AN1: Characteristics of Operational Amplifiers

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Abstract

Operational Amplifiers are extremely useful analog devices, and they are very adaptable and versatile. A simple explanation of op amps is that they amplify weak electrical signals. This experiment will dive further into three different topologies of op amps: inverting, non-inverting, and differential op amps. One of the most important characteristics of op amps is the gain, which will determine how much amplification the output voltage will receive. Op amps are very powerful, however there are certain limitations to them.

Introduction: Scope-Probe Compensation

One of the most important equipment in the field of electronics is the oscilloscope. In particular, understanding oscilloscope probe compensation is crucial to operating such equipment. Compensation is required to match the input impedance of the oscilloscope channel. To understand how compensation works, look below in Figure 1:

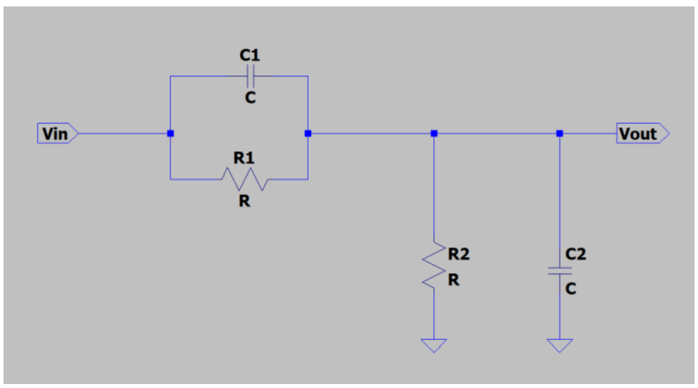

Figure 1: Network model of probe and oscilloscope connection, made in LTspice software.

Firstly, we must simplify the two circuits. R_1 and C_1 can be simplified in the schematic to Z_1 to represent the impedance of the probe. R_2 and C_2 can be simplified to Z_2 to represent the impedance of the oscilloscope. (1) is the equation for Z_1 and Z_2.

$$Z_1 = \frac{R_1}{1+sR_1C_1} \text{ and } Z_2 = \frac{R_2}{1+sR_2C_2} \tag{1}$$

From this, we can develop a transfer function, H(s), which will allow us to analyze the voltage gain. To get the transfer function, we can start off with the equation in (2).

$$V_{out} = V_{in}\left(\frac{Z_2}{Z_1+Z_2}\right) = V_{in}\left(\frac{R_2}{R_2+R_1\left(\frac{1+sR_2C_2}{1+sR_1C_1}\right)}\right) \tag{2}$$

From here, it is quite simple to get the transfer function, which is just the output voltage divided by the input voltage. (3) demonstrates the equation for H(s).

$$H(s) = \frac{V_{out}}{V_{in}} = \left(\frac{R_2}{R_2+R_1\left(\frac{1+sR_2C_2}{1+sR_1C_1}\right)}\right) \tag{3}$$

With regards to compensation, it is dependent on only part of this equation, shown in (4).

$$\frac{1+sR_2C_2}{1+sR_1C_1} \tag{4}$$

When $R_2C_2 > R_1C_1$, it is considered under-compensation, and the scope will attempt to create a square wave but will look like such in Figure 2: Under-compensation below. In LTspice, the values were set as such:
R_1 = 9 MΩ, C_1 = 0 F, R_2 = 1 MΩ, C_2 = 14 pF.

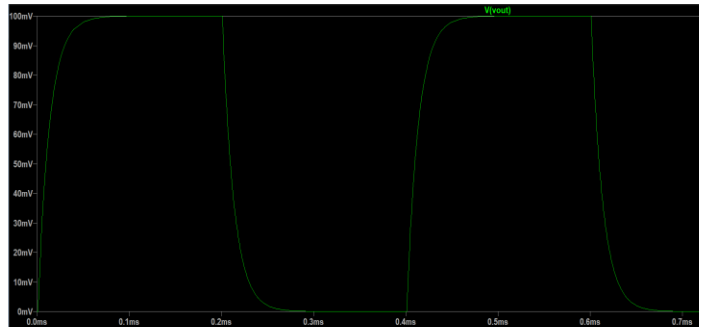

Figure 2: Under-compensation, LTspice Analysis

When $R_2C_2 < R_1C_1$, it is considered over-compensation. Figure 3: Over-compensation below shows the graph on the oscilloscope. In LTspice, the values were set as such: R_1 = 9 MΩ, C_1 = 5 pF, R_2 = 1 MΩ, C_2 = 14 pF. The values for R_2 and C_2 are equivalent to the input impedance of the oscilloscope used in the lab [3].

