Lab 6 **Zach Colbert**
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Introduction

Operational Amplifiers (op-amps) are active, voltage-amplifying devices. They come in the form of an integrated circuit, with 8-pins in the case of this lab. Two pins are used to power the op-amp with constant DC voltages, two are used as the ”inverting” and ”non-inverting” inputs, one is the output, and three others have more advanced functions.

A single op-amp may behave in very different ways based on feedback from passive devices in the circuit around it, and in this lab we take a look at some common circuit configurations to show different features of an op-amp. Because they are very complicated integrated circuits, and because their behavior changes based on feedback from other devices, we use two ”Golden Rules” to define reliable behaviors of op-amps. These rules are used in conjunction with Kirchoff rules to analyze circuits that employ op-amps.

Rule 1 says that ”the output does whatever it must to keep the voltage difference between the two inputs zero.”[1] This means that as the two inputs change, the output will also change in a way that minimizes the voltage difference between the inputs. This has to do with the feedback-response of op-amps.

Rule 2 says that ”the inputs draw no current.”[2] In reality, op-amps are made to have very high impedance inputs, so that they draw as little current as possible. These rules, combined with Kirchoff's circuit rules, turn out to be very useful when analyzing circuits with op-amps later.

1 Open Loop Gain

1.1 Experimental

For this lab, we used a LM741 op-amp, and a data sheet from Texas Instruments [3]. The literature value for the output gain of this op-amp is 200 $\frac{V}{mV}$, or 200,000 $\frac{V_{Out}}{V_{In}}$. This output gain is commonly referred to as β, a dimensionless coefficient:

$$V_{Out} = \beta V_{In} \tag{1}$$

In this part of the lab, we observe the output of our op-amp with a simple DC input signal. The signal is controlled by a potentiometer (voltage divider) with a 30 V drop.

[1] From the lab description.
[2] Also from the lab description.
[3] Datasheet: http://www.ti.com/lit/ds/symlink/lm741.pdf

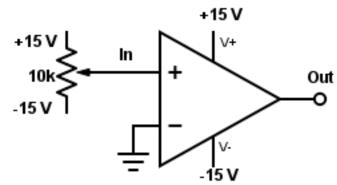

Figure 1: Op-amp in a simple circuit, with no feedback loop. The potentiometer on the left serves as a variable DC voltage source.

With no feedback loop and one of the inputs grounded, we expect to see an exceptionally large output signal (based on the exceptionally large output gain) that changes proportionally to changes in the input signal. By equation 1, only a zero input signal could result in a zero output signal.

1.2 Results

Using circuit 1 we find that very small changes to the input signal cause the output signal to hit its limits at $\pm 15\ V$. This is consistent with the very large output gain we expect from this op-amp, and the output signal was consistently capped at $\pm 15\ V$ as expected based on our constant power supply to the amplifier.

We found that the circuit was far too sensitive to changes in the input signal for us to make an attempt at adjusting it manually to $0\ V$. Instead, by connecting both inputs to a common ground (reducing the voltage difference between them to 0), we found that the output signal also went to $0\ V$ as expected.

2 Inverting Amplifier

2.1 Experimental

One of the features of an op-amp is its two inputs–called the inverting and non-inverting inputs. In contrast with part 1, in part 2 we ground the non-inverting input and the circuit with a signal at the inverting input. As the name suggests, signals at this input are inverted at the output of the amplifier.

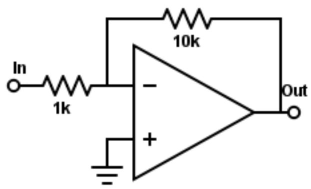

Figure 2: In this circuit, the input signal is fed to the inverting input, and there is a feedback loop between the output and inverting input.

Now that the circuit includes a feedback loop (in the form of a 10 $k\Omega$ resistor between the output and inverting input), we're required to do a little bit of extra analysis to find the expected output gain.

