Experiment #08
Operational Amplifiers

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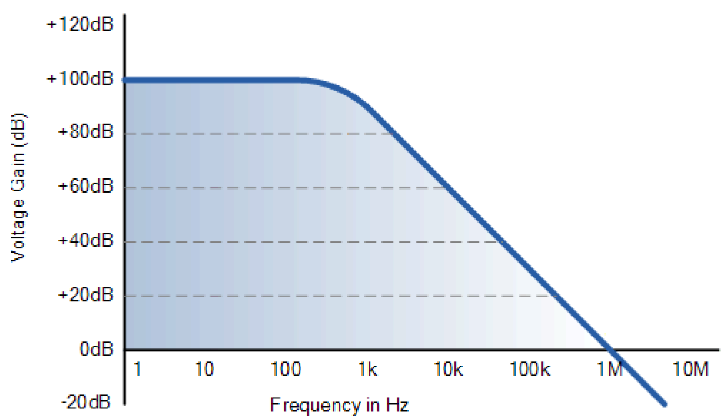

Figure 1: Typical gain versus frequency for an Op-Amp without feedback (open loop configuration).

1 Objective

Operational amplifiers (Op-Amps) are versatile devices used in a wide variety of applications. Some of the basic properties of Op-Amps will be studied in this lab, with an emphasis on the most common application: a voltage amplifier with negative feedback.

2 Learning Goals

After this lab you will be able to:

- characterize the linearity of an Op-Amp circuit
- recognize the influence of amplifier distortion/clipping
- be familiar with the behaviour and limitations of circuits using Op-Amps
- build circuits with more complex components
- begin to troubleshoot circuits with Op-Amps

3 Introduction

3.1 Background

In electronics, the term Op-Amp typically refers to a voltage amplifier that has a differential input (meaning there are two inputs- V_- and V_+) and a single ended output V_{out}. The difference between the two voltage inputs is amplified and produced as an output.

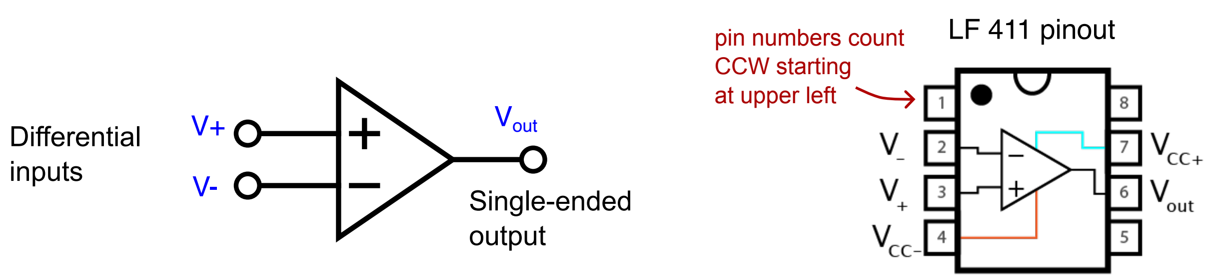

Figure 2: Left: Block diagram of an Op-Amp. Right: Pin assignment of LF 411 looking from the top; note the dimple in the upper left or notch at the top orients the numbering of the pins (image from: `https://www.physlab-wiki.com/phylabs/lab_courses/phys-226-wiki-home/lab_6_op_amps_i/start`).

The Op-Amp symbol is shown in the left of Fig. 2. In circuit diagrams, the power supply lines are usually omitted from the symbol, so always be sure to connect the DC power that is usually denoted as V_{CC} and V_{EE} (or $-V_{CC}$) (+5 and -5 Volts respectively) even if it is not indicated on the circuit diagram. Shown on the right of Fig. 2 is the pin-out of the integrated circuit (IC) for the particular model of Op-Amp you will use in this lab, the $LF411$. In this course, we are going to treat the Op-Amp as a single device. However one should be aware that the Op-Amp is an IC composed of many transistors and other elements. Each Op-Amp model has a different design that is optimized for different applications. The $LF411$ is a general purpose Op-Amp that is easy to use and is stable over a wide range of frequencies.