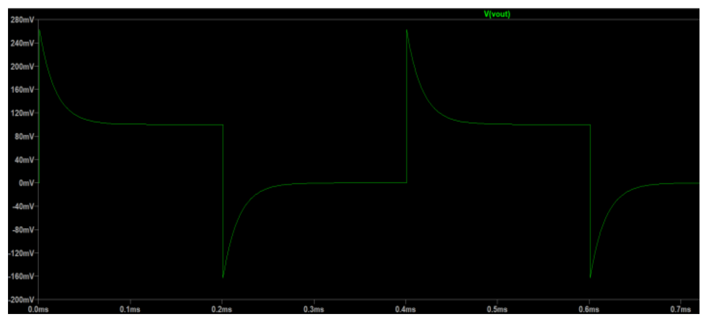

Figure 3: Over-compensation, LTspice Analysis

When $R_2C_2 = R_1C_1$, this is considered properly compensated. In fact, this would simplify the transfer function, H(s), even further, to what is shown in (5).

$$H(s) = \frac{R_2}{R_2+R_1} \tag{5}$$

When the probe is properly compensated, the oscilloscope will show a graph as shown in Figure 4: Properly Compensated below. The values in LTspice were set to: R_1 = 9 MΩ, C_1 = 1.55 pF, R_2 = 1 MΩ, C_2 = 14 pF. C_1 for proper compensation can be calculated by using $R_2C_2 = R_1C_1$ and solving for C_1.

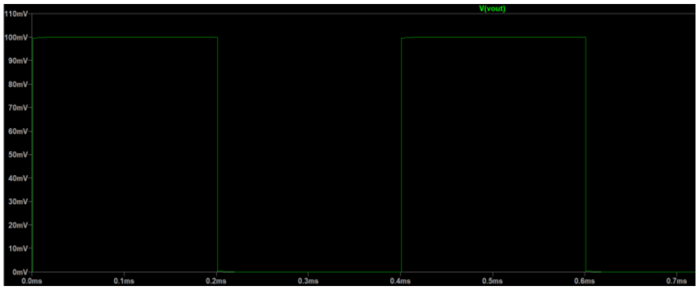

Figure 4: Properly Compensated, LTspice Analysis

As you might have noticed, the only component of which the value was adjusted for in LTspice for each of the different compensations was C_1. This is because when you are attempting to fix the compensation of a physical probe on an actual oscilloscope, the capacitance inside of the probe is changing. Essentially, that is a variable capacitor. To compensate the probe, it must be connected to the probe compensation terminal and to ground, where it will attempt to generate a square wave on the oscilloscope. Using the screwdriver that came with the probe, you can adjust the variable capacitor until the signal on the oscilloscope looks to be properly compensated.

Another important note about oscilloscope probes is that many of them are labeled as "10X". This simply means that the signal captured by the probe is divided by 10. These makes it easier to read high voltage signals. However, it is important to also set the oscilloscope to 10X as well, otherwise the signal readings will be off by a factor of ten.

Making Better Measurements

When obtaining results, it is important to minimize error as much as possible. One of the most important aspects of developing good results is understanding the effects of input and output impedance. A High-Z input (high impedance) is used to ensure that a small amount of current is pulled by the circuit, and this allows the maximum output voltage to be created. On the oscilloscope being used for these experiments, the input impedance is set to High-Z mode by default, meaning, on the network models shown earlier, the R_2 = 1 MΩ and C_2 = 14 pF, which is based on the datasheet [3]. On the Digital Multimeter used in the labs, the input impedance is also High-Z, where R_2 = 1 MΩ and C_2 < 100 pF. A High-Z output essentially does the same thing for the circuit. However, the function generator is not set to High-Z, and the only option is R_2 = 50 Ω, according to the datasheet [4]. The datasheet of the power supply does not give output impedance.

