Lab5

Operational Amplifiers (OP-Amps) II

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Contents

1 Goals

In this lab, you will characterize the gain and frequency dependence of inverting op-amp circuits. You will work with a few applications of negative feedback including a circuit to sum voltages.

Proficiency with new equipment:

- Inverting op-amps: basic, summing, differentiator, and integrator

Experimental Design:

- Designing, building, and characterizing your own op-amp circuit

Modeling the physical system:

- Frequency dependence of op-amp circuits
- Input and output impedances of op-amp circuits

Applications:

- Build a digital to analog converter

2 Definitions

Closed-loop gain, G - gain of the *op-amp circuit* at all frequencies with feedback applied

Low frequency gain, G_0 - gain of the *op-amp circuit* at DC (f = 0 Hz)

Open-loop gain, A - gain of the *op-amp itself* at all frequencies with no feedback applied

DC gain, A_0 - gain of the *op-amp itself* at DC (f = 0 Hz) with no feedback applied

$\mathbf{f_0}$ - 3 dB frequency for an *op-amp itself* with no feedback

$\mathbf{f_B}$ - 3 dB frequency for an *op-amp circuit* with feedback applied

$\mathbf{f_T}$ - unity gain frequency, frequency where the open loop gain A is equal to one

3 Inverting Amplifier Theory

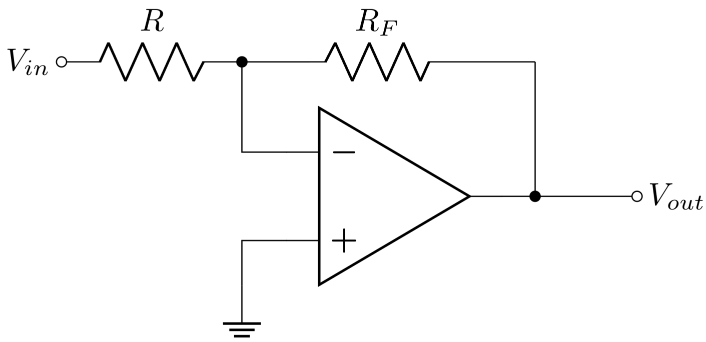

Figure 1: Inverting amplifier

The basic inverting amplifier is shown in Figure 1. We can use the Golden Rules to determine the low-frequency gain. Since the positive input is grounded, the op-amp will do everything it can to keep the negative input at ground as well. In the limit of infinite open loop gain the inverting input of the op-amp is a virtual ground, a circuit node that will stay at ground as long as the circuit is working, even though it is not directly connected to ground. When ***A is infinite,*** the gain of an inverting amplifier is

$$G_0 = \frac{V_{out}}{V_{in}} = -\frac{R_f}{R}$$

This is the "Golden Rule" result. For the frequency dependence of the gain we need to consider what happens when A is not infinite, as we did for the non-inverting case. We use the same definitions as for the non-inverting case. The op-amp open loop gain is A, and the divider ratio B is the same as before:

$$B = \frac{R}{R + R_f}$$

When ***A is finite*** the gain for an inverting amplifier is given by

$$G_0 = \frac{V_{out}}{V_{in}} = -\frac{A(1 - B)}{1 + AB}$$

The above formulas are still correct when A and/or B depend on frequency. B will be frequency independent if we only have resistors (in other cases that use complex impedance it may not be), but A always varies with frequency. For most op-amps, including the LF356, the open loop gain varies with frequency like an RC low-pass filter:

$$A(f) = \frac{A_0}{1 + j\frac{f}{f_0}}$$

The 3 B frequency, f_0, is usually very low, around 10 Hz. Data sheets do not usually give f_0 directly; instead they give the DC gain, A_0, and the unity gain frequency, f_T, which is the frequency where the magnitude of the open loop gain A is equal to one. The relation between A_0, f_0, and f_T is

$$f_T = A_0 f_0$$

The frequency dependence of the closed loop gain G is then given by

$$G = \frac{G_0}{1 + j\frac{f}{f_B}}$$

The frequency response of the amplifier with feedback is therefore also the same as for an RC low-pass filter.

