Operational Amplifiers and Negative Feedback

Purpose

This experiment shows how an operational amplifier with negative feedback can provide predictable gain and frequency response. You will build and test a non-inverting voltage amplifier using an LF356 op-amp. The amplifier will be used to make a thermoelectric thermometer to measure the temperature of your body.

Introduction

The purpose of an amplifier is to increase the voltage level of a signal while preserving the time dependence of the original waveform. When transducers are used as in Figure 4.1 to convert basic physical quantities into electric signals, an amplifier is usually needed to raise the small transducer voltage to a measurable level.

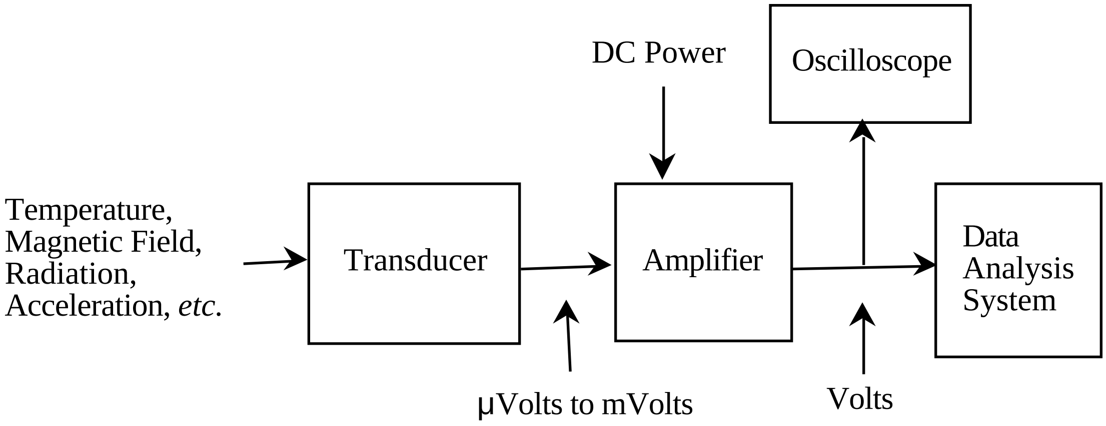

Figure 4.1 Typical Laboratory Measurement

A small voltage or current change at the input of the amplifier controls the flow of a much larger current from a dc power source into whatever circuit or instrument is connected to the amplifier output. The measuring and recording equipment typically requires input signals of 1 to 10 V. In the process of amplification the amplifier should accurately preserve the amplitude and time information in the signal. To meet such needs a typical laboratory amplifier might have the following characteristics:

1. Predictable and stable gain, typically known to about one part in a thousand. The magnitude of the gain is equal to the ratio of the output signal amplitude to the input signal amplitude.

2. Linear amplitude response. The output is proportional to input, with deviations from proportionality less than a part in a thousand.

3. According to the application, the frequency dependence of the gain may be:
   A constant gain independent of frequency up to the highest frequency component in the input signal (wideband amplifier). This could be needed to preserve time information and waveform shape. 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.

Such an amplifier may be bought off the shelf for \$1 k to \$10 k. It may have to be modified to meet the specific needs of the experiment. Since several amplifiers may be used in one experiment, it is often cheaper and more convenient to build your own amplifiers specifically matched to the task. The cost is usually a dollar or two for an op-amp chip plus a day of your time.

A simple transistor amplifier (of the kind you will build in Experiment #7) suffers from a variety of disorders: non-linearity, waveform distortion, variation of the gain with time and temperature, and sensitivity of all of the properties to the characteristics of the transistor, which will vary from device to device.

These disorders can be remedied if you use an amplifier chip with much higher gain than is needed for the experiment, and then use <u>negative feedback</u> to trade in the excess gain for other improvements, such as linearity, gain stability, and bandwidth.

With negative feedback a fraction of the output signal is returned to the input by way of the feedback loop to cancel part of the input signal. As the amount of negative feedback is increased and more of the gain is traded in, the characteristics of the circuit become less dependent on the properties of the individual amplifier. In the limit of extreme excess gain, the properties of the amplifier are determined entirely by the components of the feedback loop itself. The resistors and capacitors used to make a feedback loop have a degree of stability and linearity orders of magnitude better than the amplifier alone.

