Instrumentation Physics Lab

Lab 13: Operational Amplifiers I

Purpose of the experiment

- To understand how operational amplifiers increase voltage.
- To build circuits using the LM741 operational amplifier.

Background Info

In some next lab, we will be working with transducers. A transducer is a device that measures a physical quantity, such as pressure, temperature, magnetic field, light and so on, and converts that quantity to a (usually) small voltage. In order for that small voltage to be readable, it must be amplified. This amplification is the subject of this lab.

The purpose of an *operational amplifier* (or op amp) is as a voltage amplifier that takes the small voltage and converts it to a larger voltage while maintaining the original waveform. The universal symbol for the op amp is:

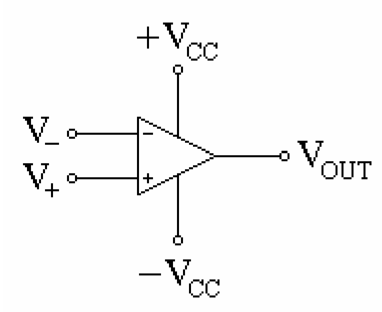


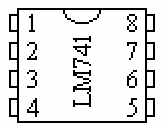
Figure A: Symbol for an Operational Amplifier.

The (-) and (+) refer to the *inverting* and *non-inverting inputs*. The $+V_{CC}$ and $-V_{CC}$ inputs are the positive and negative power supplies. The wire at the tip of the triangle is the output signal. The resulting output signal will be in phase with the noninverting input and 180^o out of phase with any signal on the inverting input. The function of the op amp is to take the potential difference between the inverting and non-inverting inputs, multiply it by a large number, and send that larger voltage to the output. Mathematically:

$$V_{OUT} = K(V_+ - V_-)$$

where K is a large number. Notice: Don't confuse K for the gain G, they are different (see below).

LM741 Operational Amplifier



We will be using the LM741 operational amplifier. The LM741 is an operational amplifier that has been placed on a single chip called an integrated chip (IC). The chip has 8 pins used to both power and use the amplifier. The pinouts for the LM741 are listed below.

Pin	Name	Description	Notes	I/O
1	NULL	Offset Null	Used to calibrate V_{OUT} (see Lab 8)	--
2	V_-	Inverting Input	± 15 V or ± V_{CC} whichever is less	I
3	V_+	Non-inverting Input	± 15 V or ± V_{CC} whichever is less	I

4	-V_{CC}	Power (Low)	-22 V minimum	--
5	NULL	Offset Null	Used to calibrate V_{OUT} (see Lab 8)	--
6	V_{OUT}	Output Voltage	$V_{OUT} = K(V_+ - V_-)$	O
7	+V_{CC}	Power (High)	+22 V maximum	--
8	NC	Not Connected		--

Table A: Pinouts for the LM741 Operational Amplifier.

We will power the LM741 with two 9 V batteries. Consequently, the maximum voltage that the input pins will take is ± 7.5 V. Anything outside this range will be read as ± 7.5 V (i.e. the op amp is said to have “railed” at 1.5 V inside the supply voltage). The circuit to power the LM741 operational amplifier is shown below:

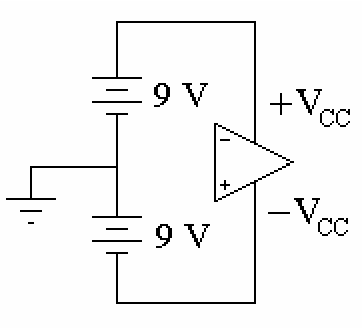


Figure B: Power circuit for LM741.

Please note that wherever we use an LM741 chip, this part of the circuit diagram will be excluded, even though you must include it in the actual circuit.

Inverting Amplifiers

The figure below shows a basic inverting amplifier.

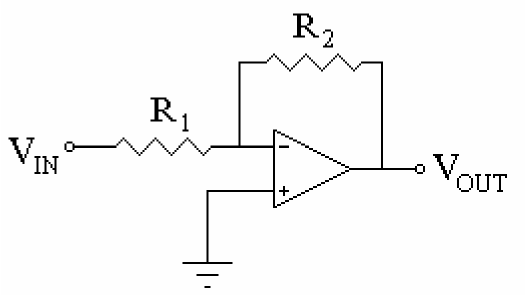


Figure C: Inverting Amplifier.

The only input to the inverting amp is that to the inverting input. The resulting output will be *180^o out of phase* with the input signal. The "feedback" resistor R_2 will return some of the output signal back to the input signal. The feedback will subtract from the input because it is out of phase. This will reduce the input signal and therefore reduce the amplified output signal. This sounds like an incredibly stupid thing to do, but there is a good reason for it. The gain (G) of an inverting amp is given by $G = - R_2 / R_1$. The negative signifies that the output signal is inverted. The negative feedback signal controlled by R_2 is what determines the gain of the amp. If R_2 were removed, the gain would explode to infinity. On the other hand if R_2 were reduced to zero (shorting the output to the input) the gain would go to zero. This makes sense because an inverted signal will feedback on the input exactly 180° of phase adding to zero. Therefore, a negative feedback must be added to the input to control the gain. Again, the maximum gain of any op amp is determined by the power supplied. The output signal can not exceed the supply voltage.

Non-inverting Amplifiers

The figure below shows the wiring diagram of a noninverting amplifier:

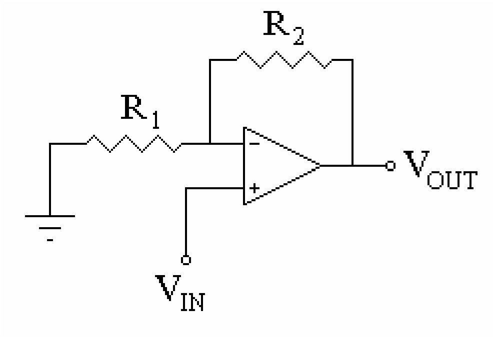


Figure D: Non-inverting Amplifier.

