Laboratory No 2.

Characterization of Some Basic Op-Amp Circuits

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***Abstract*—This laboratory report presents the characterization of basic operational amplifier (op-amp) circuits using the 741 op-amp. Various configurations, including comparator, voltage follower, non-inverting amplifier, inverting amplifier, differentiator, integrator, and digital-to-analog converter (DAC) circuits, were constructed and analyzed. The experimental results were compared to predictions from SPICE simulations to validate the dynamic behavior of these circuits. The experimental setup involved the NI ELVIS-II+ test instrument for measurement and prototyping. The study focuses on understanding the practical applications of op-amps in analog circuit design, examining factors such as signal integrity, gain, impedance, and transient response. Observations indicated good agreement between the experimental data and theoretical predictions, with minor deviations due to practical limitations and component tolerances.**

***Keywords*—electronics, NI Elvis-II+, operational amplifier**

I. Introduction

Operational amplifiers (op-amps) are fundamental building blocks in analog electronics, widely used in various applications such as amplification, signal conditioning, and mathematical operations. The 741 op-amp, in particular, serves as a versatile component for educational purposes due to its well-defined characteristics and ease of use. This laboratory experiment aims to investigate the dynamic behavior of several basic op-amp circuits, including comparators, voltage followers, amplifiers, differentiators, and integrators. Each configuration explores different aspects of op-amp functionality, such as gain, bandwidth, input/output impedance, and response to varying input signals.

The experiment utilizes the National Instruments Educational Laboratory Virtual Instrumentation Suite (NI ELVIS-II+), a comprehensive test platform that integrates multiple measurement instruments. This setup enables precise analysis of circuit performance and facilitates comparison with theoretical models and SPICE simulations. The primary objective is to bridge the gap between theoretical concepts and practical implementation by examining real-world circuit behavior and identifying factors that affect performance, such as parasitic capacitance and component non-idealities.

II. Experiment Procedures and Analysis

This section presents a detailed analysis of seven fundamental op-amp circuits: comparator, voltage follower, non-inverting amplifier, inverting amplifier, differentiator, integrator, and digital-to-analog converter (D/A converter). Each experiment is designed to investigate a specific aspect of op-amp behavior and its practical applications in electronic circuits. The experiments utilize the 741 op-amp and are conducted using the NI ELVIS-II+ platform for precise measurement and analysis.

1. **Comparator Op-Amp Circuit**: This experiment explores the use of an op-amp as a comparator, where the output indicates the relative voltage levels at the input terminals.
2. **Voltage Follower Op-Amp Circuit**: The voltage follower configuration, also known as a buffer, is analyzed for its high input impedance and unity gain properties, making it ideal for signal isolation.
3. **Non-Inverting Op-Amp Circuit**: This experiment demonstrates the amplification capabilities of the op-amp in a non-inverting configuration, focusing on gain control and signal fidelity.
4. **Inverting Op-Amp Circuit**: The inverting amplifier configuration is tested for its ability to provide precise signal inversion and gain adjustment, critical for many analog signal processing applications.
5. **Differentiator Op-Amp Circuit**: This circuit is used to highlight the op-amp's ability to perform mathematical differentiation, useful in analog computing and waveform shaping.
6. **Integrator Op-Amp Circuit**: The integrator configuration is explored for its role in accumulating input signals over time, serving functions in analog computation and signal processing.
7. **D/A Converter Op-Amp Circuit**: The final experiment involves constructing a 4-bit digital-to-analog converter using the op-amp, illustrating its utility in digital signal processing and interface circuits.

The results from these experiments will be compared with theoretical predictions and SPICE simulations to evaluate the accuracy and limitations of each configuration.

A. Part 1: Comparator Op-Amp Circuit

The input and output voltages, Vin and Vo, were measured using an oscilloscope as shown in the figure below. Power was supplied to the 741 op-amp using a variable power supply.

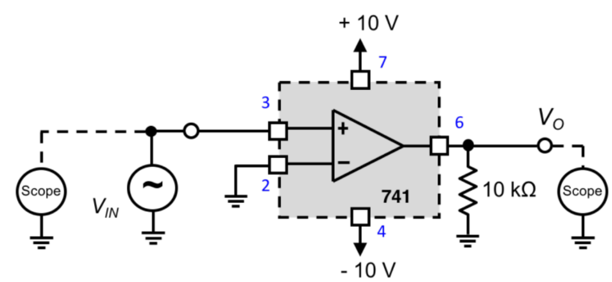


Figure 1.1: Comparator op-amp circuit

As observed in the image below, the output of the circuit is 17.376 V peak-to-peak (8.688 V amplitude voltage). This output voltage is obtained when the input voltage provided is 1V peak-to-peak sine wave with 1kHz frequency.

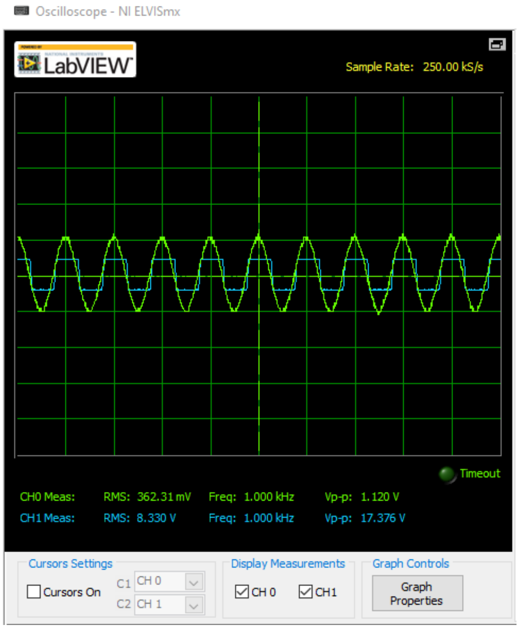


Figure 1.2: Comparator Output Response to 1 kHz Sine-Wave Input at 1V peak-to-peak

There is no significant impact on the output voltage even when the input voltage is changed from 1V peak-to-peak to 0.2V peak-to-peak (0.1V amplitude), as seen in the image below. This is due to the fact that the configuration of the comparator circuit makes the input volume irrelevant.