3.2 The ideal versus non ideal Op-Amp

An ideal Op-Amp follows three "golden rules" (some sources only discuss the first two and assume the third is obvious) which should always be the starting point when analyzing their behaviour in circuits.

The (Ideal) Op-Amp "Golden Rules"

Golden rule # 1: As long is there is a feedback resister installed appropriately between the Negative input and the output, for example as shown in Fig. 3, the Op-Amp will adjust V_{out} so that $V_+ = V_-$.
Golden rule # 2: Infinite input impedance on the $+$ and $-$ terminals: this means no current flows in or out of these two terminals.
Golden rule # 3: the open loop gain with no feedback is very large.

However, there are many circumstances where Op-Amps and resulting amplifier circuits deviate significantly from their ideal behaviour. To quantify the non-ideal behaviour one requires knowledge of a few key parameters which depend on the particular Op-Amp .

- **Open Loop Voltage Gain (A)**: when no feedback is provided, this is the amount of differential gain provided by the Op-Amp, i.e. $V_{out} = \hat{A} \times (V_+ - V_-)$ where $\hat{A}$ is a function of frequency.

$$\hat{A} = \frac{A_0}{1 + if/f_c} \tag{1}$$

  where $i = \sqrt{-1}$, A_0 is the open loop gain at zero frequency and f_c is the cutoff frequency beyond which the gain drops rapidly. Note $\hat{A}$ is a complex number due to the i in the denominator. This means there is in general some phase shift between the output and input at high frequencies. For our purposes it is sufficient to consider only the magnitude of $\hat{A}$ which is an ordinary/real number.

$$|\hat{A}| = \frac{A_0}{\sqrt{1 + (f/f_c)^2}} \tag{2}$$

  Note this looks very similar to the amplitude of V_{out} and the amplitude of V_{in} seen in the RC circuit (see Experiment 2) if you substitute $f_c = 1/(2\pi RC)$. What does this say about the inputs of the Op-Amp?

- The **input impedance** at the input terminals V_+ and V_-, although very large is in fact finite.

These lead to some "non-ideal" characteristics of Op-Amps (and the resulting amplifier) which may be important depending on the application:

- The Op-Amp draws a very small amount of current (<100 pA) through its inputs at all times. This is called the input offset current. The amplifier is also characterized by a slight, D.C. input offset voltage ($<$ 2 mV) which may also drift with time.

- For an ideal Op-Amp the open loop gain A is assumed to be infinite and frequency independent. In the case of a real or non-ideal Op-Amp A has a form given by Eqn. 1 .

- The magnitude of the output voltage signal V_{out} is always less than the power supply voltage no matter how big the product of $G \times V_{in}$ is.

In the ideal case the Op-Amp acts as a linear amplifier such that the output voltage is directly proportional to the input voltage and independent of frequency. However, there are several restrictions required to observe this ideal behaviour:

Restrictions to stay close to ideal behaviour:

1. $|V_{in}| > 10mV$ so that input noise and the input offset current and voltage can all be neglected.
2. $|G \times V_{in}| < 5V$ so that the expected output voltage is not greater than the power supply voltage which in your case is +- 5V. If $|G \times V_{in}| > 5V$ the output will be distorted or clipped at some value less than $\pm 5V$
3. G of the amplifier circuit is only constant up to some bandwidth frequency determined by the cutoff frequency f_c of the Op-Amp itself.

