Experiment 1

Op-amps and basics of signal conditioning

The operational amplifier (op-amp) is the most versatile piece of analog hardware yet developed. Originally named for its ability perform mathematical operations on analog voltages, the op-amp has become an essential building block of much of modern electronics. In this experiment, we will analyze the input-output characteristics of an op-amp as well become acquainted with some of the basic circuits in which it is used.

1.1 Introduction

Ideal op-amps

An op-amp is a differential amplifier with an inverting V_- input and non-inverting V_+ input. The output voltage V_{out} is given by the difference of these two input voltages times the open loop gain A_v:

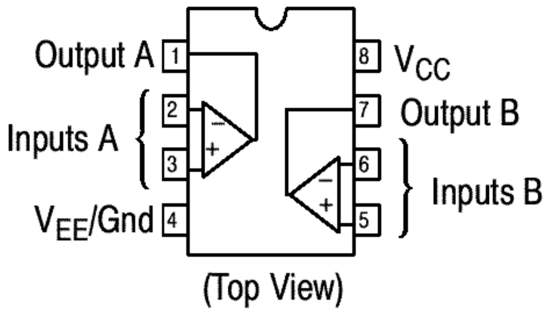
$$V_{\text{out}} = A_v \times V_{\text{in}} = A_v \times (V_+ - V_-) \tag{1.1}$$

A standard way to derive approximate theoretical equations for the circuits involving op-amps is to assume that the op-amp is an *ideal* device having the following electrical characteristics:

1. the inputs draw no current, hence $i_+ = i_- = 0$ and the input impedance $Z_+ = Z_- = \infty$;
2. the output can supply an infinite amount of current, hence $Z_o = 0$;
3. the open loop gain, or voltage amplification $A_v = \infty$.
4. The op-amp adjusts the output voltage so that $V_- = V_+$. This follows from Equation 1.1 since V_{out} cannot exceed the finite power supply voltage. This equivalence is used to determine the gain equation for an (ideal) op-amp circuit.

The LM358 op-amp

The LM358 consists of a pair of general purpose operational amplifiers capable of amplifying signals ranging from 0 Hz (DC) to 1 MHz. The chip can operate using a dual power supply of up to ±15 V down to a single 3 V battery. It can be used in mixed analog/digital circuits that typically operate from a single 3-5V power supply.



? From the LM358 data sheet, determine the values of A_v, the input bias current and output source current. Does the LM358 approximate the characteristics of an ideal op-amp? Explain.

? The slew rate dV_{out}/dt defines the maximum rate of change in V_{out}. What is the LM358 slew rate? Does the frequency response of the amplifier depend on the amplitude of the signal?

! **Care should be taken to ensure that all integrated circuits (IC's) are powered with both V_{CC} (+) and V_{EE}/Gnd (-) whenever an input signal is supplied! Failure to do this will destroy IC's**.

1.2 Open-loop operation

Since A_v of the op-amp is very large, a tiny voltage difference between the inputs causes the output to swing between the positive $V_{\text{out}}^{(\text{max})}$ and negative $V_{\text{out}}^{(\text{min})}$ power supply limits, or saturate. This effect can be used to implement a *voltage comparator* or *level detector*.

To implement a comparator, one input is set to a reference voltage. The output changes state as the voltage at the other input swings above and below the reference voltage.

Due to input signal noise and non-ideal op-amp operation, voltage differences between V_+ and V_- that are consistently less than a few millivolts will cause the op-amp output to oscillate or otherwise behave in an erratic fashion.

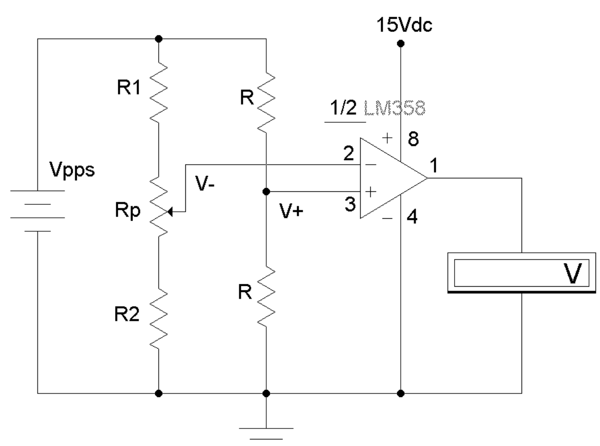


Figure 1.1: LM358 open loop analysis

Null voltage measurement

(!) Assemble the circuit shown in Figure 1.1. Start by making the power connections to the op-amp, then connect the HP benchtop programmable power supply (PPS) to the workstation and set it to the 6 V DC range. Turn on the output and adjust the output voltage to around 5 V.