The first thing to notice is that the signal is connected to the noninverting input. This means that the output will be *in phase* with the input signal. Second, the output feedback is returning to the inverting input and not to the input signal. As a result, the output will be in phase with the input signal so if the feedback were returned to the input, the two would add together and then be amplified. You can see that this will quickly send the output signal to infinity. Therefore, the feedback signal needs to be sent to the inverting input so that the gain can be controlled. The equation for the gain of a noninverting amp is given by $G = 1 + R_2 / R_1$.

The Integrator

To make an *integrator*, replace R_2 in the inverting amplifier with a capacitor (C):

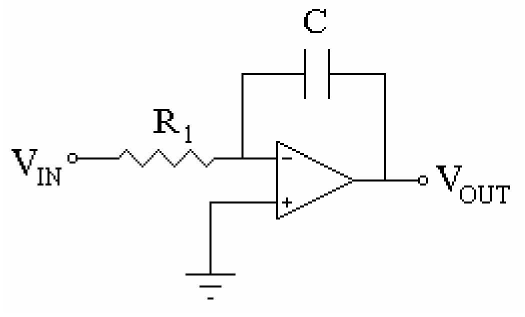


Figure E: Integrator.

The gain of the amp is now dependent on the reactance of the capacitor. Replacing the resistance of R_2 in the gain equation with the reactance, we have:

$$G = -\frac{X_C}{R_1}$$

where X_C is the reactance:

$$X_C = \frac{1}{2\pi f C}$$

Therefore:

$$G = -\frac{1}{2\pi f C R_1}$$

As the applied frequency increases, the reactance of the capacitor decreases allowing a larger feedback signal. This will decrease the output signal. This circuit functions as a low pass filter. This type of circuit is referred to as an *active filter* because it is powered. An RC filter (*passive filter*) produces a slight loss at all frequencies. The active filter will amplify the desired frequencies and suppress the rest. This results in a sharper cut off value.

The Differentiator

To construct a *differentiator*, swap the position of the capacitor and the resistor in the integrator.

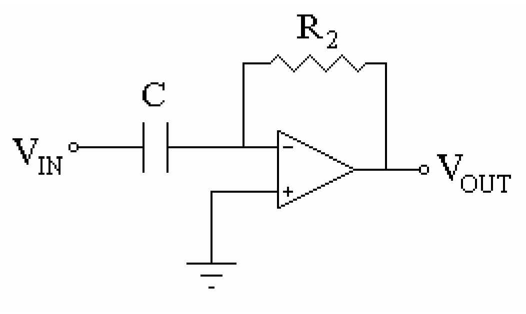


Figure F: Differentiator.

The gain is still affected by the reactance of the capacitor. The resistance of R_1 is replaced by the reactance of the capacitor in the gain equation:

$$G = -\frac{R_2}{X_C}$$

where the reactance is:

$$X_C = \frac{1}{2\pi f C}$$

Therefore:

$$G = -2\pi f C R_2$$

As with the integrator, *the gain depends on the frequency.* With the capacitor inline with the input, low frequencies are blocked before they reach the amp. This circuit functions as a high pass filter.

Prelab

Prelab 1: Read the following sections in Horn: Operational Amplifiers, Chapter 24 (pages. 339-347) and Filters, Chapter 35 (pg. 501-505).

Prelab 2: Show that the gain for an inverting amplifier is $G = - R_2 / R_1$. Assume that no current flows into or out of the inputs of the op amp.

Prelab 3: Show that the gain for a non-inverting amplifier is $G = 1 + (R_2 / R_1)$. Assume that no current flows into or out of the inputs of the op amp.

The Lab

The goal: To learn the basics of op amp circuits and their uses.

Exercise 1: Create a non-inverting amp with a gain of 11.

- a.) Test the circuit on a variety of AC signals. Vary the input amplitude, frequency and shape (sine, square and triangle).
- b.) Measure R1 and R2 with the DMM and get an exact value for the gain.
- c.) Vary V_{IN} from 0 V to 1 V and measure the resulting V_{OUT}. Plot V_{OUT} vs. V_{IN}. Be sure to take enough data to get a clear picture of the graph. Is the response linear over the entire range? Indicate on your graph the parts where the op amp is behaving normally and where it is railing. (Recall: the op amp should rail about 1.5 V below $+V_{CC}$. That is, 9 V – 1.5 V = 7.5 V.)
- d.) Compare the calculated gain from part b to the measured gain (i.e. the slope of your graph) from part c.

Exercise 2: Repeat the previous exercise using an inverting amp set up. Change the gain to -10.

Exercise 3: Construct an op amp that produces a 0.5 V amplitude, 1500 Hz sine wave. The input signal will be 2 V in amplitude. Invert the signal.

Exercise 4: Build an integrator using a 1000 Ω (or 100 Ω) resistor and a 1μF capacitor.

- a.) Make two plots of the output voltage vs. the frequency for a constant amplitude input voltage. The first should be linear and the second log-log.
- b.) Using the function generator, use different waveforms (sine, triangle, and square waves) as your input signal to the op amp. Note the change in the waveform from input to output. Why is this circuit called an integrator?

Exercise 5: Repeat Exercise 4 for a differentiator using the same components.

Exercise 6: Compare and contrast the active filters constructed in this lab to the passive filters from the AC lab.