

Operational Amplifiers and Negative Feedback

Purpose

This experiment shows how an operational amplifier (op-amp) with negative feedback can be used to make an amplifier with many desirable properties, such as stable gain, high linearity, and low output impedance. You will build both non-inverting and inverting voltage amplifiers using an LF356 op-amp.

Introduction

The purpose of an amplifier is to increase the voltage level of a signal while preserving as accurately as possible the original waveform. In the physical sciences, transducers are used to convert basic physical quantities into electric signals, as shown in Figure 4.1. An amplifier is usually needed to raise the small transducer voltage to a useful level.

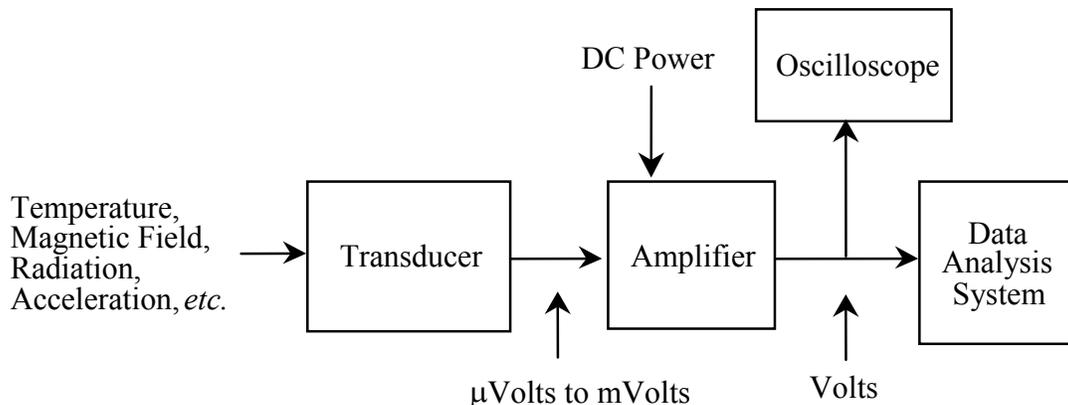


Figure 4.1 Typical Laboratory Measurement

A small voltage or current change at the input of the amplifier controls a much larger signal at the input of whatever circuit or instrument the amplifier's output is connected to. Measuring and recording equipment typically requires input signals of 1 to 10 V. To meet such needs, a typical laboratory amplifier might have the following characteristics:

1. Predictable and stable gain. The magnitude of the gain is equal to the ratio of the output signal amplitude to the input signal amplitude.
2. Linear amplitude response, so that the output signal is directly proportional to the input signal.

3. According to the application, the frequency dependence of the gain might be a constant independent of frequency up to the highest frequency component in the input signal (wideband amplifier), or a sharply tuned resonance response if a particular frequency must be picked out.
4. High input impedance and low output impedance are usually desirable. These characteristics minimize changes of gain when the amplifier is connected to the input transducer and to other instruments at the output.
5. Low noise is usually important. Every amplifier adds some random noise to the signals it processes, and this noise often limits the sensitivity of an experiment. We will learn about amplifier noise in Experiment 8.

Commercial laboratory amplifiers are readily available, but a general-purpose amplifier is expensive (>\$1000), and most of its features might be unneeded in a given application. Often, it is preferable to design your own circuit using a cheap (<\$1) op-amp chip.

Op-amps have many other circuit applications. They can be used to make filters, limiters, rectifiers, oscillators, integrators, and other devices (see FC 12.9 – 12.15). To get an idea of the variety of op-amps available, have a look at the National Semiconductor web site (www.national.com). They currently make over 300 types, offering trade-offs between speed, cost, power consumption, precision, etc. The op-amp is the most important building block of analog electronics.

Suggested Readings

1. FC Sections 12.2 – 12.15. The basic rules of op-amp behavior and the most important op-amp circuits. [Note while FC discussed basic characteristics of op amps in 12.2 it does not have the I, II “Golden Rule” analysis that we will discuss in class.] Do not worry right now about the transistor guts of op-amps. We will learn about transistors in Experiments 7-8.
2. Horowitz and Hill, Chapter 4.
3. The IC Op-Amp Cookbook, by Walter Jung, 3rd edition (Prentice Hall, 1997).
4. Diefenderfer Chapter 9
5. D.V. Bugg, Chapter 7, particularly Sections 7.1–7.4, 7.7, and 7.12.