? Why might you not want to use the already available workstation 5 V power supply?

(!) Complete the connections to the op-amp V_+ and V_- terminals. R_p is a 1 KΩ variable resistor, (a **p**otentiometer). A small screw allows for the centre tap connection to be set anywhere between the two resistor ends. The resistors labelled R can be of similar value, in the 10-100 KΩ range.

(!) Measure the resulting V_+ voltage, then determine values for R_1 and R_2 that will allow the V_- voltage to be adjusted above and below V_+.

[?] Are R_1 and R_2 necessary? What is their function in this circuit? How did you determine their values? Explain how the op-amp input bias current determines the practical range of values for the various resistors used in this circuit.

(!) Connect and scope to monitor the op-amp output and adjust V- until a transition from one output voltage limit to the other occurs. Measure and record the positive and the negative voltage limits of the op-amp output.

Note: type `GDS-1102A` in a terminal window to export the scope screen to the computer monitor and optionally save a screenshot of the scope screen for inclusion in your lab report.

(!) In the same circuit, connect the benchtop digital multimeter (DMM) to the V- op-amp input. Adjust the potentiometer carefully to where the op-amp output just begins to decrease from its positive limit (as observed on the scope), where it is as close to zero output as you can set it, and where it is not quite at the negative limit. Record these three V_- values. Repeat these observations several times.

(!) Without changing any settings, use the DMM to measure V_+.

[?] Estimate the *open loop gain*, A_v, of the op-amp and its input offset voltage from the above measurements. Compare with the nominal value that you obtained from the LM358 data sheet.

[?] Estimate the op-amp *slew rate* and compare it with the stated nominal value.

[?] Connect both inputs to the op-amp to ground and measure the *output offset voltage*. What should this value be for an ideal op-amp?

1.3 Closed-loop operation

Application of feedback from V_{out} to V_- causes the op-amp to conform to Rule 4 mentioned in the introduction. This arrangement, shown in Figure 1.2, is known as a *voltage follower* or *unity-gain amplifier.*

[?] How might this op-amp arrangement be useful? What is being amplified? Derive the gain equation.

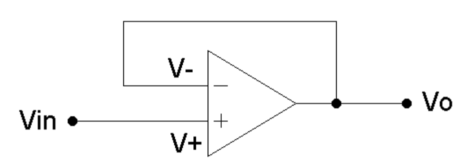


Figure 1.2: A voltage follower

An analog memory cell

It is sometimes necessary to temporarily store a voltage. This is required when converting a voltage to a digital value, or to implement an analog signal delay. Figure 1.3 shows the schematic of a typical *track-and-hold* circuit. When the switch is closed, V_{out} tracks V_{in}. With the switch open, the capacitor is effectively isolated from V_{in} and V_{out} reflects the voltage stored in the capacitor.

? Which op-amp characteristics are desirable in this type of circuit? What are the benefits/limitations imposed upon the circuit by the resistor and capacitor?

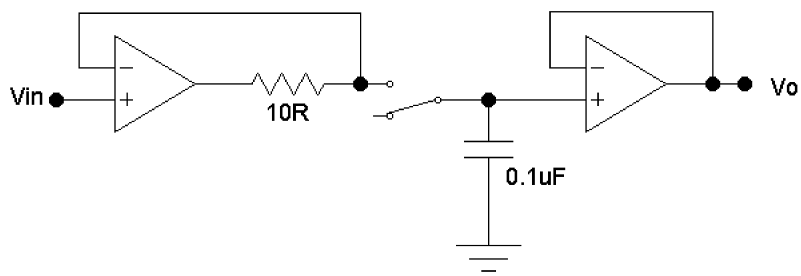


Figure 1.3: Sample and hold circuit

! Sketch the circuit of Figure 1.3 in your lab book, clearly labelling all the connections to the LM358 dual op-amp chip.

You can use a jumper in place of the switch if one is not installed on the breadboard.

? Set V_{in} to a 1 Hz sine wave. Describe the output as the switch is opened and closed.

? In track mode, with the switch closed, how are V_{in} and V_{out} related? As you increase the V_{in} frequency, what do you observe?

? With the circuit in hold mode and the switch open, describe V_{out}. Does V_{out} change in time? If so, determine the discharge rate of the capacitor. How long before V_{out} drops by 1%?

1.4 Analog computation

The op-amp was originally designed to perform mathematical operations from addition to multiplication, exponentiation and the solution of differential equations. The electrical behaviour of resistors, capacitors and diodes are used to this end. While not as precise as digital devices, analog computers are very fast and simple to implement and do not require data conversion to and from the digital domain.