Inexpensive integrated circuit operational amplifiers (IC op-amps), with basic amplification of 10^4 to 10^6 provide the source of raw gain in most feedback amplifiers. To begin with, we will consider the operational amplifier to be a "black box" with two inputs and one output. The output voltage is equal to the amplification times the voltage difference between the two inputs. the op-amp integrated circuit contains many transistors. We will learn how transistors are used to make amplifiers in Experiment #7.

In electronics the words "amplification" and "gain" mean the same thing and are used interchangeably. However, in this experiment the symbol A is used for the amplification/gain of the op-amp alone without any feedback ($A \equiv$ open loop gain) while G denotes the net gain of the feedback amplifier ($G \equiv$ closed loop gain).

Readings

1. D&H Chapter 9
2. Horowitz and Hill Sections 4.25 and 4.26, containing the basic formulas for op-amp gain, input impedance, and output impedance with finite amplification A.
3. (Optional) Other portions of Horowitz and Hill, Chapter 4. The basic rules of op-amp behavior and the most important op-amp circuits are introduced in Sections 4.01–4.06. Sections 4.08, 4.11, and 4.12 cover precautions for op-amp circuits, and some of the details of op-amp behavior that limit circuit performance. Table 4.1 is a fantastic summary of the wide variety of op-amp devices available to designers. In Chapter 4 H&H use the symbol V_{CC} for the positive supply voltage, and V_{EE} for the negative supply. Do not worry about references to the transistor guts of op-amps (things like JFETs, BJTs, long-tailed pairs, *etc.*)

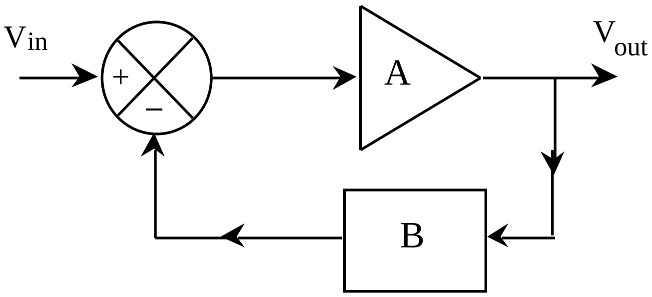

Figure 4.2 Negative Feedback

Theory

GAIN EQUATION

The basic formula for the gain of feedback amplifiers is derived in Horowitz and Hill, Section 4.25. We use the symbol A for the op-amp gain or open loop gain and we call the product A·B the loop gain. The gain of the feedback amplifier, or closed loop gain is given by

$$\boxed{G = \frac{V_{out}}{V_{in}} = \frac{A}{1+AB}.} \tag{1}$$

For the non-inverting amplifier of Figure 4.3 we have $B = R/(R+R_f)$. The above equation for the closed loop gain then gives

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

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 discussed in Sections 4.03 and 4.05 of H&H.

INPUT AND OUTPUT IMPEDANCE

Formulas for the input and output impedance for an amplifier with voltage feedback are derived in H&H Section 4.26. The results are

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

where R_i and R_o are the input and output impedances of the op-amp alone, while the primed symbols refer to the amplifier with feedback.

FREQUENCY DEPENDENCE

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:

$$A = \frac{A_0}{1 + i\dfrac{f}{f_0}}. \tag{2}$$

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

$$\boxed{f_T = A_0 f_0\ .}$$

The frequency dependence of the closed loop gain G for the feedback amplifier can be found by substituting Equation (2) into Equation (1). You will find the result

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

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

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

Since the frequency response is the same as for an RC low-pass filter, the relation between the rise time t_R and the 3 dB bandwidth is also the same

$$t_R = \frac{1}{2\pi f_B}.$$

GAIN-BANDWIDTH PRODUCT

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

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

$$\boxed{G_0 f_B = f_T.}$$

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.*.