Theory

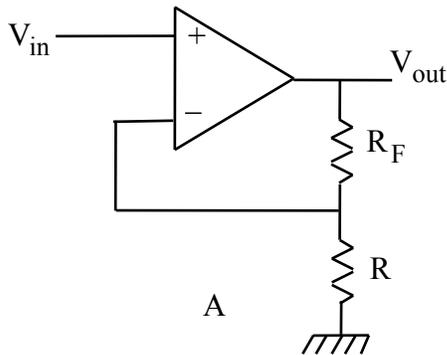


Figure 4.2 Non-inverting Amplifier

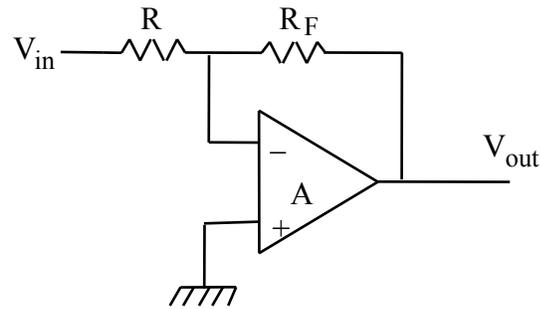


Figure 4.3 Inverting Amplifier

The two basic op-amp circuit configurations are shown in Figs. 4.2 and 4.3. Both circuits use negative feedback, which means that a portion of the output signal is sent back to the negative input of the op-amp. The op-amp itself has very high gain, but relatively poor gain stability and linearity. When negative feedback is used, the circuit gain is greatly reduced, but it becomes very stable, limited only by the temperature dependence of the resistors R and R_F . At the same time, linearity is improved and the output impedance decreases.

Both configurations are widely used because they have different advantages. Besides the fact that the second circuit inverts the signal, the main differences are that the first circuit has a much higher input impedance, while the second has lower distortion because both inputs remain very close to ground.

The gain or transfer function A of the op-amp alone is given by

$$A \equiv \frac{V_{out}}{V_{in}^+ - V_{in}^-}$$

where the denominator is the difference between the voltages applied to the + and - inputs. We use the symbol G for the gain of the complete amplifier with feedback: $G \equiv V_{out}/V_{in}$. This gain depends on the resistor divider ratio $B \equiv R/(R+R_F)$. In feedback amplifier lore A is called the open loop gain, G is called the closed loop gain, and the product $A \cdot B$ is called the loop gain. You can see the reason for these names if you imagine opening the feedback loop in Fig. 4.2 by disconnecting the - input.

If we assume that $A \rightarrow \infty$, that the op-amp input impedance is infinite, and that the output impedance is zero, then the behavior of these circuits can be understood using the simple “Golden Rules”:

- I. The voltage difference between the inputs is zero. (“voltage rule”)
- II. No current flows into (or out of) each input. (“current rule”)

The “Golden Rule” analysis is very important and is always the first step in designing op-amp circuits, so be sure you understand it before you read the material below, where we consider the effect of finite values of A , mainly so that the frequency dependence of the closed loop gain G can be understood.

GAIN EQUATION – NON-INVERTING CASE

The basic formula for the gain of feedback amplifiers is derived in FC, Section 12.5. From Fig. 4.2 we can see that:

$$V_{out} = A(V_{in} - BV_{out})$$

Solving this equation yields:

$$G = \frac{V_{out}}{V_{in}} = \frac{A}{1 + AB} \quad (1)$$

With $B=R/(R+R_F)$ the above equation for the closed loop gain then gives

$$G = 1 + \frac{R_f}{R} \quad \text{if } A \gg 1$$

which is the Golden Rule result. If we don't care about corrections due to the finite value of A , then Equation (1) is not needed and the analysis can be done using just the Golden Rules.

INPUT AND OUTPUT IMPEDANCE – NON-INVERTING CASE

Formulas for the input and output impedance are derived in H&H Section 4.26. The results are

$$\begin{aligned} R'_i &= R_i(1 + AB) \\ R'_o &= R_o / (1 + AB) \end{aligned}$$

where R_i and R_o are the input and output impedances of the op-amp alone, while the primed symbols refer to whole the amplifier with feedback. These impedances will be improved from the values for the bare op-amp if the loop gain $A \cdot B$ is large.