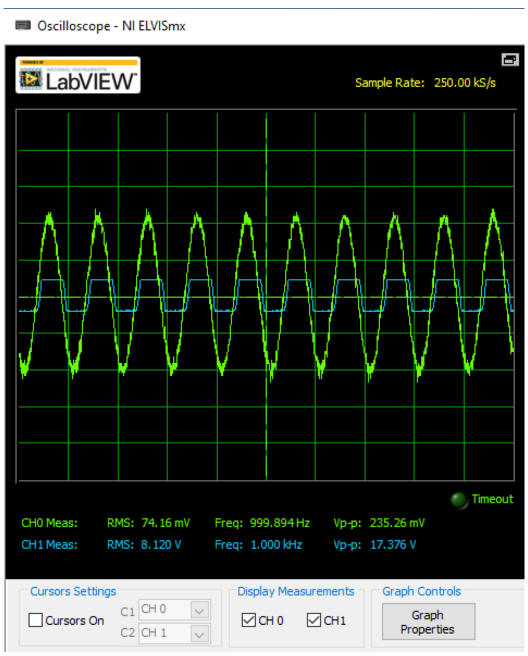


Figure 1.3: Comparator Output with 0.1V Input Amplitude at 1kHz

Furthermore, grounding the positive terminal and connecting the signal to the negative input alters the phase of the output voltage. In the diagram below, the output signal is shifted by 90 degrees. Other aspects of the sinusoidal output remain the same, it is simply the phase that got shifted.

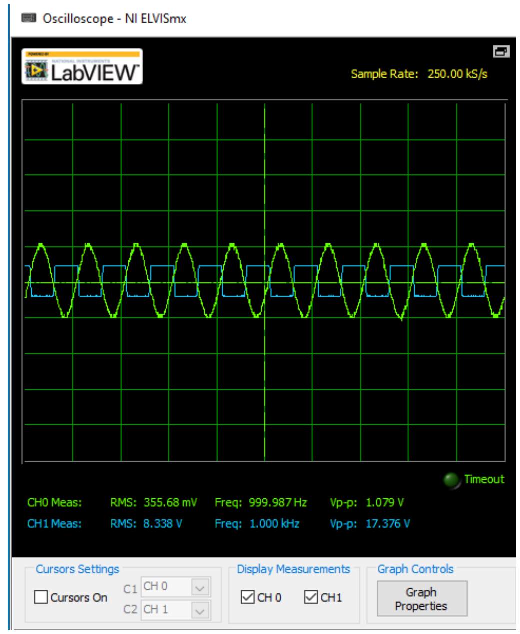


Figure 1.5: Comparator Output with 1V peak-to-peak at Negative Input and Grounded Positive Terminal at 1 kHz

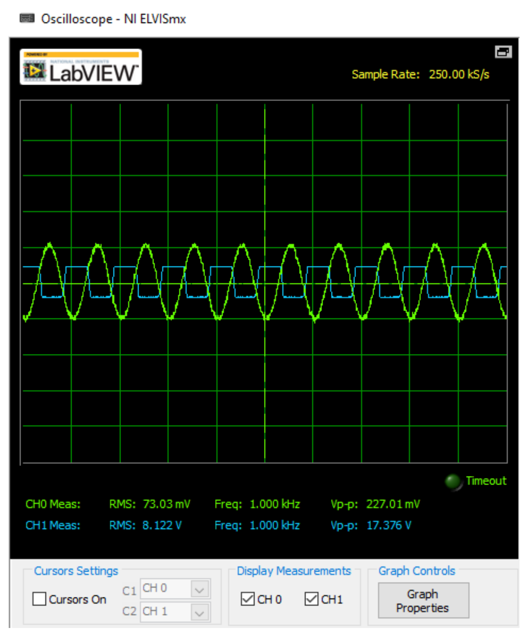


Figure 1.6: Comparator Output with 0.1V at Negative Input and Grounded Positive Terminal at 1kHz

B. Part 2: Voltage Follower Op-Amp Circuit

The output voltage, Vo, was measured as seen in the circuit below. The input signal was set to be the same as in *Part 1*, i.e. 1V peak-to-peak sine wave with 1kHz frequency.

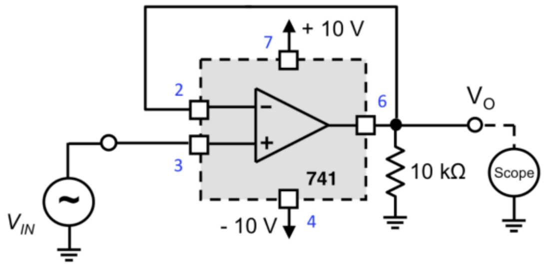


Figure 2.1: Voltage follower op-amp circuit

The measured output voltage, Vo, is found in the figure below. The output signal is a sinusoidal wave with a frequency of 1.000kHz and a peak-to-peak voltage of 1.028V. The op-amp circuit adjusts the output in a way that the output voltage and the frequency is the same as the input signal provided.