Problems

1. Data for the LF356 op-amp (same as LF156) are given in the National Semiconductor Linear Data Book, excerpts from which may be found in Appendix I at the end of this chapter. Verify that the following values are reasonable approximations to use in solving the problems. Identify the 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/µsec
Maximum output current $(I_O)_{max}$ = 25 mA
Input resistance $R_i = 10^{12}\ \Omega$ (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 = 30pA

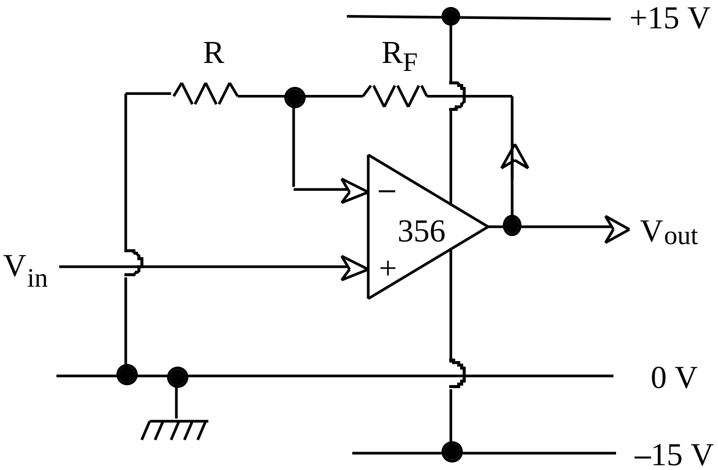

Figure 4.3 Non-Inverting Amplifier

2. Calculate the values of low frequency gain G_0 and the bandwidth f_B for the non-inverting amplifier in Figure 4.3. Consider the cases with R_F = 100 kΩ for all, and R = 100 Ω, 1 kΩ and 10 kΩ. Also consider the voltage follower, with R_F=0 and R=∞. Draw Bode plots for the open loop gain and the four closed loop gains on the same graph.

What is the exponential rise-time for square waves in each case? Make a table of your results.

3. Estimate the input and output impedances of the amplifier with R_F = 10 kΩ and R = 100 Ω for 1 kHz sine waves.

4. At dc, what is the maximum output voltage with no load? This should be independent of R_F and R values. It is related to one of the parameters discussed in problem 1. What would be the maximum output voltage when a 220 Ω load is connected from the output to ground? This is again related to one of the parameters of table 1 and is independent of R_F and R.

5. 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? (See H&H p. 192.) Draw a voltage vs. time plot showing a sine wave input and a typical slew rate limited output superimposed on the same plot.

Outline of the Experiment

1. Connect power supplies to the circuit board and test an op-amp chip.

2. Make a voltage follower by applying 100% negative feedback to the op-amp. Verify that the closed-loop voltage gain is unity for 1 kHz sine waves. Vary the frequency and determine the upper cut-off point using both amplitude and phase criteria. Hence find the unity gain frequency f_T of the op-amp.

3. Make an amplifier of closed-loop gain 100 by changing the feedback loop in your circuit. Measure the low frequency voltage gain G_0 for sine waves at 1 kHz. Compare this measurement with the value of gain G_0 predicted from the components. Vary the frequency of sine waves to obtain sufficient data to verify the Bode diagram. Determine the bandwidth f_B. Do your results satisfy the gain-bandwidth product rule $G_0 f_B = f_T$?

5. Determine the gain-bandwidth product another way by measuring the asymptotic gain G_0' and output rise-time t_R with input square waves. Compare with previous results.

6. Construct a thermoelectric thermometer. Use the amplifier to raise the voltage from a homemade copper-constantan thermocouple to a measurable level. Set the sensitivity to 10 mV/˚C by adjusting the gain and dc offset, with the ice point and boiling point as references. Measure the temperature of your body.

New Apparatus and Methods

DC POWER SUPPLIES

For the operational amplifier you will need dc power at both +15 V and -15 V. The dc voltage needs to be steady in time to ± 0.1 % and independent of current drawn (± 0.1 % voltage change for 1 A current). The dc level must also be free from 60 or 120 Hz "ripple" and transients from machinery in the building. The regulated dc power supplies convert 115 V, 60 Hz, ac power from the wall outlets into the dc required for your circuits.

Note that the power supply produces only a voltage difference between the "+" output and the "-" output. The actual terminal voltage is determined only when one of the outputs is connected to a definite external potential. The minus terminal can grounded to give a positive dc voltage at the "+" output, or the positive terminal can be grounded to give a negative dc voltage at the "–" output. It is important to connect the power supply correctly.