The second op-amp rule tells us that the inputs draw no current–so all of the current flowing through the 1 $k\Omega$ resistor must also be flowing through the 10 $k\Omega$ resistor.

$$I_{1k} = I_{10k} \tag{2}$$

By applying Ohm's Law, we find that

$$\frac{V_{In} - V_{-}}{R_{1k}} = \frac{V_{-} - V_{Out}}{R_{10k}} \tag{3}$$

The first op-amp rule tells us that the difference between the inputs should be zero. Since the non-inverting input is grounded, we must assume that the circuit will react to make the voltage at the inverting input zero. Then,

$$\frac{V_{In}}{R_{1k}} = \frac{-V_{Out}}{R_{10k}} \tag{4}$$

$$V_{Out} = \frac{-R_{10k}}{R_{1k}} V_{In} = \frac{-10\ k\Omega}{1\ k\Omega} V_{In} \tag{5}$$

$$V_{Out} = -10\ V_{In} \Longrightarrow \beta = -10 \tag{6}$$

This negative-valued gain also confirms that we expect the output signal to be inverse of the input signal.

2.2 Results

For a 10 Hz sine wave input, and powering the op-amp with $\pm 20\ V_{DC}$, we measured $V_{In} = 2.20\ V$ peak-to-peak, and $V_{Out} = 19.4\ V$ peak-to-peak for a gain of 8.82. The output signal was also inverted, consistent with a negative (inverting) gain.

By returning our op-amp power to $\pm 15\ V_{DC}$, we found that the maximum output voltage swing was about 15 V, consistent with what we saw in the first part of the lab.

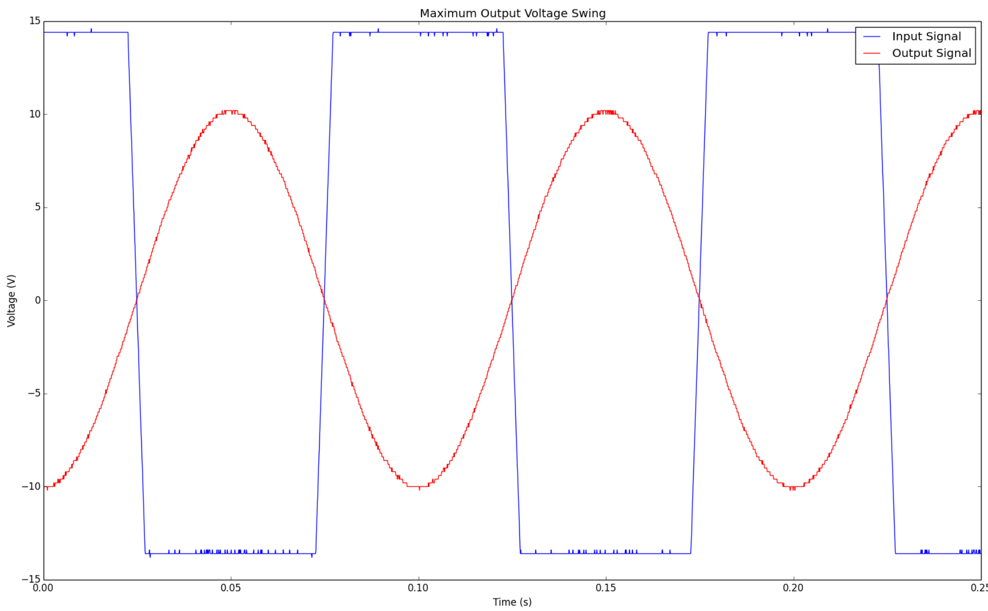

Figure 3: The flat regions at the peaks of the output signal show how the voltage swing is restricted by the DC voltage used to power the op-amp.