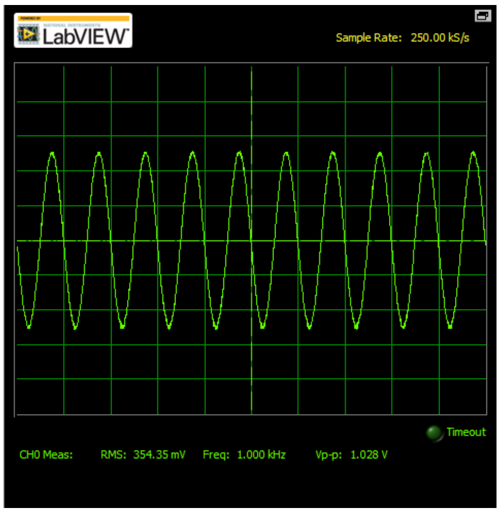


Figure 2.2: Output voltage signal with sine-wave input signal at 1V peak-to-peak

Next, the input impedance (Z) is calculated. To calculate the input impedance, a known resistor R_{test} of 1MΩ is used. The figure below shows the voltage across the op amp input V_{in}.

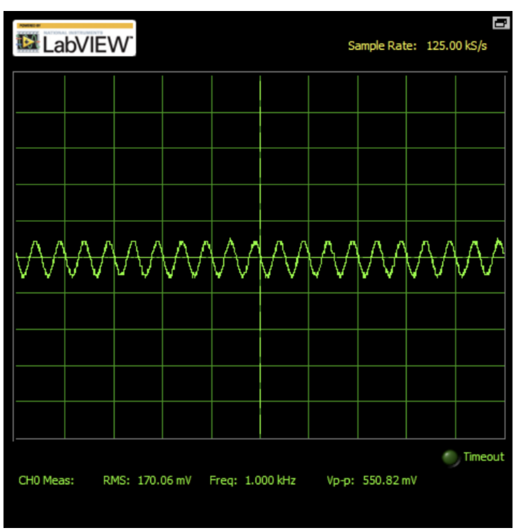


Figure 2.3: Input voltage signal with R_{test}

The following formula was used to calculate the input impedance:

$$R_{in} = \frac{V_{in}}{I_{test}} = \frac{V_{in}}{\frac{V_{test} - V_{in}}{R_{test}}} = \frac{550.82\ mV}{\frac{1V - 550.82\ mV}{1Mohms}} = 1226278.997\Omega$$

where the value of R_{test} is 1MΩ, V_{in} is 550.82 mV and V_{test} is 1V.

Then, the input signal is switched to a 1V peak-to-peak square wave with 1kHz frequency. The output signal is as seen in the figure below.

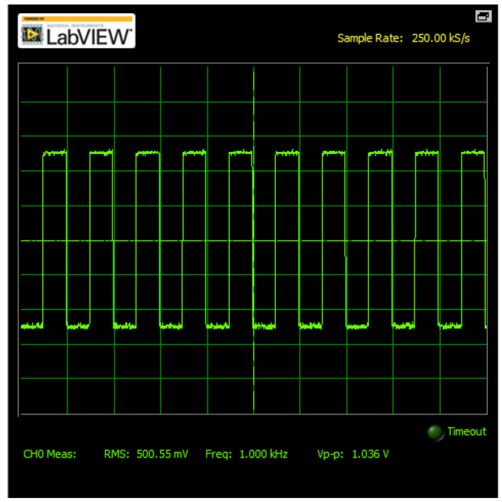


Figure 2.4: Output voltage signal with square-wave input at 1V peak-to-peak

Note that the output voltage is a square wave. Again, it has a frequency of 1.000kHz and a peak-to-peak voltage of 1.036V which is approximately the equal to the input signal.

C. Part 3: Non-Inverting Op-Amp Circuit

The input and output voltages, Vin and Vo, were measured using an oscilloscope. The input signal was kept at 1V peak-to-peak with a frequency of 1kHz, as in *Part 1*. The circuit used for this measurement is shown in the diagram below.

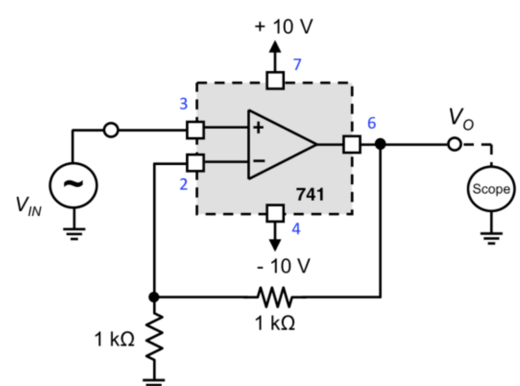


Figure 3.1: Non-inverting op-amp circuit

In the oscilloscope display, CH0 represents the input voltage and CH1 shows the output voltage. The measured output voltage Vo is 2.053V when the input Vin is 1.036V.

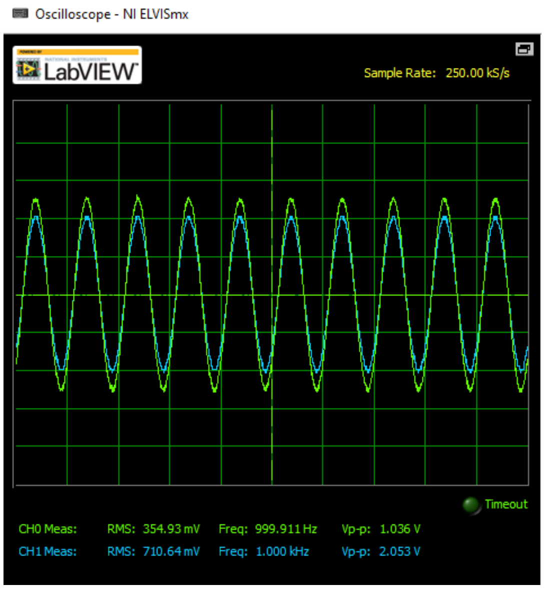


Figure 3.2: Output voltage signal with 1 V peak-to-peak sine wave input voltage signal

Both the input and output signals have the same phase, confirming that the non-inverting op-amp does not introduce any phase shift. Additionally, the circuit amplifies the input signal, doubling its amplitude. The frequency was also observed to remain stable, shifting slightly from 999.91Hz to 1.000kHz, indicating that the circuit maintains consistent signal frequency. This analysis shows that the non-inverting op-amp behaves as expected, amplifying the signal without altering its phase or frequency significantly.