Another tip is to twist your wires. This is to help eliminate electromagnetic interference in your measurements. When a signal is applied to a wire, the current in the wire induces an electromagnetic field around it and the surrounding cables will pick up a lot of noise when making measurements. However, when you twist the wires, the two interferences will cancel each other out, because the two currents flowing within each other are equal and opposite amongst themselves. That is not to say that this is perfect and will eliminate every single piece of interference, but it certainly helps reduce the noise.

Introduction: Operational Amplifier

In this experiment, the OP27 op amp was used for all three op amp topologies: the inverting, non-inverting, and differential. Figure 5Figure 5: OP27 Pinout Diagram, From Datasheet below shows the pinout for wiring purposes [1].

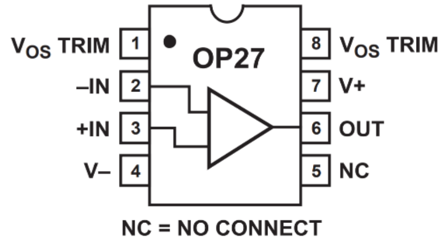

Figure 5: OP27 Pinout Diagram, From Datasheet

First Order Inverting Operational Amplifier

The goal of the first experiment is to compare the theoretical and practical gains of a first order, inverting op amp. The schematic for an inverting op amp is shown below in Figure 6, with given values.

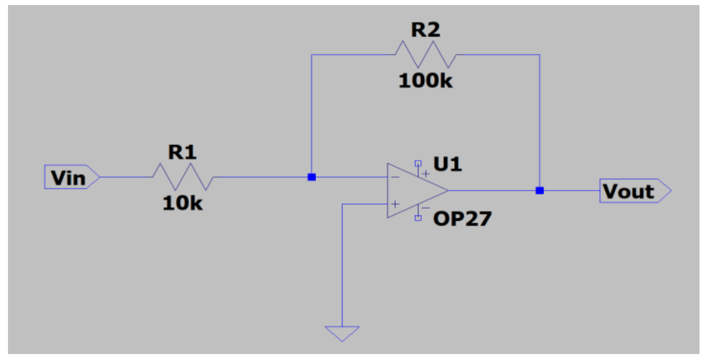

Figure 6: Inverting Op Amp

The voltage gain can be defined as the output voltage divided by the input voltage. Mathematically speaking, this is the reference resistor divided by the input resistor, as shown in equation (6). Theoretically, using this equation, the gain is equal to -10.

$$A_v = \frac{V_{out}}{V_{in}} = -\frac{R_2}{R_1} \tag{6}$$

After getting this gain, we can now calculate the output voltage, and this is simply the gain multiplied by the input voltage. I decided to give the op amp an input voltage of 1V, so theoretically, the output voltage should be -10V. The OP27 takes a maximum supply voltage of 22V, so the op amp was given bipolar power (+11V into V+ pin and -11V into V- pin). It is not possible to expect the op amp to output outside of its supply range, thus why it is given bipolar power. All the grounds in the circuit were connected to common ground. Channel 1 of the oscilloscope was connected to V_{in}, while channel 2 was connected to V_{out}.

Figure 7 below is zoomed-in reading of the inverting topology on the oscilloscope, with max voltage readings on the side. The output (green) is with 100 mV divisions on the oscilloscope.

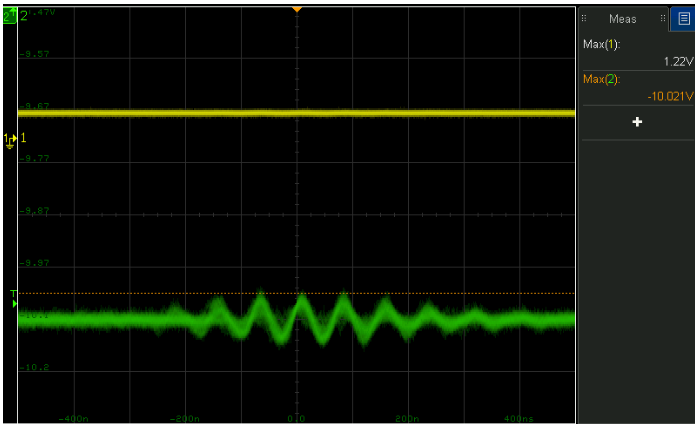

Figure 7: Inverting Op Amp Voltage Reading

The yellow line (channel 1) is input, and the green (channel 2) is output. The reason why the output has a sine wave that dies out is because of the 60Hz noise that is around us, and this was only visible after increasing the time divisions on the horizontal axis. The input voltage reads 1.22 V, while output voltage reads -10.021 V.