3.1 Input and output impedances of inverting amplifiers

Formulas for the input and output impedance for an inverting amplifier are derived in H&H Section 4.26. When the open loop gain is large, the negative input of the op-amp is a virtual ground and so the input impedance is just equal to R. This is very different from the non-inverting case where the input impedance is proportional to A for large A. In practice, the input impedance of an inverting amplifier is not usually greater than about 100 kΩ, while the input impedance of a non-inverting amplifier can easily be as large as 10^{12} Ω. When A is not large the formulas for the input impedance and output impedance of the entire circuit are derived in H&H Section 4.26. The results are

$$R_i' = R + \frac{R_f}{1 + A}$$

$$R_o' = \frac{R_o}{(1 + AB)}$$

The output impedance is the same for both the inverting and non-inverting amplifiers.

The gain-bandwidth product for inverting amplifier is slightly modified compared to non-inverting amps.

$$A_0 f_0 = \frac{-G_0 f_B}{1 - B} = f_T$$

This is the same (except for the sign) as the non-inverting result when the closed loop gain is large ($B \ll 1, |G0| \gg 1$), but at unity closed loop gain ($B = 1/2, G_0 = -1$) the inverting amplifier has only half as much bandwidth as a non-inverting amplifier.

4 Summing Amplifier Theory

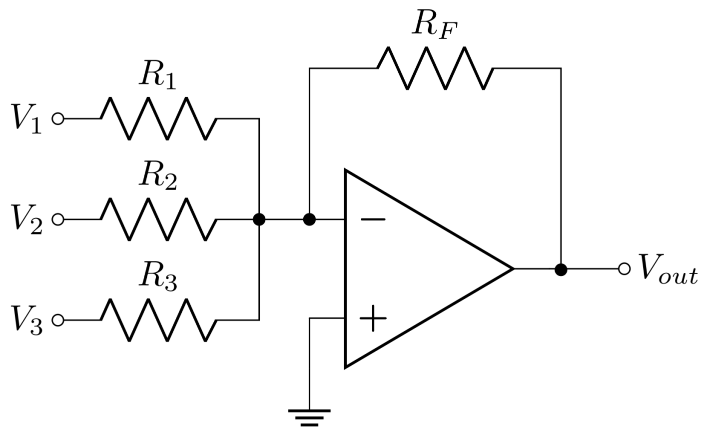

Figure 2: Summing amplifier

The Summing Amplifier, shown in Figure 2, is a very flexible circuit based upon the standard inverting op-amp configuration that can be used for combining multiple inputs. The standard inverting amplifier, shown in Figure 1, has a single input voltage, V_{in}, applied to the inverting input terminal. If we add more input resistors to the input, the circuit can become a voltage adder with different gain for each input. There are many applications for summing amplifiers including audio mixers and digital to analog converters. Using the Golden Rules we can determine the transfer function listed below.

$$V_{out} = -\left[V_1\left(\frac{R_F}{R_1}\right) + V_2\left(\frac{R_F}{R_2}\right) + V_3\left(\frac{R_F}{R_3}\right)\right]$$

This circuit has many applications including working as an adder in any basis-set you specify. If you only restrict yourself to input voltages of 0 or 1 V (or on and off), you get to a binary adder and can convert binary signals to analog (e.g. base 2 to base 10). Digital-to-analog converters are found in every research lab (or computer, or phone, etc.) where you want to create any value of a signal from just 1's and 0's. If you want a refresher on binary or counting in binary, you can use this Wikipedia entry.

5 Integrator Theory

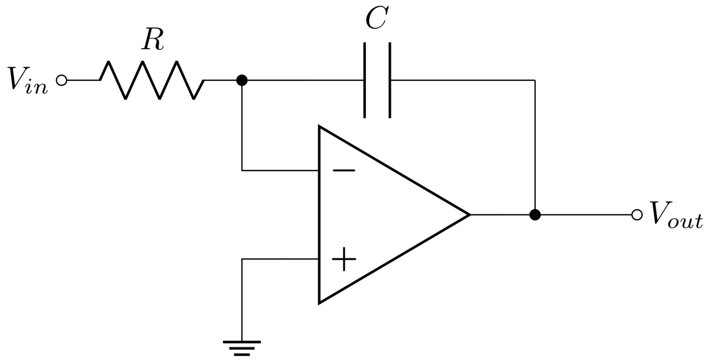

Figure 3: Integrator

The basic op-amp integrator is shown in Figure 3. As compared to the inverting amplifier in Figure 1, the only change is a replacement of the feedback resistor R_F with a capacitor C. An integrator is the same circuit as a low-pass filter. If you are interested in what frequencies get passed, you call it a low-pass filter. If you are interested in integrating the input signal, you call it an integrator. We can understand how the integrator works by applying the Golden Rules and remembering the defining equation for capacitors. Just as in the integrating amplifier, the Golden Rules tells us that $V_- \approx V_+ = 0$ and that the current across both components is the same because no current flows into the op-amp. We label I_R as the current through the resistor, which is V_{in}/R since V_- is at ground. We label I_C as the current across the capacitor. The defining equation for capacitors is $Q = CV$. The current through a capacitor is $I = dQ/dt = d(CV)/dt = CdV/dt$. Therefore, the equation $I_R = I_C$ becomes:

$$\frac{V_{in}}{R} = -C\,\frac{dV_{out}}{dt}$$

Solving this equation for V_{out} gives the following:

$$V_{out} = -\frac{1}{RC}\int V_{in}\,dt$$

This is why it is called an integrator. Choosing values for the resistor and capacitor depends on several considerations. First, one needs to determine the value of the product RC. This will depend on the expected signal (size and shape), the expected integration time, and the desired output (remembering the op-amp limitations on maximum output voltage and slew rate). Once RC is determined, some considerations for choosing R and C are:

- Availability: resistors from 1 Ω to 10 MΩ and capacitors from 2 pF to 1 μF are readily available.

- Input impedance: generally a high input impedance (> 1 kΩ) is desired to avoid loading the input signal.
- Avoiding effect of stray capacitance: there are many sources of capacitance, such as cables, which can unintentionally couple to your circuit. For this reason, it is advisable to avoid very small capacitors as the stray capacitances may end up dominating. A few hundred pF should be sufficient.
- Dealing with DC signal: A DC signal in the input results in the capacitor eventually charging up to the
  maximum output voltage of the op-amp. This DC signal can result from the op-amp. One way to mitigate this is to add another resistor in parallel with the capacitor such that at low frequencies (large impedance in capacitor) the circuit acts like an inverting amplifier. As the impedance of a resistor is proportional to R while the impedance of a capacitor is inversely proportional to C, to ensure that the signal mainly goes through the capacitor, one would like large resistor and/or large capacitor values. Of course, the resistor chosen here in combination to the main resistor in the circuit leads to a DC gain as calculated for the inverting amplifier so this should be considered in making your choice. You can alternatively try placing the high impedance resistor between V_{out} and ground instead of in parallel with the capacitor.

6 Useful Readings

1. Steck Sections 7.1, 7.2, 7.3.1, 7.3.2, 7.3.4, 2.2.1, 7.4.2
2. Fischer-Cripps Sections 12.2–12.15
3. Horowitz and Hill 2$^{\text{nd}}$ Ed., Sections 4.04–4.08, 4.19–4.20 and Sections 1.13–1.15

7 Prelab

Answer the following questions using Mathematica for the plots. You can use either Mathematica for the rest the questions as well or do them by hand in your lab book. **Bring an electronic copy of your notebook to lab, preferably on your own laptop. You will use it to plot your data during the lab session.**

7.1 Inverting amplifier

1. Calculate the values of low frequency gain, G_0, and the bandwidth, f_B, for the inverting amplifier in Figure 1 for the following circuit you will build in lab with the following resistors: $R_F =$

$10\,k\Omega$ and $R = 10\,\Omega$.

2. Graph a Bode plot for the open loop gain and the closed loop gain for the circuit from above on the same graph using Mathematica (making sure to label axes and curves).

7.2 Summing amplifier - digital to analog converter

1. Design a three input summing amplifier (Figure 2) that can create an analog voltage of integers from 0 to -7 volts ($|V_{out}| = 0, 1, 2, 3, 4, 5, 6,\ and\ 7\ V$) using only two possible input states on each input ($V_{low} = 0\ V$ and $V_{high} = 1\ V$). Draw a schematic of your circuit and label all the resistors. *Hint: Write down the binary numbers from 000 binary = 0 in decimal to 111 binary = 7 in decimal.* Think about the relative values of R_1, R_2, and R_3. We suggest you use $R_F = 40k\Omega$.
2. Draw a table that lists the input voltages and corresponding output voltages to create $|V_{out}| = 0, 1, 2, 3, 4, 5, 6,\ and\, 7\, V$.

7.3 Integrator

So far you have been looking at the output versus frequency (Bode plots). Now you will also consider the output versus time.

1. Design an integrator based on Figure 3 and the discussion above. Choose values for the components (resistors and capacitors) and describe why you chose those values.
2. List some possible applications for the integrator.
3. Sketch the time response of your circuit (or you could use Mathematica if you wish) for the following input waveforms: square wave, triangle wave, and sine wave. *Hint: What happens when you integrate a constant, a linear function, and a sine function?*

7.4 Lab activities

1. Read through all of the lab steps and identify the step (or sub-step) that you think will be the most challenging.
2. List at least one question you have about the lab activity.