Then, the input signal Vin was changed to 2V peak-to-peak with 1kHz frequency using a function generator. Again, CH0 represents the input voltage and CH1 shows the output voltage.

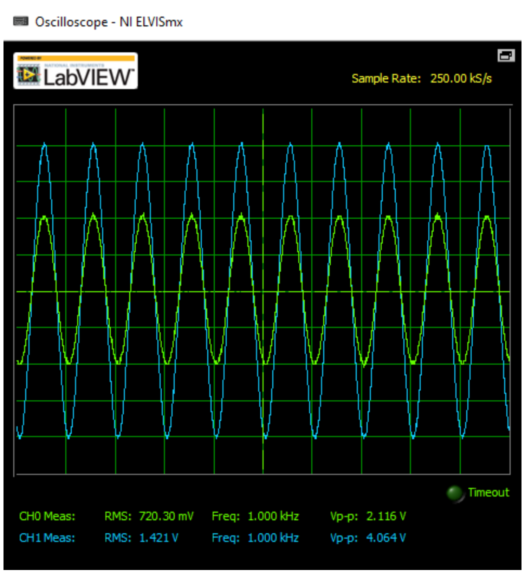


Figure 3.3: Output voltage signal with 2 V peak-to-peak sine wave input voltage signal

Again, we can observe that the output frequency and phase remain constant as the input voltage. As for the output voltage, the Vo peak-to-peak is measured to be 4.064V when the input voltage Vin is 2.116V. Thus, the circuit doubles the output voltage. This linear trend remains constant for other input voltage as well.

After, the input voltage Vin is changed to a square-wave signal with 1V peak-to-peak with 1kHz frequency. In the display below, CH0 represents the input voltage and CH1 shows the output voltage.

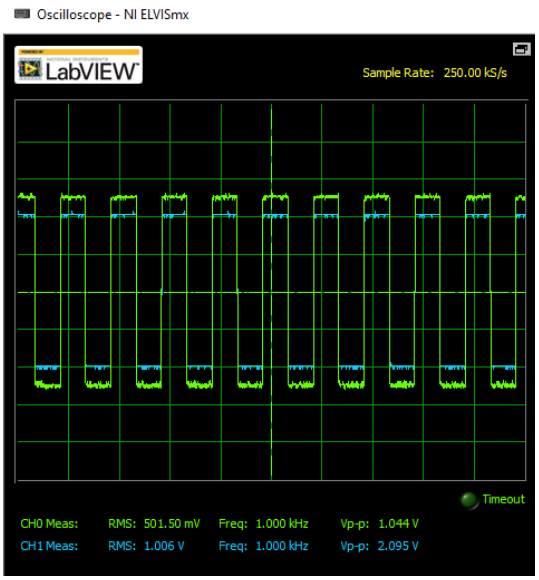


Figure 3.4: Output voltage signal with 1 V peak-to-peak square wave input voltage signal

The phase and the frequency of the input and output signals remain the same. Vo peak-to-peak is seen to be 2.095V and Vin peak-to-peak is observed to be 1.044V. Thus, the output voltage Vo is doubled from the input voltage Vin. Note that the trend continues when the input signal is changed to a 2V peak-to-peak signal with 1kHz frequency.

The following table shows the peak-to-peak voltage of both input and output signals and calculates the average gain of the non-inverting op-amp circuit. Note that the gain is calculated using the following equation:

$$Gain\left(\frac{V}{V}\right) = \frac{V_o}{V_{in}}$$

where Vo is the output voltage and Vin is the input voltage.

Table 1: Collected data for non-inverting amplifier

	Sine wave		**Square wave**
Input peak-to-peak (V)	1.036	2.116	1.044
Output peak-to-peak (V)	2.053	4.064	2.095

Gain (V/V)	1.98	1.92	2.01
Average Gain (V/V)	1.97		

The average gain was 1.97, which is approximately 2 for all input signals.

Last, it is possible to alter the op-amp circuit's gain by modifying the resistance in the feedback loop, i.e. change the 1kΩ resistor between pin 2 and 6 of the op-amp. The resistor was replaced by a 9kΩ resistor which was built by the circuit below. Since there were no 9kΩ resistors at the lab, we combined 4 existing resistors as such:

$$(10k\Omega//10k\Omega) + 3.9k\Omega + 0.1k\Omega = 9k\Omega$$

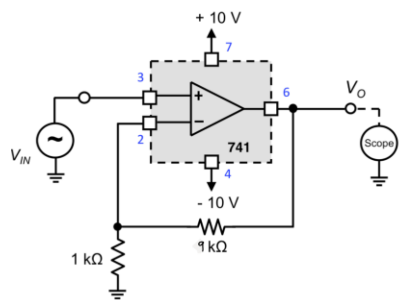


Figure 3.5: Non-inverting op-amp circuit with gain of 10

We validated our design through experimentation. The input was set to a 1 V peak-to-peak, 1 kHz square wave, and the output was measured using an oscilloscope. CH0 on the oscilloscope recorded the input signal, while CH1 captured the output signal.