4 Experiment

4.1 Building an Inverting Voltage Amplifier

A simple inverting amplifier circuit is shown in Fig. 3. Assuming the Op-Amp is treated as ideal, show that closed loop voltage gain:

$$\frac{V_{out}}{V_{in}} = -\frac{R_f}{R_g} \equiv G \tag{3}$$

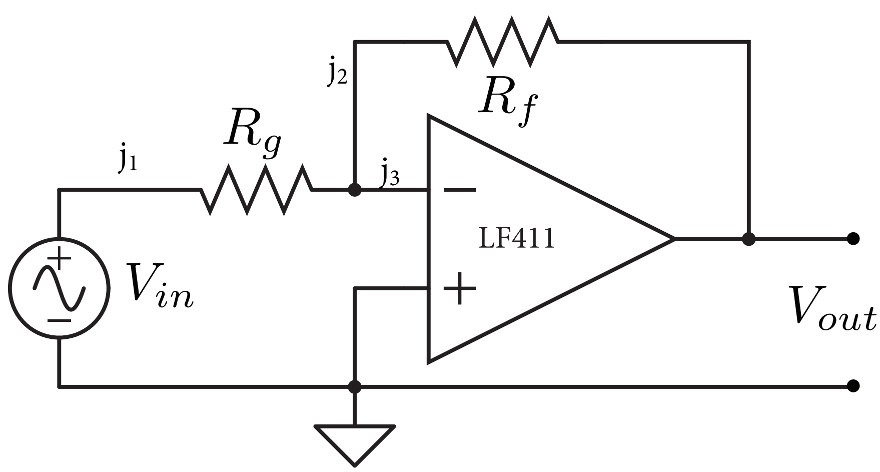

Figure 3: Inverting amplifier

Construct the circuit shown in Fig. 3. **Important: do not power up the protoboard until you have checked all connections twice! Make sure you and your partner agree that it is set up correctly!** In order not to short any of the pins of the Op-Amp together it must be installed in such a way that all 8 pins are in different columns (e.g. as shown in Fig. 4 where pins 1,2,3 and 4 are in different columns in the upper half of the protoboard and pins 5, 6, 7 and 8 are in different columns of the bottom half of the protoboard). Also note that the LF411 Op-Amp has a small circle imprinted on the top between pins pin 1 and 2 to indicate where the numbering starts and goes counter-clockwise. You can see this if you expand Fig. 4.

Build the circuit shown by installing R_g = 1 kOhms for the input resistor and R_f = 10 kOhms for the feedback resistor. You should measure the resistors with the DMM and calculate the expected gain for *your* circuit according to Equation 3.

- With the **power supply OFF** connect the +5V power line to pin 7 and the -5V power line to pin 4, as shown in the right hand side of Fig. 2.
- Set the frequency on the function generator to sine wave with an amplitude of 100 mV, a frequency of 100 Hz and with no offset.
- Use DC coupling on the oscilloscope channels so you can observe any DC component in the signals.
- Before turning on the power to the protoboard check all the connections one more time, especially the power connections.

Tip 1

Remember to keep your wiring tidy and as 2-dimensional as you can. This makes circuits easier to troubleshoot. Your in-class grade will depend on neatness as well as the circuit working.

The input and output signals should look the same when the power is off. Now turn on the power supply. The amplitude of the output signal should be amplified. What do you notice about the amplitude and phase of the output signal relative to the input signal? Explain what you observe. Save the screenshots of the input and output signals with power supply off and then with the power supply on. Take a photo of your circuit to include in your notes.

Checkpoint 1

Show your circuit along with the input and output signals displayed on CH1 and CH2 of the oscilloscope. While waiting, you can carry on with the measurements below unless you believe there is a problem.