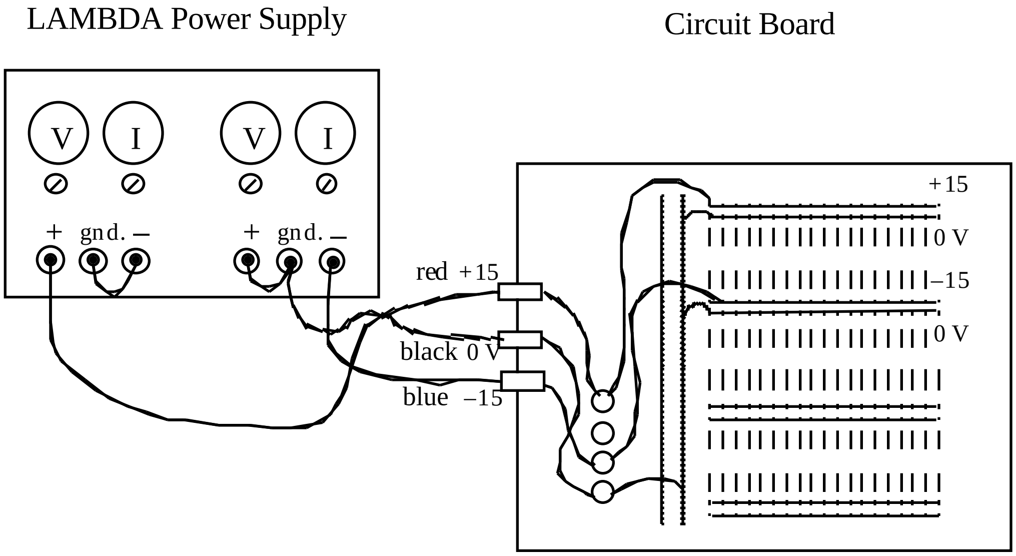

Figure 4.4 dc Power Connection for the LAMBDA Power Supplies

DC POWER CONNECTIONS

First, connect the power supplies to your circuit board:

- For the LAMBDA dual independent supply, connect negative to ground on the left-hand unit, and positive to ground on the right-hand unit.
- For the KEPCO dual tracking supply, connect common to ground.

Next, connect the circuit board power lines:

- Connect wires from the +15 V, 0 V, and -15 V color coded binding posts to the long lines on the plug board as shown in Figure 4.4.

Finally, connect the power supply to the circuit board front panel.

- Use red wire for +15 V, black for 0 V (ground) and blue for -15 V.

Turn on the power supply. Set voltages to +15 V and -15 V using the panel meters. Set the current limit to about 100 mA on LAMBDA supplies by temporarily short circuiting the output and reading the current meter.

Test that the dc level on each connected long line of holes on the circuit board is correct. Also check that there is 0 volts between the ground lines and the front panel using the multimeter. The front panel is the reference ground since the coax cable shields connect it to the ground of every