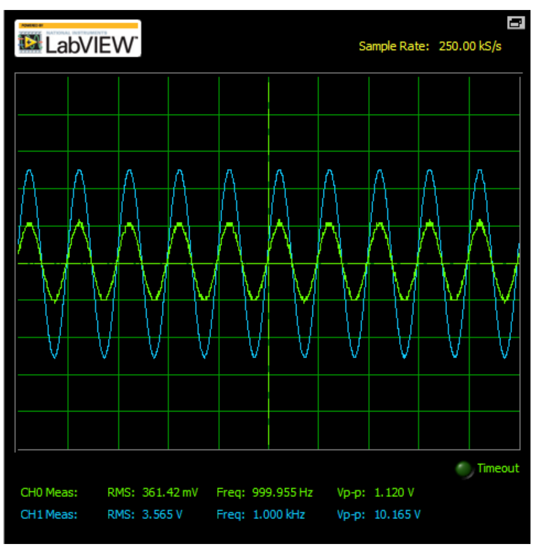


Figure 3.6: Output voltage signal with 1 V peak-to-peak sine wave input voltage signal with gain of 10

The measurement results showed that the output frequency and phase matched the input frequency and phase. Additionally, the output peak-to-peak voltage was measured at 10.165V, confirming that the circuit's gain is approximately 10. This result demonstrates that the op-amp circuit functions as expected with a gain of 10, consistent with theoretical predictions.

D. Part 4: Inverting Op-Amp Circuit

For this part of the lab, Vin is measured at the inverting input terminal of the op-amp, which is also known as the virtual ground. The input and output voltages, Vin and Vo, were measured using an oscilloscope. The input signal was kept at 1V peak-to-peak with a frequency of 1kHz, as in *Part 1*. The circuit used for this measurement is shown in the diagram below.

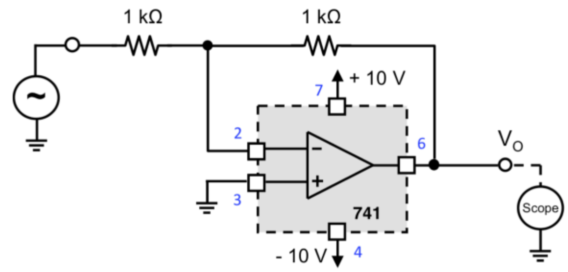


Figure 4.1: Inverting Amplifier

The oscilloscope output is shown in the diagram below. The sinusoid output signal is measured to be 971.55 mV peak-to-peak with a frequency of 1 kHz, represented by CH1. CH0 represents the input signal measured at pin 2 (inverting input terminal as virtual ground), which is 7.96 mV. This value is close to zero.

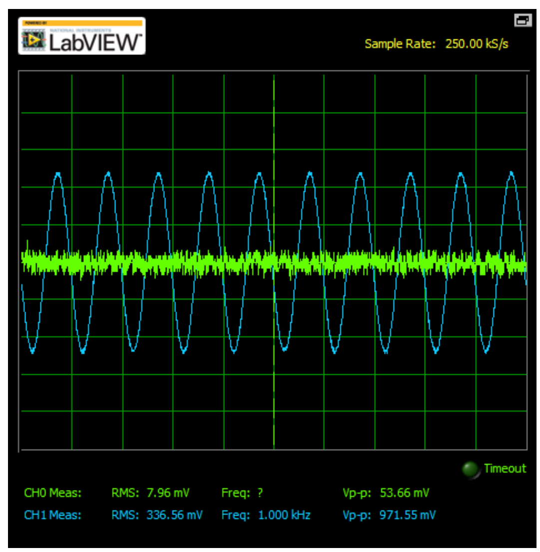


Figure 4.2: Input and Output signal of inverting circuit

The two measurements allow us to calculate the gain, as seen in below:

$$gain = \frac{V_o}{V_{in}} = \frac{\frac{971.55mV}{2}}{\frac{1000mV}{2}} = 0.97155\frac{V}{V} \approx 1\frac{V}{V}$$

Then, we connect the inverting input terminal (previously virtual ground) to real ground. Then, the oscilloscope shows the output in the figure below. CH1 represents the input voltage at the inverting terminal, connected to the real ground, which reads 0.38 mV. On the other hand, CH0 shows the output voltage signal, which reads 995.15 mV peak-to-peak. Note that there is no significant difference in outputs measured between connecting the inverting terminal to the virtual ground and connecting the inverting terminal to the real ground.

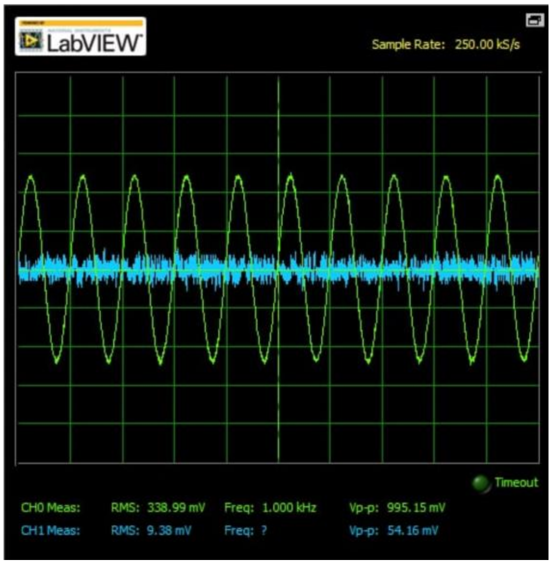
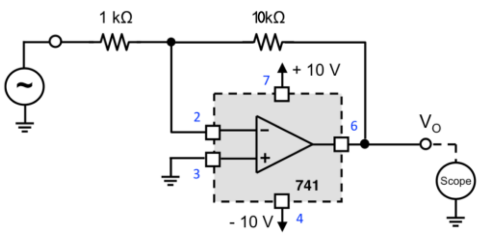


Figure 4.3: Inverting Amplifier Output with Inverting Input Connected to Real Ground

In order to change the magnitude of the gain to 10 V/V, the 1 kΩ between pin 2 and 6 can be replaced by a 10 kΩ resistor. The updated circuit diagram is seen below.