As mentioned earlier, the gain is the output voltage divided by the input voltage, so using the maximum voltage readings on the side of the graph in Figure 7, the measured gain is -8.21. The gain error is just 1 minus the measured gain divided by the theoretical gain. So that would be an error of 0.179, or 17.9%.

Second Order Non-Inverting Operational Amplifier

After the first portion of the lab was done, another op amp was used, simply because I did not have a OP27 op amp with me when I went to the lab. For the experiments moving forward, an OP2337 is used, and the pinout diagram is shown below in Figure 8 [2]. The OPA2337 has a maximum supply voltage of 5.5 V, so it was given a bipolar supply with -2.5 V and +2.5 V.

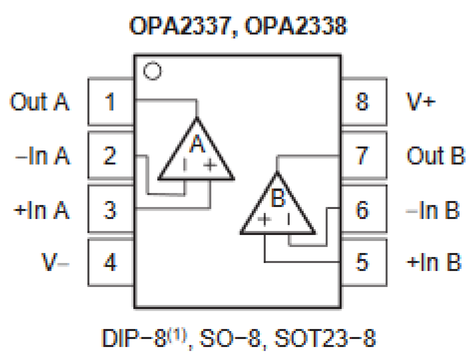

Figure 8: OP2337 Pinout Diagram, From Datasheet

The goal of this second experiment is to measure the E_{os}, which is the Referred to Input error (RTI). This is also referred to as the input offset voltage. This is simply the voltage required to be applied at the input to get an output of 0 V. In a non-inverting topology, the input voltage is connected to the positive input terminal of the op amp. However, for this experiment, it must be grounded. Figure 9 below shows the schematic of such configuration.

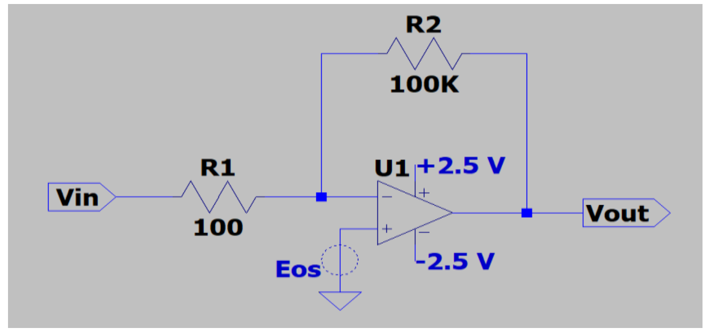

Figure 9: Non-Inverting Op Amp Schematic, Made with LTspice

Ideally, the output voltage would be zero because there is no input voltage since it is grounded. However, practically, the output voltage would be the gain multiplied by E_{os}, as shown in (7).

$$V_{out} = E_{os}\left(1 + \frac{R_2}{R_1}\right) \tag{7}$$

Based on the resistor values specified in the schematic in Figure 9, and equation (7), we can conclude that there is a gain of 1001. This E_{os}, the offset voltage of the op amp, is usually very small. The datasheet of the OPA2337 claims that the op amp has a typical input offset voltage of 0.5 mV [2]. Figure 10 below shows the output voltage reading from the Digital Multimeter. Based on equation (7), we can calculate the E_{os} by simply dividing this output value by the gain. E_{os} is then equal to 0.38 mV. Based on the value from the datasheet, that is an error of 24.4%.