FREQUENCY DEPENDENCE – NON-INVERTING CASE

The above formulas are still correct when A and/or B depend on frequency. B will be frequency independent if we have a resistive feedback network, but A always varies with frequency. For most op-amps, including the LF356 (and others with dominant pole compensation, see H&H Section 4.34), the open loop gain varies with frequency like an RC low-pass filter:

$$A = \frac{A_0}{1 + i \frac{f}{f_0}} \quad (2)$$

The 3dB 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 can be found by substituting Equation (2) into Equation (1). You will find the result

$$G = \frac{A_0 / (1 + A_0 B)}{1 + i \frac{f}{f_0 (1 + A_0 B)}} = \frac{G_0}{1 + i \frac{f}{f_B}}$$

The frequency response of the amplifier with feedback is therefore also the same as for an RC low-pass filter. The 3dB bandwidth f_B with feedback is given by

$$f_B = f_0 (1 + A_0 B)$$

At frequencies well below f_B the gain is

$$G_0 = \frac{A_0}{1 + A_0 B}$$

GAIN-BANDWIDTH PRODUCT – NON-INVERTING CASE

We can now derive an example of a very important general rule connecting the gain and bandwidth of feedback amplifiers. Multiplying the low frequency gain G_0 by the 3 dB bandwidth f_B gives

$$G_0 f_B = \frac{A_0}{1 + A_0 B} \cdot f_0 (1 + A_0 B) = A_0 f_0,$$

$$G_0 f_B = f_T.$$

In words, this very important formula says that the gain-bandwidth product $G_0 f_B$ equals the unity

gain frequency f_T . Thus if an op-amp has a unity gain frequency f_T of 1 MHz, it can be used to make a feedback amplifier with a gain of one and a bandwidth of 1 MHz, or with a gain of 10 and a bandwidth of 100 kHz, *etc.*

GAIN EQUATION – INVERTING CASE

The basic inverting configuration is shown in Figure 4.3. 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. Since the op-amp inputs draw no current, it follows that

$$V_{in} / R = -V_{out} / R_F$$

and the dc closed loop gain 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 above for the non-inverting case.

The gain equation is discussed in FC 12.4. 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 given as before by

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

The voltage V_{in}^- at the negative op-amp input is related to V_{out} and V_{in} by

$$V_{in}^- = V_{in} + B(V_{out} - V_{in})$$

But V_{in}^- is also related to V_{out} by the open-loop gain: $V_{out} = -AV_{in}^-$. Eliminating V_{in}^- from these two equations gives the gain equation for an inverting amplifier

$$\boxed{G = \frac{V_{out}}{V_{in}} = \frac{-A(1-B)}{1+AB}} \quad (3)$$

(This equation is misprinted on p. 235 of H&H.) The result is almost the same as for a non-inverting amplifier except for the sign and the factor (1-B) in the numerator. When the open loop gain is large ($A \gg 1$) we have $G = 1 - 1/B = -R_F/R$, the “Golden Rule” result.

INPUT AND OUTPUT IMPEDANCE – INVERTING CASE

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 10¹² Ω. When A is not large the formula for the input impedance is

$$Z_{in} = R + \frac{R_F}{1 + A}.$$

The formula for the output impedance is the same as for a non-inverting amplifier:

$$R'_o = R_o / (1 + AB).$$

FREQUENCY DEPENDENCE – INVERTING CASE

As for the non-inverting case, all of the above formulas are still correct when A and/or B depend on frequency. (To make B frequency dependent, R and/or R_F may be replaced by networks containing capacitors or inductors.) We again assume that the op-amp has dominant pole compensation:

$$A = \frac{A_0}{1 + i \frac{f}{f_0}}, \quad (4)$$

so that the relation between the open loop 3 dB frequency f₀, the dc open loop gain A₀ and the unity gain frequency f_T is still

$$f_T = A_0 f_0.$$

The frequency dependence of the closed loop gain G for the feedback amplifier can be found by substituting Equation (4) into Equation (3). The result is

$$G = -\frac{\frac{A_0(1-B)}{(1+A_0B)}}{1 + i \frac{f}{f_0(1+A_0B)}} = \frac{G_0}{1 + i \frac{f}{f_B}}.$$