This hypothesis can be tested by measuring the Vo on the oscilloscope, as shown below.

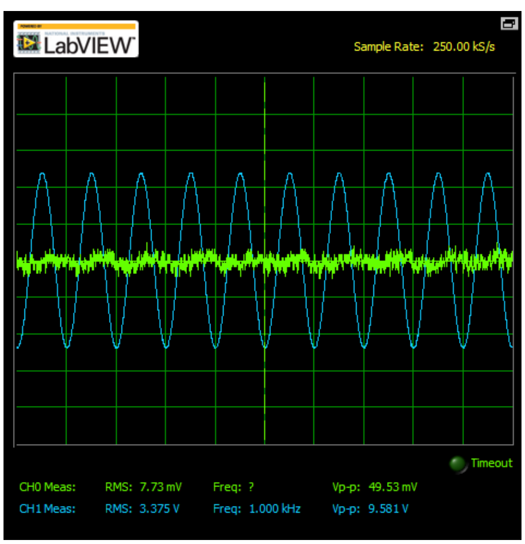


Figure 4.4: Adjusted Inverting Amplifier for 10 V/V Gain

The Vo peak-to-peak is 9.581 V when Vin peak-to-peak is set to 1 V on the function generator. Therefore, the gain can be calculated as such:

$$gain = \frac{V_o}{V_{in}} = \frac{\frac{9.581V}{2}}{\frac{1V}{2}} = 0.9581\frac{V}{V} \approx 10\frac{V}{V}$$

After, a 5 V peak-to-peak signal is applied to the input, as shown below.

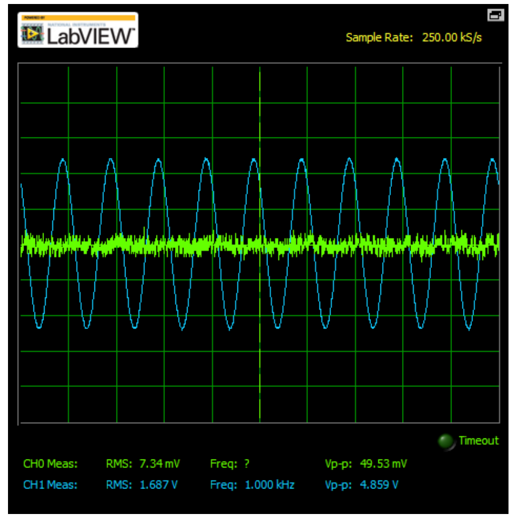


Figure 4.5: Input and Output signal of inverting circuit with 5V peak-to-peak input

It is possible to compute the current flowing through the 1kΩ resistor as such:

$$I_{1k\Omega} = \frac{V_{in} - V_{-}}{1k\Omega} = \frac{\frac{5000mV - 49.53mV}{2}}{1k\Omega} = 2.475mV$$

Next, the input impedance (Z) is calculated. To calculate the input impedance, a known resistor R_{test} of 1000Ω is used. The figure below shows the voltage across the op amp input V_{in}.

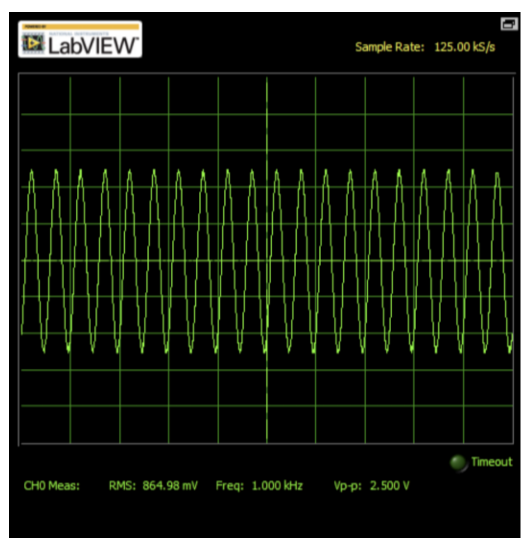


Figure 4.6: Voltage Across Op-Amp Input for Input Impedance Calculation

The following formula was used to calculate the input impedance:

$$R_{in} = \frac{V_{in}}{I_{test}} = \frac{V_{in}}{\frac{V_{test} - V_{in}}{R_{test}}} = \frac{2.5V}{\frac{5V - 2.5V}{1000\ ohms}} = 1000\Omega$$

where the value of R_{test} is 1000 Ω, V_{in} is 2.5 V and V_{test} is 5V.

E. Part 5: Differentiator Op-Amp Circuit

For the differentiator op-amp circuit diagram below, an oscilloscope was set up to obtain the input and output values.