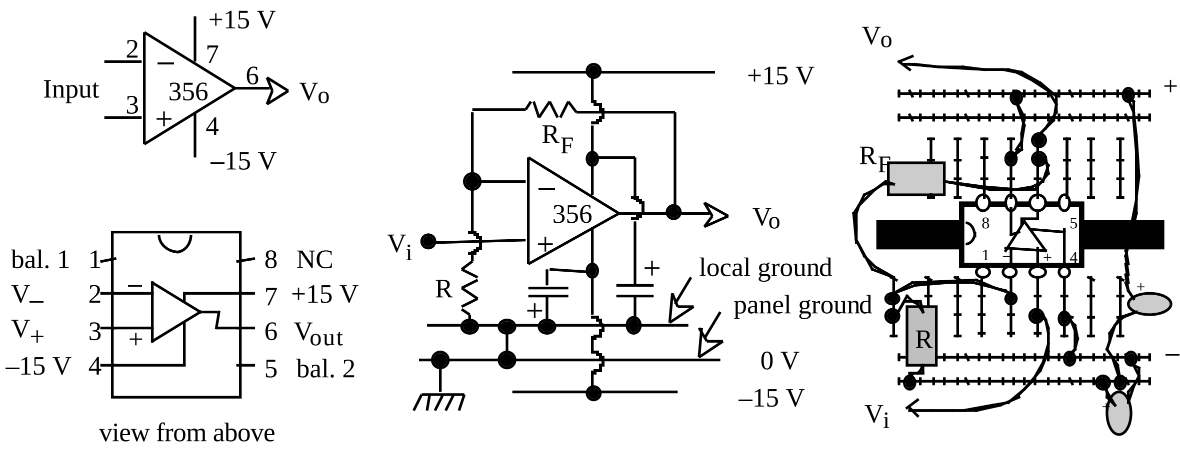

Figure 4.5 Op-amp pin diagram and layout for gain 100 amplifier

other instrument. Turn off the power while wiring your op-amp circuits.

WIRING THE OP-AMP INTEGRATED CIRCUIT

Everyone makes mistakes in wiring up circuits. An essential step in the work is to check and correct errors before switching on the power. You may well save a transistor or chip from burn-out and save yourself a lot of frustration. The checking is easier if you can visualize the schematic circuit diagram in your head while you compare it with the actual circuit on the board.

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

1. Draw a wiring diagram in your lab book next to the schematic diagram (as in Figure 4.5). For a complex circuit, it may be too tedious to show each wire, but it is very helpful to show the location of each component. Also include pin diagrams for each chip (at left in Figure 4.5).

2. Know the color or number code for resistors and capacitors. Do not attach adhesive labels to resistors or capacitors.

3. Adhere to a color code for wires. Red for positive power and black for ground is a very widely honored standard. We suggest the following code:

0 V (ground)	Black
+15 V	Red
-15 V	Blue
Input signals	Yellow
Output signals	Green
Other connections	Some other color

The op-amp chip sits across a groove in the circuit board. Before insertion, 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.

To help prevent spontaneous parasitic oscillations due to capacitive coupling and inductance of connecting wires, use bypass capacitors to filter the supply lines close to your circuit. The bypass capacitors can be of any value in the range 5 μF – 50 μF. Most compact capacitors in this range are <u>polarized</u>, meaning that one terminal (marked +) must always be positive relative to the other. If you put a polarized capacitor in backwards, it may burn out. Also arrange that the <u>output wire</u> to the front panel is as distant from the input wire as possible.

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. 4.6). Since $V_{out} = V_{in}$ for a follower, you expect $V_{out} = 0$ for this circuit. A "bad" chip will often have $V_{out} = \pm V_{sat}$ because of a burned out output circuit.

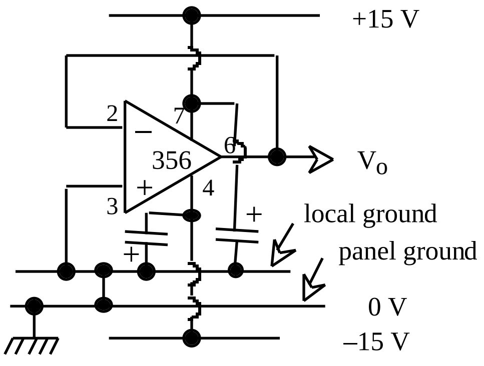

Figure 4.6 Test circuit for op-amp

Measure the dc voltages with a multimeter. Be careful not to connect pins 6 & 7, since this will burn out the op-amp.

First, check that power reaches the op-amp: Pin 4 = –15 V.

Pin 7 = +15 V.

Then check that the chip is OK: Pin 2 = 0 V.

Pin 3 = 0 V.

Pin 6 = 0 V.

The voltage on pin 2 is precisely equal to the input offset voltage V_{OS}. Typically V_{OS} is less than 3 mV. If $V_{out} \approx \pm 12$ or ± 15 V, then the chip is bad. Throw it in the trash.

TEST SET-UP FOR MEASURING WAVEFORMS

The set-up shown in Figure 4.7 is similar to the one we used for Experiment #3.