When B is frequency independent, the frequency response of the amplifier with feedback is again the same as an RC low-pass filter. The 3dB bandwidth f_B with feedback is the same as for the non-inverting amplifier

$$f_B = f_0(1 + A_0B)$$

At frequencies well below f_B the gain is

$$G_0 = -\frac{A_0(1-B)}{1 + A_0B}.$$

The gain-bandwidth product relation is

$$G_0 f_B = -\frac{A_0(1-B)}{1 + A_0B} \cdot f_0(1 + A_0B) = -A_0 f_0(1 - B).$$

$$G_0 f_B = -f_T(1 - B).$$

This is the same (except for the sign) as the non-inverting result when the closed loop gain is

large ($B \ll 1$, $|G_0| \gg 1$), 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 follower.

Problems

1. (2 points) Data for the LF356 op-amp (same as LF156) are given at the National Semiconductor Web Site: <http://www.national.com/ds/LF/LF155.pdf> (there is a link from the 3330 web page and a copy in the lab). Verify that the following values are reasonable approximations to use in solving the problems. Identify your source of each item by quoting the graph or table number and page number.

DC voltage gain	$A_0 = 2 \cdot 10^5$ (same as A_{VOL} in tables)
Unity gain frequency	$f_T = 5$ MHz (same as GBW in tables)
Maximum output voltage	$V_{sat} = \pm 13$ V (same as V_O in tables)
Maximum slew rate	$SR = (dV_{out}/dt)_{max} = 12$ Volts/ μ sec
Maximum output current	$(I_O)_{max} = 25$ mA
Input resistance	$R_i = 10^{12}$ Ω (R_{IN} in tables)
Output resistance	$R_o = 40$ Ω (See the theory section for help with R_o .)
Input offset voltage	$V_{OS} = 3$ mV
Input bias current	$I_B = 30$ pA

2. (3 points) Calculate the values of low frequency gain G_0 (choose the correct version of the formula) and the bandwidth f_B for the non-inverting amplifier in Fig. 4.2. Consider the cases with $R_F = 100$ k Ω for all, and $R = 100$ Ω , 1 k Ω , and 10 k Ω . Also consider the voltage follower, with $R_F=0$ and $R=\infty$ (note there are four cases). Draw Bode plots for the open loop gain and the four closed loop gains on the same graph. Estimate the input and output impedances of the amplifier with $R_F = 10$ k Ω and $R = 100$ Ω for 1 kHz sine waves.
3. (3 points) What is the maximum output amplitude for 5 MHz sine waves if they are not to be distorted by the slew rate of the LF356 op-amp? (For help, see H&H p. 192.) Draw a voltage vs. time plot showing a sine wave input and a typical slew rate limited output on the same plot. (Note that an amplifier limited by slew rate will change a curved line to a straight line on the oscilloscope.)
4. (2 points) Design an inverting amplifier (Fig. 4.3) with a closed-loop gain somewhere between 10 and 100. Select appropriate values for R and R_F . Choose R_F large enough so that the maximum output current of the op-amp is not exceeded when the output is near the saturation voltage. Predict the bandwidth and the input impedance at the signal input. How would you measure the input impedance in the lab? [The DMM is not going to properly read the input or output impedance when connected to a circuit because of all the other resistors and bias voltages present. Here is a hint: Recall that when the signal generator with a 50 Ω output impedance has a 50 Ω load the signal into the load drops by a factor of two.]

Apparatus

This experiment will use both +15V and -15V to power the LF356 op-amp. Look back at Experiment 2 to remember how to connect the power supply to your prototyping board.

Turn off the power while wiring your op-amp circuits. Figure 4.4 shows pin-out data and a layout for the gain=100 amplifier.