8 LF356 Pin Out and Schematic

All op-amp circuits start out by making the basic power connections. Op-amps are active components, which means they need external power to function unlike passive components such as resistors.

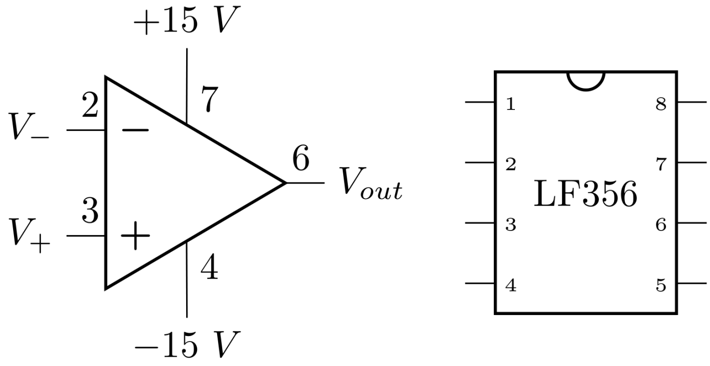

Figure 4: LF356 schematic and pin-out

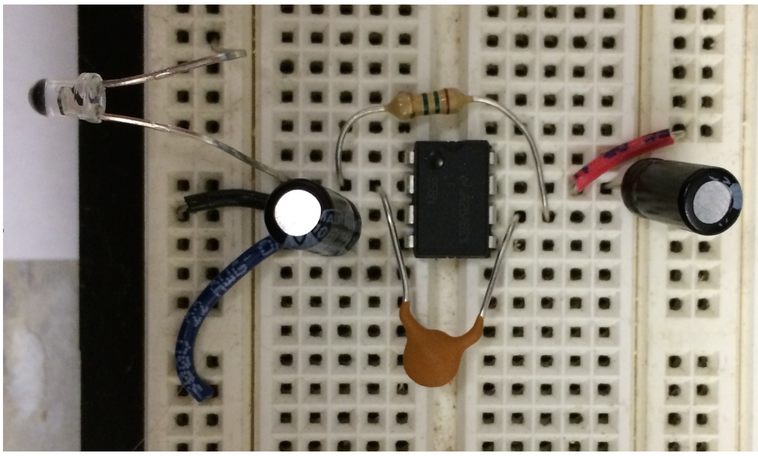

Figure 5: Good placement of op-amp and bypass capacitors on a protoboard. Note that short wires are used for all connections.

9 General Op-Amp Tips

These are reminders of the basics steps you should always follow when working with op-amps.

1. This experiment will use both +15 V and –15 V to power the LF356 op-amp. Make sure you **unplug** the DC supplies while wiring your op-amp (you may find it useful to plug them into their own power strip). Everyone makes mistakes in wiring-up circuits. You should always check your circuit over before applying power. Figure 4 shows a pin-out for the LF356 chip. Familiarize yourself with the layout. The following procedure will help you wire up a circuit accurately:

1. Draw a complete schematic in your lab notebook, including all ground and power connections, and all IC pin numbers. Try to layout your prototype so the parts are arranged in the same way as on the schematic, as far as possible.
2. Measure all resistor values before putting them in the circuit. Make sure you are using the correct capacitors. Some capacitors indicate the capacitance directly, but small capacitors usually just have a number where 10 = 10 pF, 102 = 10x10^2 pF = 1 nF, 103 = 10x10^3 = 10 nF, 104 = 10x10^4 pF = 100 nF. Also, see the important note below about polarized capacitors.
3. Adhere to a color code for wires. For example:
   - 0V (ground) Black
   - +15V Red
   - -15V Blue