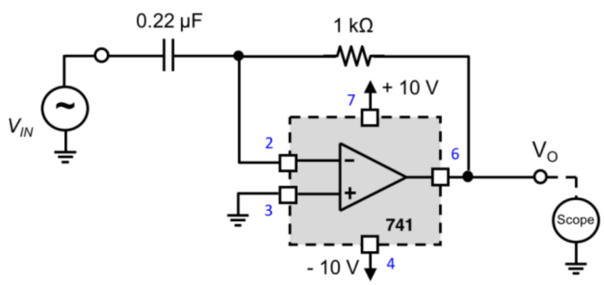


Figure 5.1: Differentiator op-amp circuit

As shown below, CH0 represents the input voltage signal and the CH1 represents the output signal. CH0 reads 1.053 V peak-to-peak with 1 kHz frequency, and CH1 reads 1.354 V peak-to-peak with 1 kHz frequency. The amplitude of the output signal is slightly larger than the input signal, and the phase of the output signal is also slightly shifted to the right compared to the input signal.

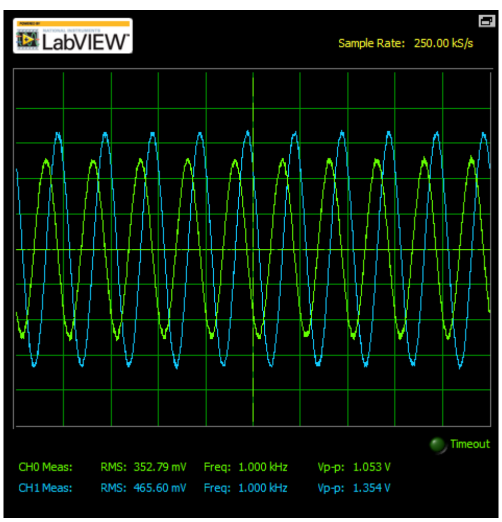


Figure 5.2: *Output voltage signal with 1 V peak-to-peak sine wave input voltage signal*

Then, the input wave is changed to be a triangular wave instead of a sinusoidal wave. However, the peak-to-peak voltage and the input frequency is kept constant. As shown below, the input signal, measured by CH0, is 1.012 V peak-to-peak whereas the output signal, measured by CH1, is 896.81 mV peak-to-peak. Note that the output signal resembles a square wave. Just like for the sine wave, the phase of the output signal is slightly shifted to the right compared to the input signal.

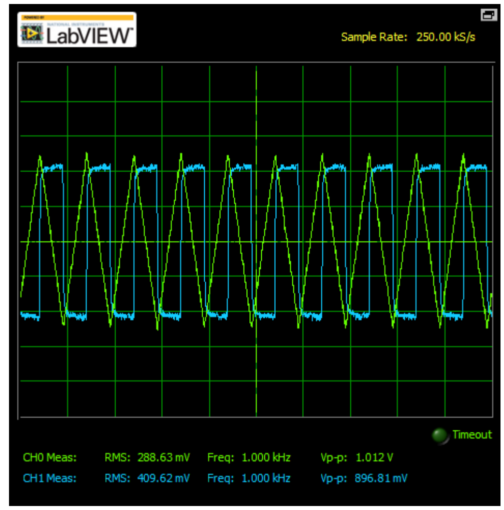


Figure 5.3: *Output voltage signal with 1V peak-to-peak triangular wave input voltage signal*

F. Part 6: Integrator Op-Amp Circuit

The following integrator op-amp was set up with the input voltage as a 1 V peak-to-peak sinusoidal signal with a frequency of 1 kHz.

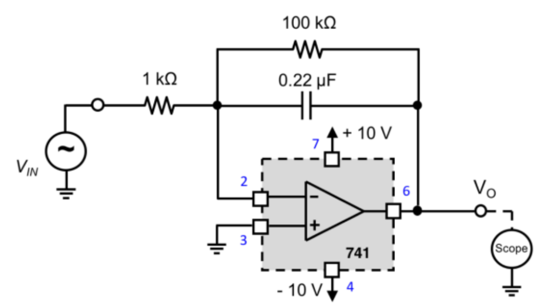


Figure 6.1: Integrator op-amp circuit

An oscilloscope was connected to the circuit with CH0 representing the input signal and CH1 measuring the output signal. Seen below, V_{in} is 986.93 mV peak-to-peak at 999.997 kHz and V_o is 739.04 mV peak-to-peak at 1 kHz.

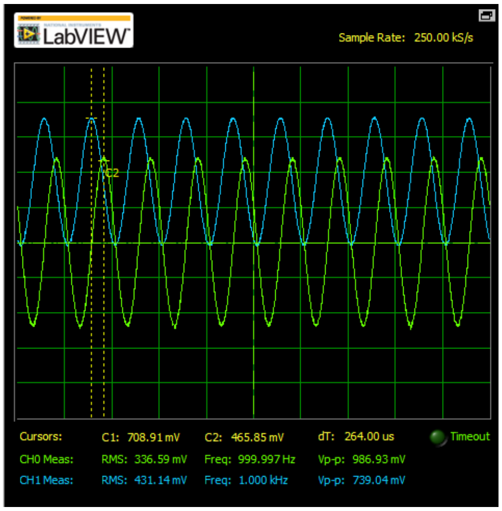


Figure 6.2: Output voltage signal with 1V peak-to-peak sine wave input voltage signal

Unlike the differentiator op-amp circuit, the output signal is slightly smaller than the input signal. Also, the output signal seems to be shifted slightly to the left compared to the input signal.

Then, the sinusoidal wave of the input signal is replaced by a square wave with the same peak-to-peak voltage and frequency. The output is seen in the figure below.