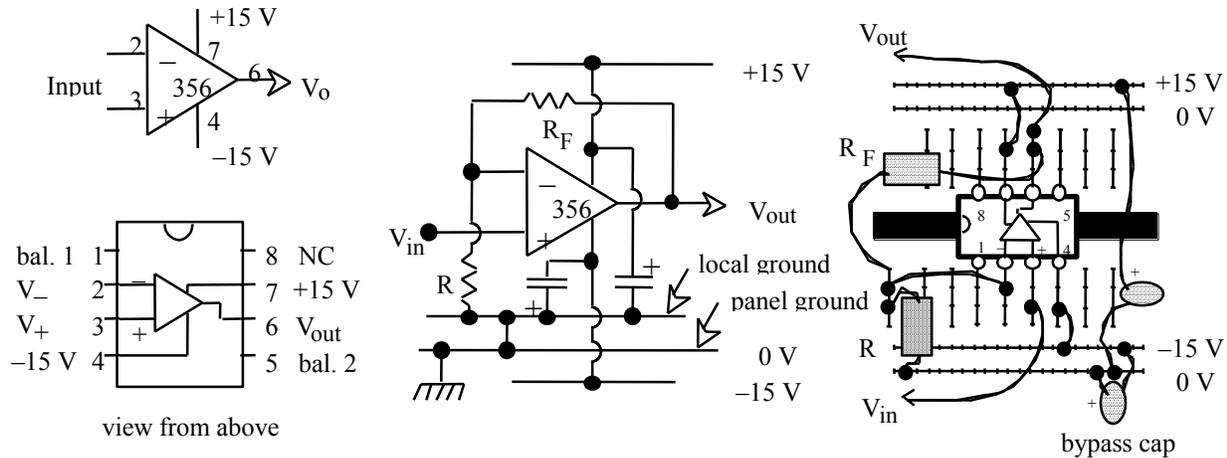


Figure 4.4 Op-amp pin diagram and possible layout for gain 100 amplifier

Everyone makes mistakes in wiring-up circuits. Thus, it's a good idea to check your circuit before applying power. You may well save a transistor or chip from burnout and save yourself a lot of frustration.

The following procedure will help you wire up a circuit accurately:

1. Draw a complete schematic in your lab book, 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. Know the color or number code for resistors and capacitors so you can avoid putting the wrong part into the circuit. When in doubt about the value of a part, measure it with an Ohm meter or impedance bridge.
3. Adhere to a color code for wires. Red for positive power and black for ground is a very widely honored standard. Beyond that, just try to be consistent. For example:

0 V (ground)	Black
+15 V	Red
-15 V	Blue
analog signals	Yellow
digital signals	Purple

The op-amp chip sits across a groove in the circuit board. Before inserting a chip, gently straighten the pins. 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.

You will have less trouble with spontaneous oscillations if the circuit layout is neat and compact, especially the feedback path should be as short as possible to reduced unwanted capacitive coupling and lead inductance.

To help prevent spontaneous oscillations due to unintended coupling via the power supplies, use bypass capacitors to filter the 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 $1\ \mu\text{F} - 10\ \mu\text{F}$. Compact capacitors in this range are usually electrolytic tantalum or aluminum and are polarized, meaning that one terminal (marked +) must always be positive relative to the other. If you put a polarized capacitor in backwards, it will burn out. It is often helpful to put a smaller ($0.01\text{-}0.1\ \mu\text{F}$) non-polar ceramic capacitor between power and ground as well. Bypass capacitors should be placed as close as possible to the op-amp supply pins.

Experiment

GETTING STARTED: TESTING THE OP-AMP

You can save yourself some frustration by testing your op-amp chips to make sure they are not burned out. Connect the op-amp as a voltage follower with the input grounded (see Fig. 4.5). Since $V_{\text{out}} = V_{\text{in}}$ for a follower, you expect $V_{\text{out}} = 0$ for this circuit. A "bad" chip will often have $V_{\text{out}} = \pm V_{\text{sat}}$ because of a burned-out output circuit.

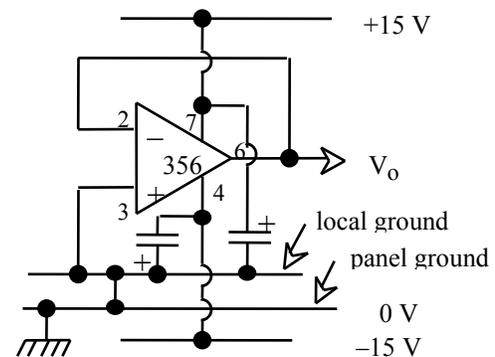


Figure 4.5 Test circuit for op-amp

Measure the DC voltages with a multimeter. Be careful

not to connect pins 6 & 7, since this will burn out the op-amp. You should find Pin 4 = $-15\ \text{V}$, Pin 7 = $+15\ \text{V}$, Pin 2 = $0\ \text{V}$, Pin 3 = $0\ \text{V}$, Pin 6 = $0\ \text{V}$. The small voltage on pin 2 is equal to the input offset voltage V_{OS} , typically less than $3\ \text{mV}$. If $V_{\text{out}} = \pm 15\ \text{V}$, then the chip is bad. Throw it in the trash to save another person from having to deal with it. (In case you are wondering, the LF356 costs $\$0.50$ when purchased in quantities of 100. Check out a distributor like www.digikey.com if you are curious about the cost of any part we use.)