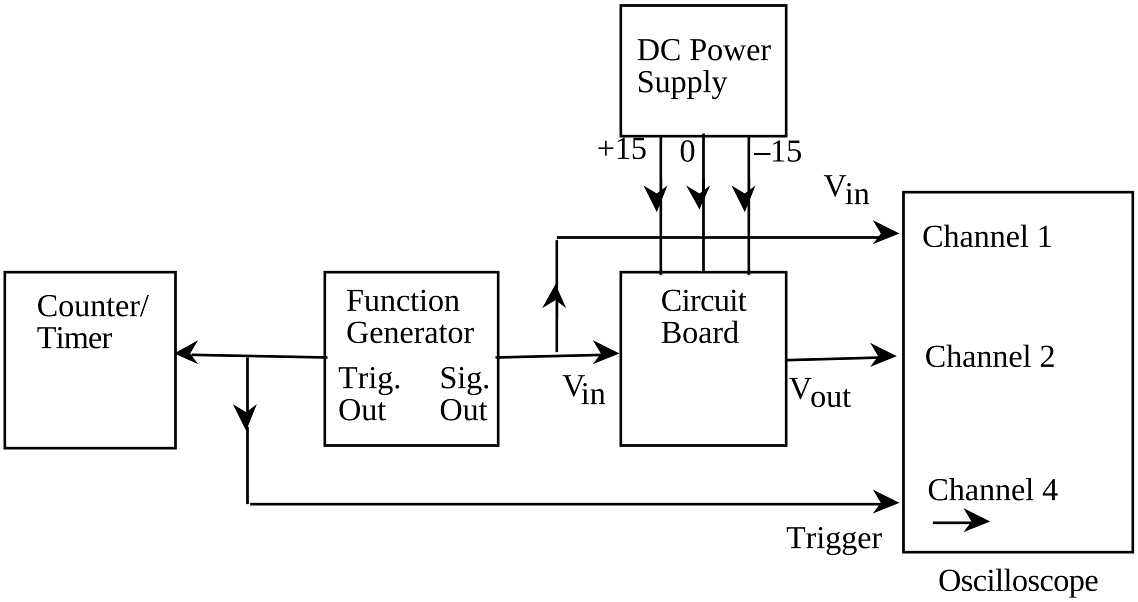

Figure 4.7 Test Set-up

Procedure

THE VOLTAGE FOLLOWER

The voltage follower has no voltage gain ($G_0=1$), but it lets you convert a high impedance signal to a much lower impedance for driving loads. The voltage follower is also called a unity gain buffer. There are specialized follower chips with exceptional properties, like high speed and high output current, but it is usually adequate to use an op-amp.

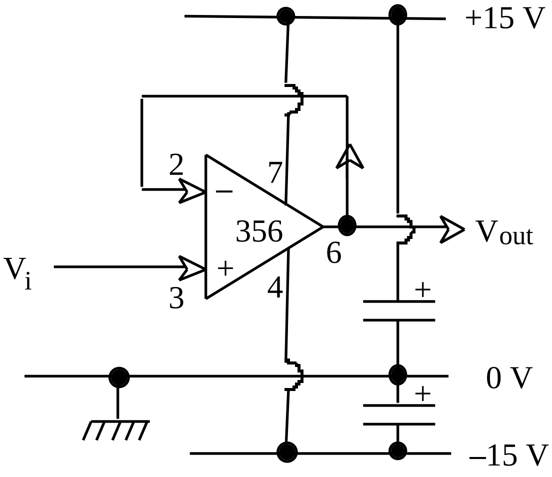

Figure 4.8 Voltage Follower

The circuit is the same as the test circuit except that now the signal enters the positive input (Figure 4.8).

For <u>sine waves</u> at 1 kHz:

- Change the input amplitude while you observe V_{out} on the scope. What are the output saturation levels $+V_{sat}$ and $-V_{sat}$?
- 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.
- Now vary the frequency and measure the bandwidth f_B by finding the half-power point. This measurement can be tricky because of the high frequency. Try using the scope probe. The result gives you the unity gain frequency f_T for your particular op-amp. ($f_T = f_B$ for a voltage follower). It may differ by up to a factor of 2 from the "typical value" in the data sheet.
- Be sure that the output amplitude is below the level affected by the slew rate. Measure the gain at decade steps in frequency (10^{-6} f_B, 10^{-5} f_B, … f_B, 10 f_B). Test the predicted frequency response by marking these data on your Bode diagram.
- Warning: You may find for the voltage follower that your measured frequency response differs from your predictions at frequencies above a few MHz. This is because our simple model for the frequency response of the op-amp (see theory section) is not accurate near f_T. Our model will work very well at lower frequencies.