2. The op-amp chip sits across a groove in the prototyping board (see Figure 5). Before inserting a chip, ensure the pins are straight (using a needle-nose pliers or something similar). After insertion, check visually that no pin is broken or bent under the chip. To remove the chip, use a small screwdriver in the groove to pry it out.
3. You will have less trouble with spontaneous oscillations if the circuit layout is neat and compact, in particular the feedback path should be as short as possible to reduce unwanted capacitive coupling (see Figure 5). Also, wire around the chip rather than over it.
4. To help prevent spontaneous oscillations due to unintended coupling via the power supplies, use bypass capacitors to filter the power supply lines. A bypass capacitor between each power supply lead and ground will provide a miniature current "reservoir" that can quickly supply current when needed. This capacitor is normally in the range 1-10 µF. Compact capacitors in this range are usually ***polarized***, meaning that one terminal must always be positive relative to the other. If you put a polarized capacitor in backwards, it will burn out. You will probably hear a pop and smell something foul. Please don't do this. The negative side should have an arrow on the capacitor. Also, the positive side should have a longer lead but this is not a good identification method as the leads can (and should) be cut. Bypass capacitors should be placed close to the op-amp pins. If you are connecting the +15 V supply to ground, the negative capacitor lead is connected to ground and the positive lead is connected to +15 V. If you are connecting the -15 V supply to ground, the negative capacitor lead is connected to -15 V and the positive lead is connected to ground.

10 Inverting Amplifier Application - Frequency Dependent Gain

1. Build the inverting amplifier shown in Figure 1, with $R_F = 100\ k\Omega$ and $R = 10\ k\Omega$. Measure R and R_F with the DMM before inserting them into the circuit board. Predict G_0 and f_B from these measured values and the op-amps value of f_T from the data sheet. (You should be able to review your prelab work here!)
2. Use the function generator to measure the low frequency gain. What frequency should you use to test the low frequency gain (i.e., what frequency should the signal be below?) Consider the gain-bandwidth product and how it relates to your circuit. What is the predicted gain for the frequency you chose? Measure the low frequency gain G_0 by measuring V_{in} and V_{out} using the scope (as you did in Lab 4). Do your measurements agree with your predictions?
3. Update your prediction of the 3 dB frequency for your circuit. Include your calculations in your lab book. Now, determine the 3 dB frequency experimentally. Describe the procedure you followed to determine f_B. Does your measurement agree with your prediction? Explicitly record what criteria you used to determine whether or not the model and measurements agree.
4. Using the gain-bandwidth relation and your measurements of G_0 and f_B to determine f_T for your op-amp. Does your measured value of f_T agree with the one from the datasheet?
5. Measure the frequency dependence of your circuit. Measure the gain at every decade in frequency from 10 Hz to 10 MHz. Should you use a 10X probe or coax cable to make your measurements? Explain your reasoning. Plot your measurements and predicted gain curve on the same plot. Where, if at all, is the simple model of the op-amp circuit not valid? Can you suggest possible model refinements and/or physical system refinements to get better agreement between the model predictions and measurements.

11 Summing Amplifier Application - Digital to Analog Conversion

1. Modify your basic inverting op-amp circuit to make it a summing amplifier as shown in Figure 2. Use the component values you determined in your prelab for the resistors (you may want to check with your instructor to be sure they make sense). Draw the schematic in your lab notebook and label all components. Measure the resistors before inserting them into your circuit and record the values.
2. Determine the transfer function for your exact component values. What is V_{out} in terms of V_1, V_2, and V_3?
3. Confirm your summing amplifier is working by testing a couple of input voltages to compare to your predicted V_{out} from you prelab. What is the best available measurement device to make

these measurements? Why did you choose that device? Do these initial measurements agree with your predictions? Create a table listing all possible input voltages, of 0V or 1V, to the 3 input voltages (binary counting from 0V-7V output) and measure the output of your circuit. This is a digital-to-analog converter mode. How accurately were you able to make integer values of output voltage? What criteria did you use to determine the accuracy? Describe a way to refine the physical system to more accurately create exact integer voltages at the output.

12 Integrator Application

By now, you should be somewhat comfortable with experimental design and reporting of outcomes, especially with op-amps and voltage dividers. In this last section, you will design and characterize an integrator. Your starting point should be the integrator circuit you designed in the prelab. Items you likely wish to include in your lab notebook:

- Describe the circuit you are building and testing. It is suggested that you use R = 10 kΩ and the necessary capacitor to obtain a time constant of 1 ms.
- Draw the schematic of the circuit with component values labeled.
- List your predictions / models. It is fine to start by using ideal models.
- How do you plan to test it? Be sure to use square, triangle, and sine waves at various frequencies.
- The results of the tests with various inputs.
- Do the results match your model? What didn't match?
- How would you refine your model or physical system to get better agreement?

If you have an issue where the output seems to be at the rail voltage of the op-amp, you likely have a DC signal on the input (in addition to the AC signal). You should review the integrator theory section for ways to alleviate this.

13 Summary and Conclusions

Write a two-paragraph summary in your lab notebook of what you learned and any important takeaways.