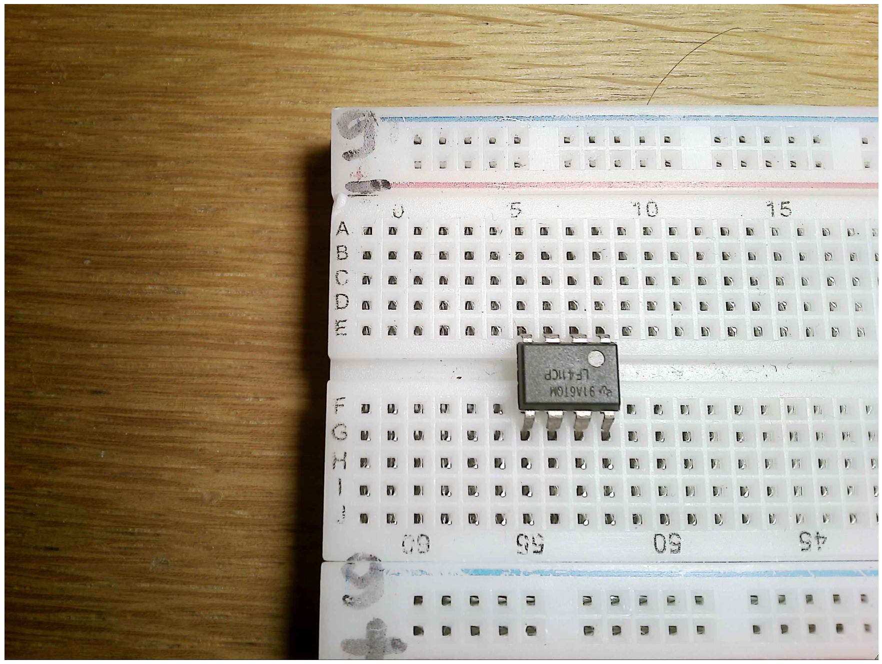

Figure 4: The LF 411 op-amp used to make an inverting amplifier. Note how the location of the LF411 on the protoboard straddles the electrical barrier between the top and bottom halves of the protoboard.This is required so that each pin has its own column and thus is electrically isolated from the other pins. Also note the small circular dot which is between pins 1 and 2 identified in Fig 2. This means the V_{+} and V_{-} inputs are in columns 6 and 7 respectively for the location of the op-Amp in the picture. The power connections go to pins 4 and 7 (i.e. columns 5 and 53 for the location in the picture).

4.2 Amplifier Measurements

4.2.1 Distortion and clipping

First, start with a small amplitude low frequency sine wave input signal (e.g. 100 mV and 100Hz you started with) with no offset. Vary the offset voltage and amplitude of the signal and report under what conditions there is distortion of the output signal (deviation from sinusoidal). Save a few screenshots to supplement your description.

Describe the nature of the distortion that is observed when the output signal reaches a some limiting value for both positive and negative voltages. (This kind of distortion is commonly called clipping). These limiting voltages on the positive and negative side depend on the particular Op-Amp and are always less than the power supply voltages of $\pm 5V$. Save images of both channels with and without distortion. Report the limiting values for your Op-Amp . For the measurements below always check for such distortions. Make a note of any such checks you do in your notebook. It is a good idea to take a few points where there is some noticeable distortion. However most of the points should be taken in a region where there is minimal distortion. Make sure you include a detailed sketch of the circuit as well as a photo showing all the connections.

Checkpoint 2

Discuss your observations of the distortion and clipping of your amplifier.

4.2.2 Linearity and Gain

Measure the linearity of the amplifier gain under conditions where there is minimal distortion, but take a couple of points where you see some small amount of distortion. Make measurements of the amplitude V_{out} versus V_{in} at $100Hz$. A plot of this allows you to check the range over which this is linear, meaning the gain (which is the slope) is constant. Ensure you have enough data to do a good linear fit plus a few points that may be beyond the linear range.

Tip 2

Plot your data as you go with a line for your expected gain to visualize deviations.

Checkpoint 3

Show the data you have obtained to determine the gain and linearity, and discuss how you will analyze the data.

Repeat these measurements at high frequency e.g. 500kHz. Describe and explain any differences between the low and high frequency data sets.

Before you leave the lab!

Make sure you have:

- saved screenshots of the input and output signals with the Op-Amp power off and on
- description and screenshots of both distorted and undistorted amplified signals from section 4.2.1
- a data set of V_{out} vs. V_{in} at 100Hz
- a data set of V_{out} vs. V_{in} at a high frequency (e.g. 500kHz)