Figure 1.4 shows a two op-amp circuit that can be used to evaluate the equation

$$Y = mX + b = m \times (X + b/m). \tag{1.2}$$

The first adds an offset b/m to V_{in}. The second op-amp sets the gain, or slope m.

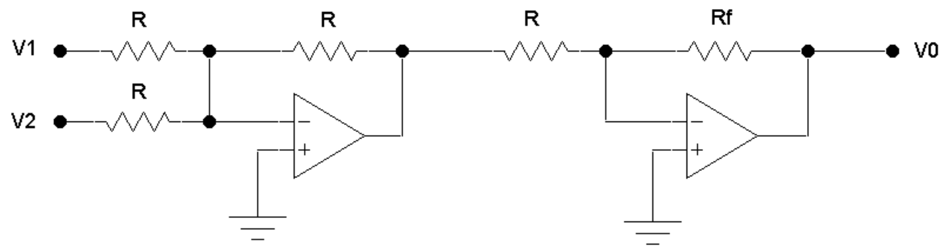


Figure 1.4: Two op-amp solution of $Y = mX + b$

? Derive the transfer function for the two op-amp circuit of Figure 1.4.

The above is not the only way to implement our equation $Y = mX + b$ using op-amps. It may not seem readily apparent, but the circuit of Figure 1.5 also evaluates $Y = mX + b$, this time using a single op-amp. Due to the feedback path, the op-amp adjusts the output V_{out} so that $V_- = V_+$. Because of the very large input impedance of the op-amp, no appreciable current flows into the op-amp inputs. Thus the presence of an op-amp is not affecting the currents flowing through the resistors, and we can draw the electrically equivalent circuit as two separate voltage dividers as shown on the right-hand side of Figure 1.5.

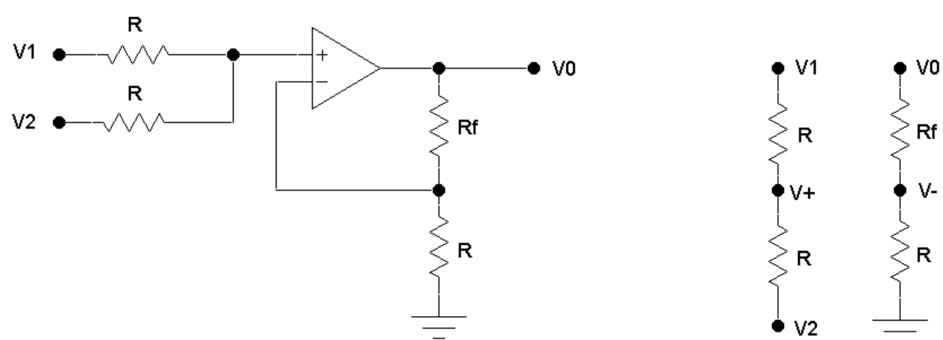


Figure 1.5: Single op-amp solution of $Y = mX + b$

? Show that the equation below is valid and that it does represent the equation $Y = mX + b$:

$$V_{\text{out}} = \frac{R_f + R}{2R} \times (V_1 + V_2) \tag{1.3}$$

A practical example

It is often useful to convert a transducer output voltage to a voltage range that quantitatively represents the actual quantity that the sensor measures.

Suppose that you wish to build an analog thermometer calibrated to display temperature on a voltmeter in units of 100mV/°C so that 0°C displays 0V, 10°C displays 1V, and so on.

Suppose that the temperature sensor used is an LM61 temperature-to-voltage converter. The output voltage of this device corresponds to 600 mV at 0°C and varies linearly at a rate of 10 mV/°C.

(!) Determine for the circuit of Figure 1.4 the transfer function parameters required to properly display the LM61 output as temperature on the voltmeter.

(!) Build the circuit. Set $V_{\text{CC}} = +15$ V and $V_{\text{EE}} = -15$ V. Select $R \approx 10\text{k}\Omega$.

(!) Simulate the LM61 output voltage with the PPS. Vary the PPS voltage and verify that the circuit behaves as expected.

(!) Now replace the PPS with the LM61. The LM61 is a three-pin device. With the flat face toward you, connect the left pin to +5 V and the right pin to 0 V. The centre pin is the output voltage, as described.

Connect the LM61 to the op-amp circuit and verify that the circuit converts the LM61 output voltage as predicted.

[?] What output voltage do you expect at room temperature? When you hold the LM61 with your fingers, does the output voltage increase?