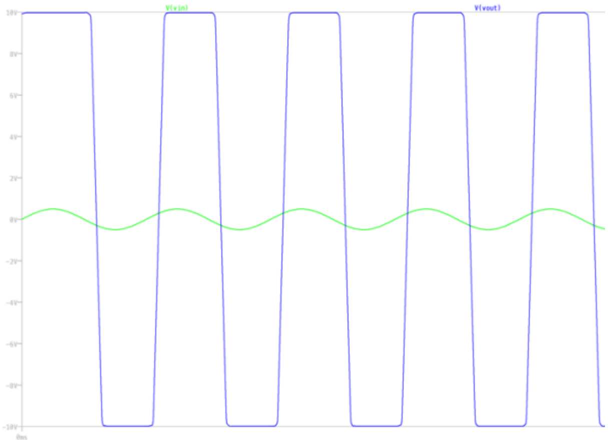

Figure I: LT Spice Plot with 1kHz, 1 Vp-p Sine Wave Input for Comparator Circuit

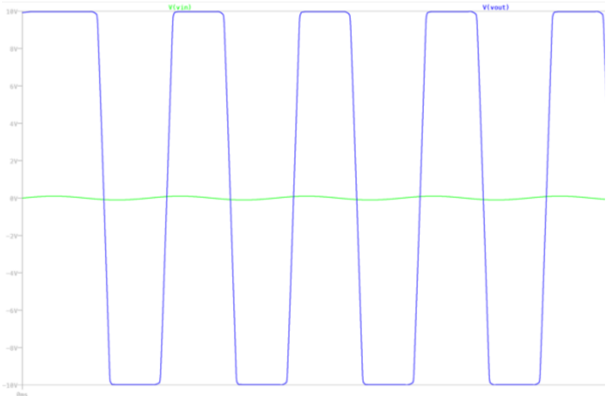

Figure II:LT Spice Plot with 1kHz, 0.2 Vp-p Sine Wave Input for Comparator Circuit

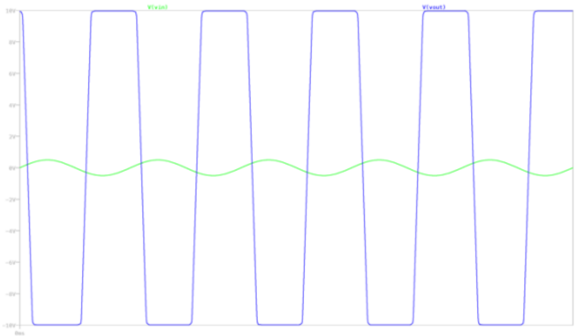

Figure III: LT Spice Plot with Positive Terminal Grounded for Comparator Circuit

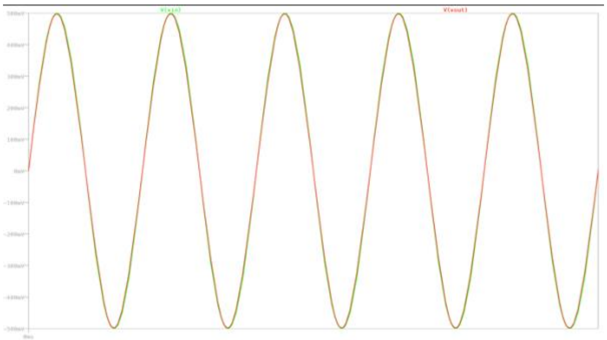

Figure IV: LT Spice Plot for Voltage Follower Circuit with Sine Wave input

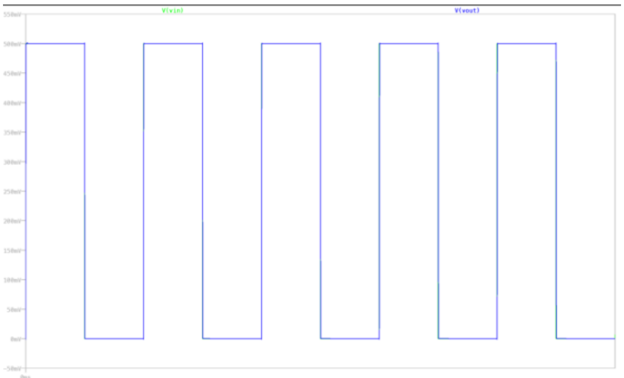

Figure V: LT Spice Plot for Voltage Follower Circuit with Square Wave input

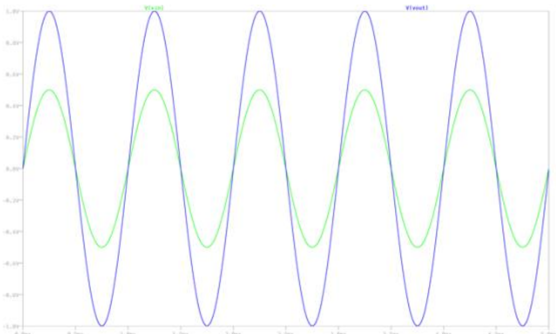

Figure VI: LT Spice Plot for Non-Inverting Circuit with 1kHz, 1 Vp-p Sine Wave input