1. VOLTAGE FOLLOWER

The following section makes use of the basic test configuration as shown in Figure 4.6:

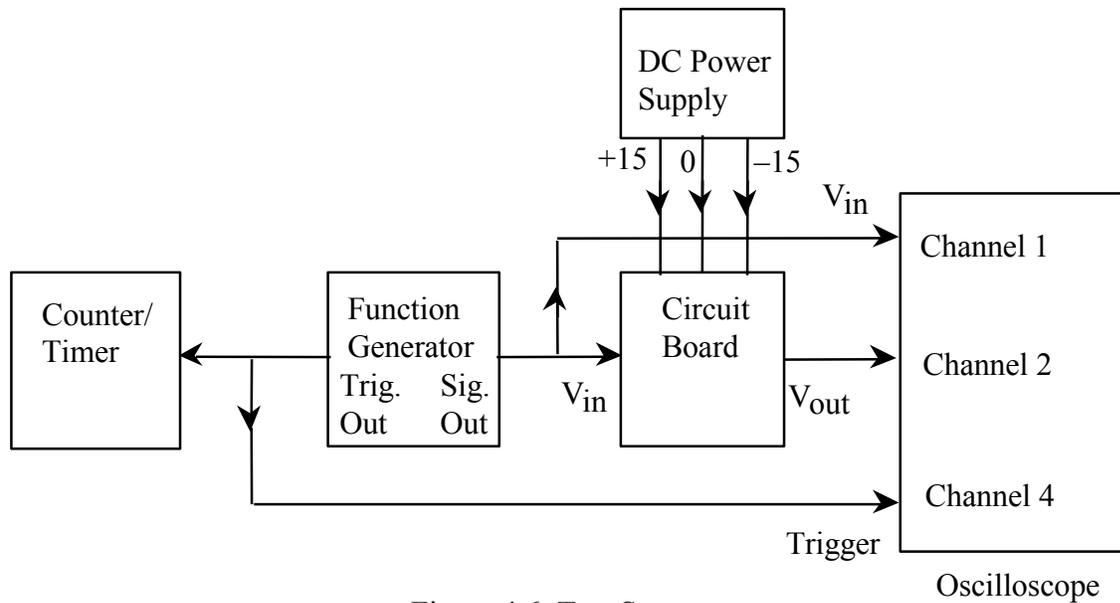


Figure 4.6 Test Set-up

This is similar to the one we used for Experiment #3. The Counter-timer is optional in this set-up, since the function generator has a direct frequency readout that can also be verified using the measurement functions on the TDS3014B oscilloscope.

The voltage follower has no voltage gain ($G_0=1$), but it lets you convert a signal with high impedance (i.e. very little current) to a much lower impedance output for driving loads. The voltage follower is also often called a unity gain buffer.

The voltage follower circuit is nearly the same as the test circuit, except that now a signal enters the positive input (Figure 4.7).

Set your function generator to produce a 1 kHz sine wave (~ 1 volt p-p initially). Then:

1A. Measure the low frequency gain G_0 by measuring V_{in} and V_{out} with the voltage cursors. Make both waveforms at least 4 divisions high for accuracy. Compare your results with the prediction.