In observing the frequency-dependent behaviors of the output signal, we began to see some interesting effects at freqencies of 100 kHz, 1 MHz, and 5 MHz:

Theory Gain	Input Frequency	Output Waveform	Phase Shifted?	DC Offset	Exp. Gain
-10	100 kHz	Triangle	Yes	0	<10
	1 MHz	Triangle	Yes	Down	<1
	5 MHz	Sawtooth	Yes	Down	<1
-100	100 kHz	Sine	Yes	Up	<100
	1 MHz	Sine	Yes	Up	≈ 1
	5 MHz	Sine	Yes	Up	<1
-1000	100 kHz	Sine	Yes	Up	<1000
	1 MHz	Signal too fuzzy			
	5 MHz	Signal too fuzzy			

From these observations it appears that as the theoretical gain of the circuit increases (effectively, as the impedances grow larger), the phase shift and DC offset of the input signal increase.

At higher frequencies, we see the output signal become smaller and more distorted.

It seems to me that the phase shift is a result of the input signal (or possibly the feedback signal) is passing through a resistor, and is "slowed down." The DC offset could be the result of a voltage difference across the resistor in the feedback loop, which is effectively a DC voltage added to the AC signal resulting in an amplitude shift. The distortion and diminished output gain are a little harder to explain.

3 Non-Inverting Amplifier

3.1 Experimental

In the part 3 of the lab, we use a circuit very similar to the one in part 2. Here, there are a couple of fundamental differences:

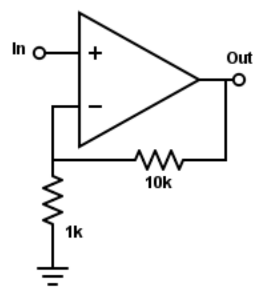

Figure 4: Non-inverting amplifier circuit, with negative feedback.

First and foremost, the circuit is non-inverting because we feed the input signal to the non-inverting input. We can verify this by calculating the expected gain of the circuit using the op-amp rules and Kirchoff's rules.

By the first rule, we know that the input voltages will be equal. We also know from the circuit diagram that the voltage at the non-inverting input will be equal to the voltage of the input signal:

$$V_{-} = V_{+} = V_{In} \tag{7}$$

We can also relate V_{In} and V_{Out} by using the voltage drop across the 10 $k\Omega$ resistor:

$$V_{In} = V_{Out} - V_{10k} \tag{8}$$

$$V_{In} = V_{Out} - IR_{10k} \tag{9}$$

After applying Ohm's Law, it's necessary to find the current through the 10 $k\Omega$ resistor. Fortunately, the second op-amp rule tells us that there is no current flowing to the inverting input–then, by Kirchoff's junction rule, the current through the 10 $k\Omega$ resistor must be the same as the current flowing through the 1 $k\Omega$ resistor.

Then, using the voltage drop across that resistor:

$$V_{In} - V_{1k} = 0 \tag{10}$$

$$V_{In} = V_{1k} = IR_{1k} \Longrightarrow I = \frac{V_{In}}{R_{1k}} \tag{11}$$

We can then use this definition for I in the relationship between V_{In} and V_{Out}:

$$V_{In} = V_{Out} - V_{In}\frac{R_{10k}}{R_{1k}} \tag{12}$$

$$V_{Out} = V_{In}(1 + \frac{R_{10k}}{R_{1k}}) \tag{13}$$

$$\beta = 1 + \frac{10\ k\Omega}{1\ k\Omega} = 11 \tag{14}$$

A positive gain indicates that the output we observe should not be inverted.

The other key difference between this circuit and the one from part 2 is that the resistors remain on the inverting side of the op-amp. Now, instead of forcing the input signal and feedback to flow on the same side of the circuit, they are flowing on opposite sides.

3.2 Results

Driving the circuit with a 1 V peak-to-peak sine wave at 100 Hz, we measured $V_{In} = 2.2\ V$ peak-to-peak, $V_{Out} = 22.6\ V$ peak-to-peak, resulting in a gain of $\beta = 10.3$. This is reasonably close to the theoretical gain, $\beta = 11$.

4 Follower

4.1 Experimental

For part 4, we use a very simple circuit called a follower. In this case, there are no resistors or grounded inputs involved–just negative feedback. This makes analysis of the circuit fairly simple.