AMPLIFIER WITH GAIN OF 100

Change the negative feedback loop to the one in Figure 4.9, with R_F = 10 kΩ and R = 100 Ω. 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. Redraw the Bode diagram for closed and open loop gains.

Perform any dc diagnostic tests you think are necessary.

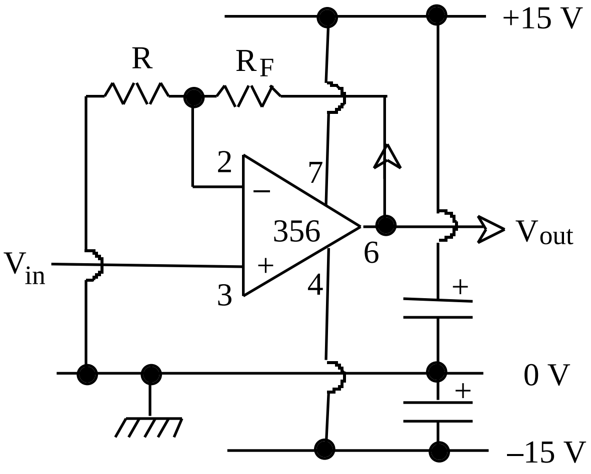

Figure 4.9 Gain of 100 Amplifier

Response to <u>sine waves</u>:

- Measure the low frequency gain G_0 for 1 kHz sine waves. First reduce the input amplitude to a low enough level that the output voltage is less than half the saturated value.
- Determine the 3dB bandwidth f_B. Then vary the frequency to obtain data at decade intervals for checking your Bode diagram.
- Do the observed values satisfy the gain-bandwidth relation $G_0 f_B = f_T$?

The input impedance of the amplifier should be exceptionally high. Can you see any change in output when you connect a 1 MΩ resistor in series with the input? Is this consistent with your homework result?

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 Ω from output to ground? Explore as a function of output amplitude. Be sure to pull out this 220 Ω before proceeding to the next section.

Response to square waves:

- Change the input to square waves. Reduce the frequency until the interval between steps in the square wave allows the output to reach its asymptotic value.
- Set the input amplitude low enough that the output is not limited by saturation or slew rate.
- Set the scope sweep speed so that you can see both the rising front and the asymptotic level.
- Adjust the scope sensitivity to give a large enough sized waveform for accurate measurement.

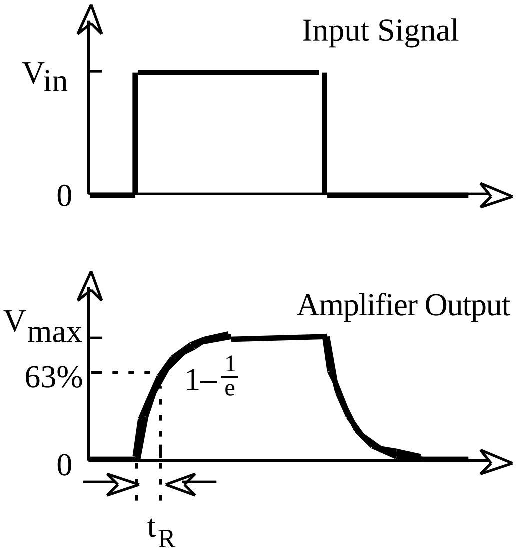

Figure 4.10 Square Wave Response

- Determine the asymptotic gain ($G_0 = V_{max}/V_{in}$) in the flat region of the waveform.
- Measure the exponential time constant t_R for the rising part of the wave output using the time and voltage cursors for accuracy. Calculate the bandwidth from $f_B = (2\pi t_R)^{-1}$. This relation is the same as that for low pass filters.
- Compare the values G_0 and f_B obtained from square waves with G_0 and f_B from sine wave measurements. Is it true that $G_0 f_B = f_T$?