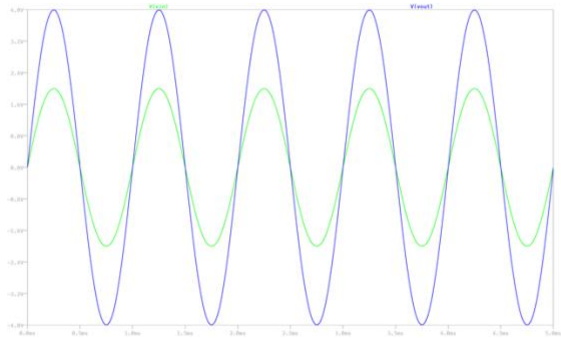

Figure VII: LT Spice Plot for Non-Inverting Circuit with 1kHz, 4 Vp-p Sine Wave input

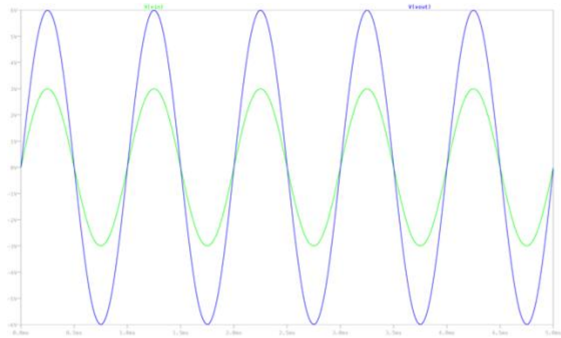

Figure VIII: LT Spice Plot for Non-Inverting Circuit with 1kHz, 6 Vp-p Sine Wave input

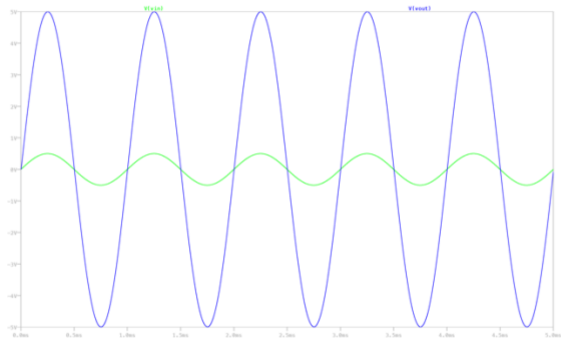

Figure IX: LT Spice Plot for Non-Inverting Circuit That Has 10 V/V Gain

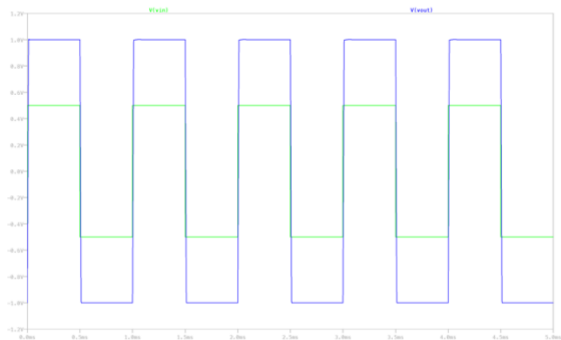

Figure X: LT Spice Plot for Non-Inverting Circuit with Square Wave Input

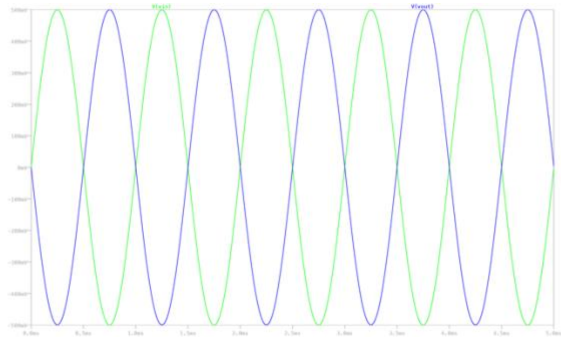

Figure XI: LT Spice Plot for Inverting Circuit with 1kHz, 1 Vp-p Sine Wave Input

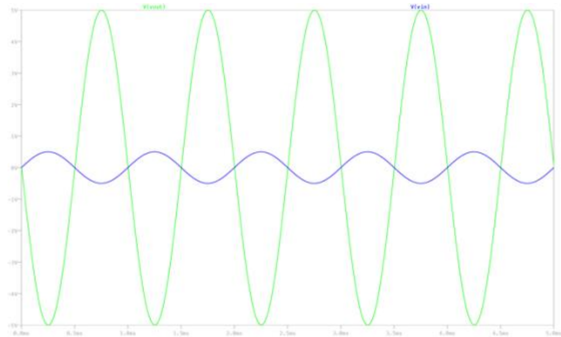

Figure XII: LT Spice Plot for Inverting Circuit that has 10 V/V Gain

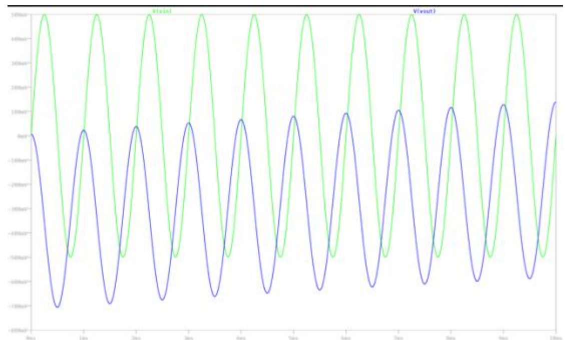

Figure XIII: LT Spice Plot for Integrator Circuit with 1kHz, 1 Vp-p Sine Wave Input