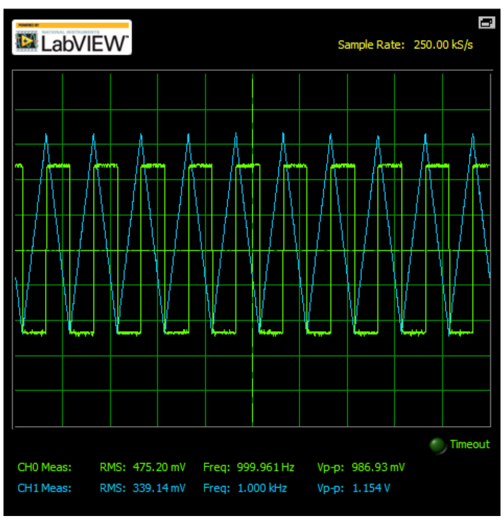


Figure 6.3: Output voltage signal with 1 V peak-to-peak square wave input voltage signal

The input signal, measured by CH0, reads 986.93 mV peak-to-peak. On the other hand, the output signal, measured by CH1, reads 1.154 V peak-to-peak. Again, just like we observed with the sinusoidal wave input, the output signal seems to be shifted slightly to the left compared to the input signal. Also, the output signal resembles a triangular input signal.

Note that the V_o signal of the integrator circuit behaves like the V_{in} signal of the differentiator circuit, and the V_{in} signal of the integrator circuit behaves like the V_o signal of the differentiator circuit.

G. *Part 7: D/A Converter Op-Amp Circuit*

The following D/A converter op-amp was set up with 5V DC input voltage source.

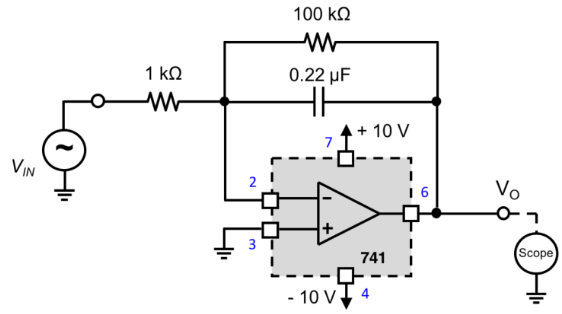


Figure 7.1: D/A converter op-amp circuit

The following table shows the output voltage measured at Vo for every possible switch configuration. 0 signifies that the switch is open and 1 signifies that the switch is closed.

Table 2: Collected output voltage data for each switch configuration

Integer	Switch Arrangement (b3b2b1b0)	Output Voltage (V)
0	0000	0
1	0001	-0.3
2	0010	-0.6
3	0011	-0.9
4	0100	-1.25
5	0101	-1.56
6	0110	-1.87
7	0111	-2.18
8	1000	-2.49
9	1001	-2.81
10	1010	-3.09
11	1011	-3.41
12	1100	-3.74
13	1101	-4.06
14	1110	-4.37
15	1111	-4.65

The following graph maps the output voltage of the D/A converter as a function of the integer value of the digital control signal. The graph is observed to be linear.

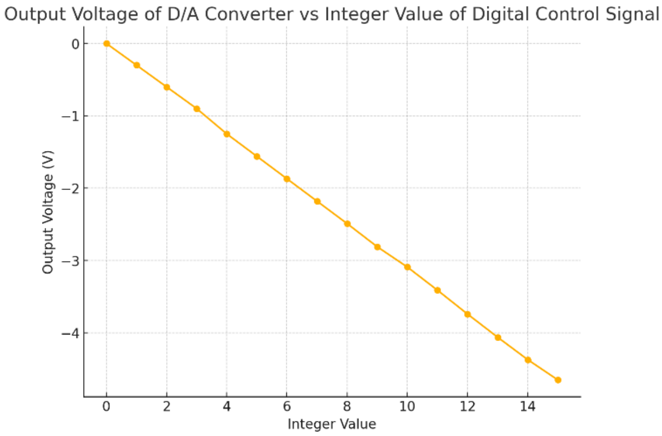


Figure 7.2: Output voltage of D/A converter vs Integer value of digital control signal

Then, we added a straight-line graph to our original graph for further comparison and calculated the maximum distance that the measured points deviate from the straight line graph.

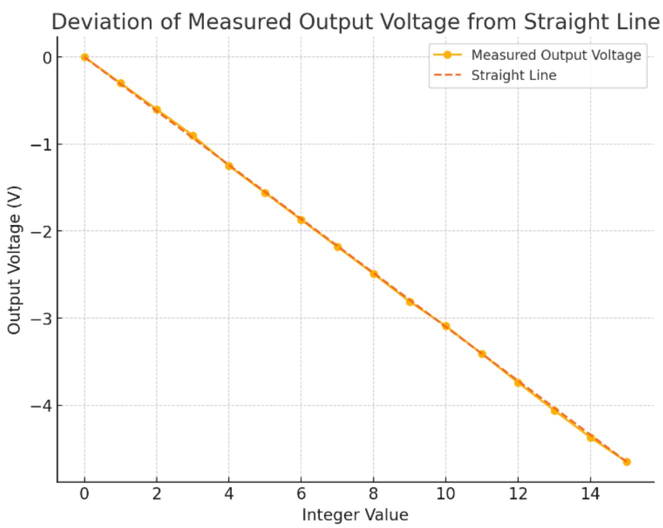


Figure 7.3: Output voltage of D/A converter vs Integer value of digital control signal compared to a straight line graph

The maximum distance that the measured points deviate from the straight line is approximately 0.03 V. Note that the graph was generated and the deviation value was calculated using Python's pandas, matplotlib.pyplot and numpy libraries.

III. Conclusion

In this lab, we constructed and tested seven different op-amp circuits, including comparator, voltage follower, non-inverting amplifier, inverting amplifier, differentiator, integrator, and D/A converter. These experiments enhanced our understanding of op-amp circuit mechanisms, such as the impact of component placement and load resistance on circuit performance. Building these circuits provided practical insights into the behavior of op-amps, reinforcing theoretical concepts and demonstrating their applications in various electronic systems.