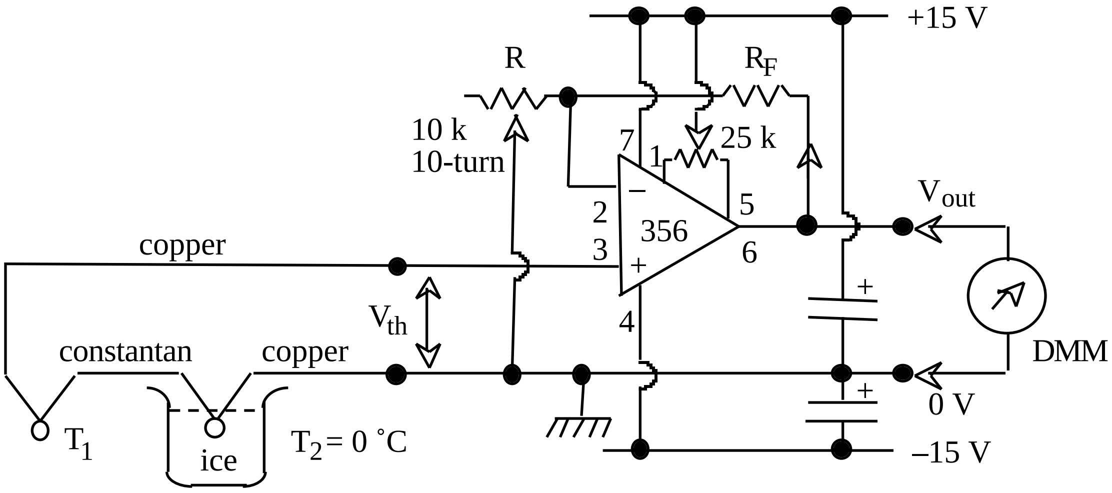

Figure 4.11 Thermocouple Thermometer

THERMOCOUPLE THERMOMETER (OPTIONAL)

A thermocouple consists of two dissimilar metals joined as in Fig. 4.11. A thermoelectric voltage difference V_{th} appears across the terminals when the two junctions are at different temperatures T_1 and T_2. For a copper-constantan thermocouple we have:

$$V_{th} = (42.77\ \mu\text{V}/^\circ\text{C}) \cdot (T_1 - T_2).$$

This is strictly true only for $T_2 = 0$ ˚C and $T_1 = 100$ ˚C because of non-linearity, but it will do for design purposes. If the reference junction at T_2 is placed in melting ice ($T_2 = 0$ ˚C), then the voltage V_{th} gives an absolute measure of the temperature T_1. The thermoelectric voltage is too small to observe directly with the multimeter. However, your amplifier can be used to bring the signal up to a measurable level. Let us design the system so that a temperature of $T_1 = 100$ ˚C gives an output reading of 1.0 Volts. It is important to remember that the boiling point is not 100˚C in mile-high Boulder.

At 100 ˚C, the thermoelectric voltage is 4.277 mV, so the gain must be 233. Let us use the 10 kΩ pot for controlling the gain and have it at about midrange (5 k) to begin with. So we need $R_F \approx R \cdot (G_0 - 1) = 5000 \cdot 233 = 1.2$ MΩ. Since R is adjustable we could use 1 MΩ for R_F.

Modify your amplifier to the circuit in Figure 4.11. To set the zero, connect a 25 kΩ trimpot between pins 1 and 5 of the op-amp, with the wiper at + 15 V. Place both junctions in the ice/water mix and adjust the 25 kΩ trim-pot until the multimeter reads zero.

Now set the scale. Leave the reference junction in the ice and put the other junction in boiling water. Find the boiling point of water in Boulder. There are mercury thermometers in the lab. Decide what the multimeter should read to give you the desired sensitivity of 10 mV/˚C. Change the gain by adjusting R until the multimeter reads the correct value.

Measure your body temperature with your thermometer. How accurate is the result? Is there an important systematic error due to nonlinearity of the thermoelectric voltage (see the thermoelectric data in Appendix II)? What about nonlinearities of the amplifier? Correct any important systematic errors. Is your result consistent with your normal body temperature?

Appendix I

LF356 data sheets. Reprinted from National Semiconductor product information website at http://www.national.com/catalog/

Appendix II

The following table for copper-constantan (Type T) thermocouples is reprinted from Powell *et al.*, NBS Monograph 125, (March 1974).