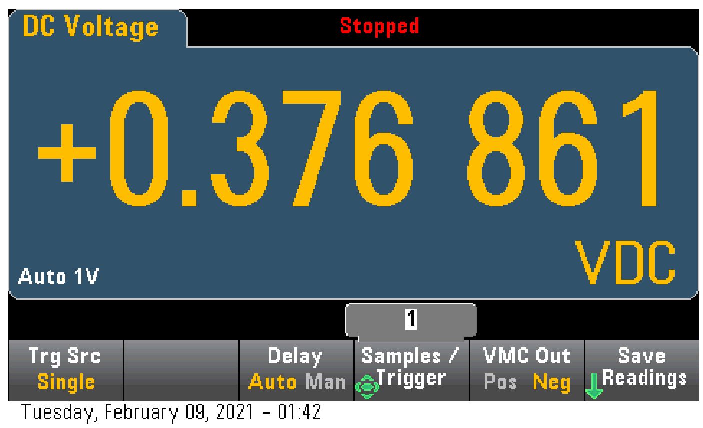

Figure 10: Output Voltage Reading From DMM

CMRR of a Differential Operational Amplifier

A differential op amp is given two voltage input signals, and the output voltage is typically proportional to the difference between the two signals. This configuration is seen below in Figure 11.

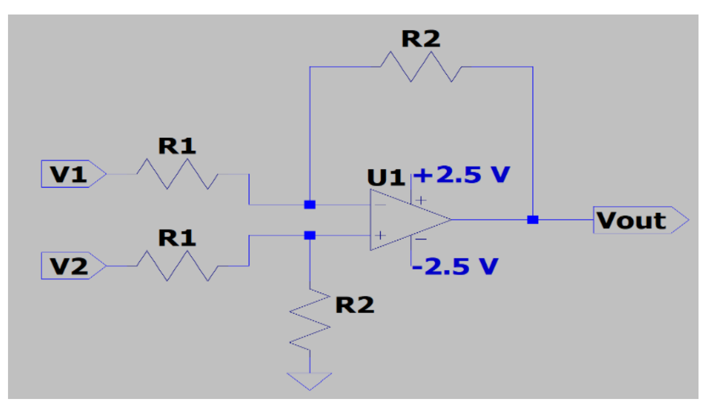

Figure 11: Differential Operational Amplifier, Made with LTspice

The Common Mode Rejection Ratio, abbreviated to CMRR, is a useful specification that allows us to understand how effectively the op amp can reject any changes in voltage, represented in dB. Ideally, in a differential op amp topology, when both inputs are given the same differential voltage, the output voltage V_{out} should equal to the differential voltage multiplied by the differential gain (as shown in equation (8)), but since the two voltages are the same the differential voltage is equal to zero.

$$V_{out} = (V_2 - V_1)(\frac{R_2}{R_1}) \quad (8)$$

However, we will not see the zero volts in a practical sense because op amps are not perfect. The output, realistically, will have a nonzero voltage, because there is a common mode signal from the input, V_{cm}. The smaller this value, the better the op amp is at rejecting the common mode voltage and will give more accurate results. In this experiment, the goal is to measure the CMRR. Firstly, the schematic for a differential op amp is simplified based on our objectives, as shown below in Figure 12. In the schematic, V_{cm} is connected to a function generator, giving it a sine wave with a frequency of 100 Hz.

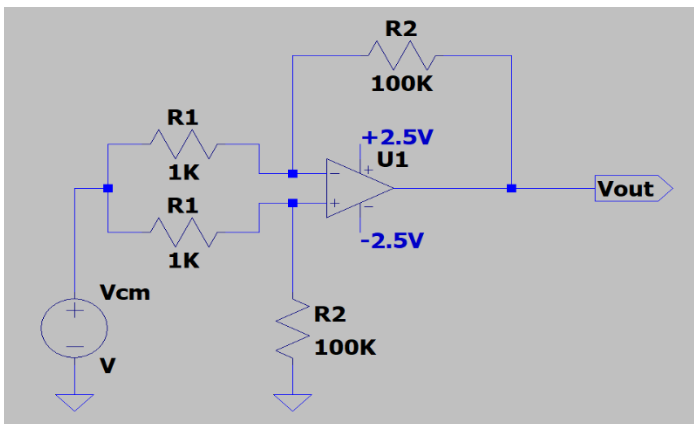

Figure 12: Modified Schematic of Differential Op Amp, Made with LTspice

Because we are giving the op amp an AC signal, we must define the equation for the input voltage signal, V_{cm} which is shown below in equation (9), with f being the frequency.