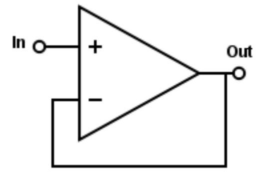

Figure 5: Simple follower circuit with a negative feedback loop.

The first rule tells us that the input voltages will be equal:

$$V_+ = V_- \tag{15}$$

From the circuit diagram, we can tell that the voltage of the input signal and the voltage of the output signal, respectively, will be equal to those input voltages:

$$V_{In} = V_{Out} \Longrightarrow \beta = 1 \tag{16}$$

So, we expect the output signal to look exactly like the input signal.

4.2 Results

Driving the circuit with a 500 mV peak-to-peak sine wave at 10 Hz, we could find no measurable difference between the input and output signals. This indicates a circuit gain of 1, as expected.

5 Summing Amplifier

5.1 Experimental

In the final part of the lab, we use an inverting amplifier circuit to add AC and DC input signals together. As in part 1, here we use a potentiometer as a voltage divider, which allows us to vary the DC voltage that we add to our AC input signal.

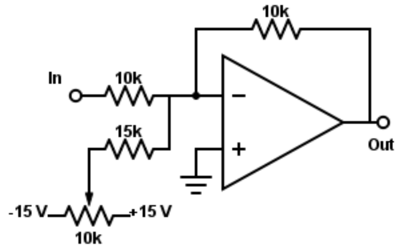

Figure 6: The summing amplifier circuit.

Finding the circuit gain turns out to be a little different this time, because we're effectively working with two different inputs. Starting on the left side of the circuit, we can observe that the currents from our respective input signals combine at the leftmost junction, and meet another junction at the inverting input of the op-amp. Since the second op-amp rule tells us that the inputs draw no current, Kirchoff's junction rule tells us that the sum of the two input currents is equal to the current in the feedback loop:

$$I_1 + I_2 = I_f \tag{17}$$

Using the voltage drop across the resistor in the feedback loop, we can relate the current I_f to our known output voltage V_{Out}:

$$V_- - I_f R_{10k} = V_{Out} \tag{18}$$

The first op-amp rule tells us that the input voltages will be the same, so V_- goes to zero (as V_+ is grounded):

$$I_f = \frac{-V_{Out}}{R_{10k}} \tag{19}$$

Then, we can use this new equation to apply Ohm's law to equation 17:

$$\frac{-V_{Out}}{R_{10k}} = \frac{V_1}{R_1} + \frac{V_2}{R_2} \tag{20}$$

$$V_{Out} = -R_f(\frac{V_1}{R_1} + \frac{V_2}{R_2}) \tag{21}$$

This shows that there are individual gains for each of the input signals, based on the ratio of feedback resistance to input resistance. For this circuit in particular, we find the respective gains to be:

$$\beta_{AC} = \frac{-R_f}{R_1} = \frac{-10\ k\Omega}{10\ k\Omega} = -1 \tag{22}$$

$$\beta_{DC} = \frac{-R_f}{R_2} = \frac{-10\ k\Omega}{15\ k\Omega} = -\frac{2}{3} \tag{23}$$

So, we expect the output signal to be inverted, with a DC offset of $-2/3$ the DC input voltage.

5.2 Results

Driving the circuit with a 1 V peak-to-peak sine wave at 10 Hz, we could find no measurable gain in the output signal. It was inverted, and had a DC offset that changed proportionally with adjustments to the potentiometer.

As in previous parts of the lab, the output signal was cut off near $\pm 15\ V$, based on the constant DC voltage used to power the op-amp (in other words, the output voltage swing is within the range we have found it throughout the lab). Overall, the output signal behaved as expected.

6 Conclusion

Throughout this lab, we found op-amps to behave very consistently with theory at reasonably low frequencies. As with any other circuit element, it seems reasonable to expect strange effects at very high frequencies, so that will be a notable point to remember when employing op-amps in circuits in the future.

The two golden rules for op-amps make them very easy to analyze in a complex circuit, which makes them very convenient devices for controlling and amplifying voltage in complex ways.