1B. Now vary the frequency and look for

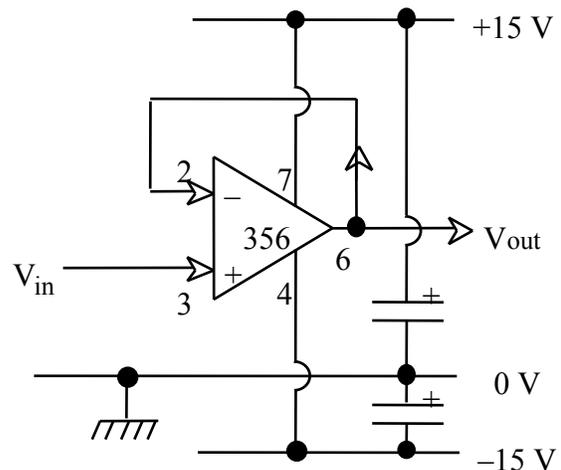


Figure 4.7 Voltage Follower

deviation from the performance of an ideal follower. The measurement at high frequency will depend on many details of your setup and you are unlikely to find a simple RC filter type falloff. Using the 10X probe, measure the gain at every decade in frequency from 10 MHz down to 10 Hz. Do you find any deviation from unity gain? Be sure that the output amplitude is below the level affected by the slew rate! Plot the low and high frequency data on a Bode diagram. Do you find a simple fall-off as suggested by the theory for the ideal follower ($f_T=f_B$)? If so, find the 3dB frequency. How does your measured 3dB frequency compare to what is expected from the op-amp datasheet? Even if the fall-off doesn't have a simple behavior, at what frequency do you observe more than a 10% deviation from the ideal gain?

If you observed "ideal" behavior, you're lucky! At frequencies above a few MHz, the simple model of the frequency response of the op-amp (see theory section) is not accurate. Furthermore, once you are in this frequency range, many physical details of your circuit and breadboard can have large effects in the circuit. Building reliable circuits at these frequencies typically requires careful attention to grounding and minimization of capacitive and inductive coupling between circuit elements and to ground. At lower frequencies, our op-amp model will work much better.

2. GAIN = 100 NON-INVERTING AMPLIFIER

Change the negative feedback loop to the one in Figure 4.8, with $R_F = 10\text{ k}\Omega$ and $R = 100\ \Omega$. Use 1%, 1/2 Watt, precision resistors for the feedback loop. Measure R and R_F with the multimeter before inserting them into the circuit board. Recalculate G_0 and f_B from these measured values and the op-amp's value of f_T measured in the last part.

2A. Measure the low frequency gain G_0 for 1 kHz sine waves. Vary the input amplitude until you observe saturation in the output. What are the output saturation levels, $+V_{sat}$ and $-V_{sat}$? Now, reduce the input amplitude so that the output voltage is less than half the saturated value.

2B. Determine the 3dB bandwidth f_B . Then vary the frequency to obtain data at decade intervals for checking your Bode diagram.

2C. Using the gain-bandwidth relation $G_0 f_B = f_T$, determine the f_T for your op-amp. How does this compare with the value from the op-amp datasheet?

2D. The input impedance of the amplifier should be exceptionally high. Can you see any change in output when you connect a $1\text{ M}\Omega$ resistor in series

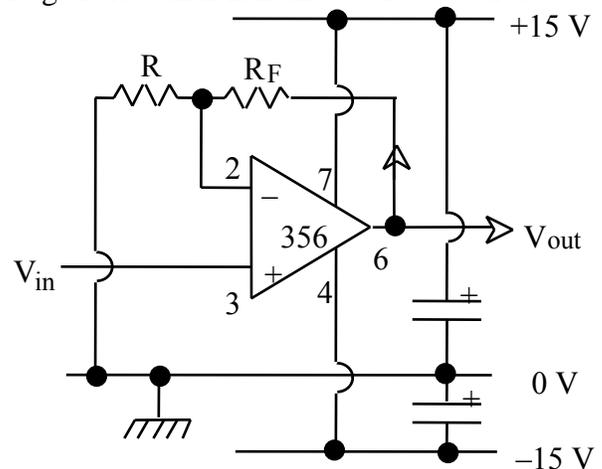


Figure 4.8 Gain of 100 Amplifier

with the input? Is this consistent with your homework result?

2E. The output impedance should be very low, provided that the output current is less than the maximum available (25 mA). What happens when you connect a load of $220\ \Omega$ from output to ground? Explore as a function of output amplitude. Be sure to pull out this $220\ \Omega$ before proceeding to the next section.

3. INVERTING AMPLIFIER

Build the inverting amplifier that you designed in Problem 5.

3A. Measure the gain versus frequency and record the result on a Bode plot, comparing with your prediction.

3B. Find the gain-bandwidth product and see how it compares to the value you observed for the gain 100 non-inverting amplifier.

3C. Measure the input impedance and see if it agrees with your expectations.