$$V_{CM} = 10\sin(2\pi f t) \quad (9)$$

Additionally, the equation for CMRR must also be defined mathematically as the ratio of the differential gain over the common mode gain, as shown in equation (10) below. The resistor values are the same as earlier with the non-inverting configuration, R_1 = 1K Ω and R_2 = 100K Ω, meaning that the differential gain $A_{diff} = 100$.

$$CMRR = 20\log(\frac{A_{diff}}{A_{CM}}) \quad (10)$$

The common mode gain, A_{CM}, can be calculated as such in equation (11) below. What this equation means is that we must measure the peak-to-peak voltage values at both the input and output ends of the op amp. The common mode gain will then simply be the inverse of the ratio of the input over the output.

$$A_{CM} = \left[\frac{V_{ip-p}}{V_{op-p}}\right]^{-1} \quad (11)$$

The experiment concluded with the results below in Figure 13, with $V_{ip-p} = 2.94$ V and $V_{op-p} = 0.015$ V. In the figure, there is a lot of noise on the output signal, and the V_{op-p} measurement from the oscilloscope is actually very large because it accounts for the noise. Therefore, it was scaled down to 10 mV divisions, where we can clearly see with the unaided eye that it is about 15 mV, peak-to-peak.

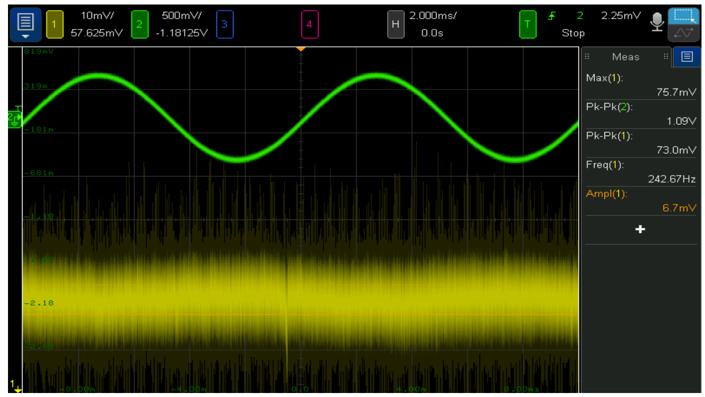

Figure 13: Results of Differential Operational Amplifier

This gives an $A_{CM} = 0.015$ which means that $CMRR = 85.8$ dB. This is an incredibly good CMRR measurement, especially considering how much noise there is in the environment.

In an attempt to measure the maximum CMRR, the 100 KΩ resistor at the positive terminal (R_2 in the schematic in Figure 12) was replaced with a 90 KΩ resistor (which is 10% less than 100 KΩ and is now referred to as R_2') and two 10 KΩ potentiometers (which are referred to as R_V), which would allow variable resistance. More specifically, this would allow the R_2 value to go from 90 KΩ to 110 KΩ. This configuration can be seen below in Figure 14.

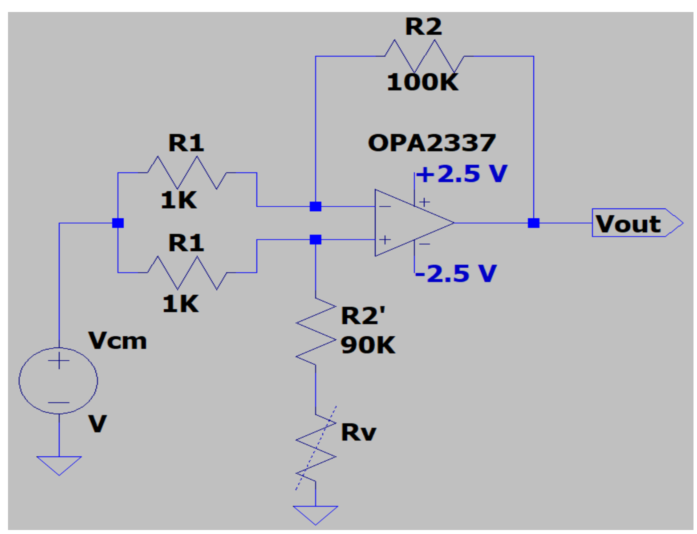

Figure 14: Differential Op Amp with Variable Resistance

The results of this portion of the experiment did not yield much of a difference in CMRR in comparison to the earlier experiment without variable resistance, which already had a high CMRR value. Figure 15 below shows the results on the oscilloscope, after varying the resistance. This was the best possible result after trying to vary the resistances. This had a V_{ip-p} of 1.051 V, and

$V_{op\text{-}p}$ = 10.8 mV, which means that the A_{CM} = 0.01, which then gives a CMRR of 80 dB.

Figure 15: Results After Varying Resistance in Differential Op Amp

This CMRR is actually worse than what was measured in the other differential topology without the variable resistance. This could mean that the original R_2 resistor, 100 KΩ, was incredibly accurate and precise. In fact, after redoing that portion of the experiment with the same R_2 resistor, the oscilloscope showed the same results as found earlier in Figure 13.

Conclusions

Operational amplifiers are certainly very powerful, but they are not without their limitations. It is important to consider that, while the results of the Input Offset Voltage and CMRR have some error when compared to the datasheet of the OPA2337 op amp, the manufacturers were most likely testing these variables under ideal environments and with real PCBs instead of breadboards, so it is very reasonable to expect lots of error.

From the first experiment, a conclusion that can be made is that the gain of an operational amplifier is simply the output divided by the input. Even if you do not know anything about the schematic, or if you do not know the values of the resistors, you can measure the gain by taking the measurements of the output voltage and input voltage and find the quotient. We also learned from this experiment that a negative voltage must be supplied to the op amp, if we expect a negative output.

The second experiment concluded with results of the input offset voltage. It is evident from here that op amps are certainly not perfect. When the two inputs are grounded, the output is surprisingly non-zero because of the input offset voltage. The output must be as close to zero as possible for the op amp to be considered as accurate as possible. Therefore, that means, the lower the input offset voltage of the op amp, the better. This is especially useful information when selecting op amps for other projects or labs in the future.

The third and fourth experiment played around with the Common Mode Rejection Ratio, or CMRR. When the two inputs of a differential op amp are equal, we would ideally expect the output to be zero, but that is not the case practically. The ratio represents how effective the op amp is at rejecting the common mode voltage at the input terminals. So for the future, when selecting op amps, the higher the CMRR the better.

References

[1] Analog Devices, "Low Noise, Precision Operational Amplifier," OP27 datasheet, 1981, https://www.analog.com/media/en/technical-documentation/data-sheets/OP27.pdf.

[2] Texas Instruments, "MicroSIZE, Single-Supply CMOS Operational Amplifiers MicroAmplifer™ Series," OPA2337 datasheet, 1997, https://www.ti.com/lit/ds/symlink/opa2337.pdf?ts=1613267962633&ref_url=https%253A%252F%252Fwww.ti.com%252Fproduct%252FOPA2337.

[3] Keysight, "InfiniiVision 6000 X-Series Oscilloscopes," MSOX6004A datasheet, December 14, 2020, https://www.keysight.com/us/en/assets/7018-04316/data-sheets/5991-4087.pdf.

[4] Keysight, "30 MHz Function/Arbitrary Waveform Generators," 33522A datasheet, November15, 2019, https://www.keysight.com/us/en/assets/7018-02567/data-sheets/5990-5914.pdf

Appendix A: Bill of Materials

- Equipment
  - Keysight MSOX6004A Mixed Signal Oscilloscope
  - Keysight E3631A Power Supply
  - Agilent 33521A Function Generator
  - Keysight 34465A Digital Multimeter
- Cables
  - BNC to Clip lead
  - Two sets of banana-to-clip leads and one extra lead
  - One set of DMM probes
  - Two 10X oscilloscope probes
  - Jumper Wires
- Lab Components
  - OP27, OPA2337
  - Two 1 KΩ resistors, two 10 KΩ resistors, one 90 KΩ resistor, one 100 Ω resistor
  - Two 10 KΩ potentiometers