Laboratory 7: Operational Amplifiers

1.0 Introduction

An ***operational amplifier*** ("op amp") is a DC-coupled, differential-input, high-gain amplifier. It is usually an integrated circuit fabricated on a small single-crystal piece of silicon. The term "operational" dates back to the early days of analog computers when these devices were employed in circuits that performed mathematical operations such as addition, subtraction, multiplication, division, integration, and the solution of differential equations. Today, op amps are used in a wide variety of applications. Modern operational amplifiers are very versatile building block for thousands of circuits in applications as diverse as audio, control systems, video, communications, process automation, instrumentation, aerospace, and medicine.

The linear circuit forming the heart of the operational amplifier is a fairly complicated device consisting of 30 or more active and passive devices. However, the beauty of operational amplifiers is that the input-output characteristics are very simple. The circuit designer using the op amp need not be overly concerned with its inner workings and can treat it as a "black box" with certain specified behavior, as long as one remembers its real limitations.

2.0 Ideal Op Amps

In this section, we will consider the op amp to be an "ideal" operational amplifier. It is the simplest model to analyze and it describes the operation that the circuit designer would consider "perfect" were it not for real-world limitations. The symbol for an operational amplifier is shown in Figure 2.1 on the following page. V_+ and V_- are the input voltages and V_o is the output voltage. These are related by the simple expression

$$V_o = a(V_+ - V_-) \qquad (2.1)$$

where a is the open-loop voltage gain. $+V_{CC}$ and $-V_{CC}$ are the positive and negative DC power supply voltages, respectively. There is no internal "ground" or "common" connection. Instead, voltages are measured relative to the common connection of the two power supplies.

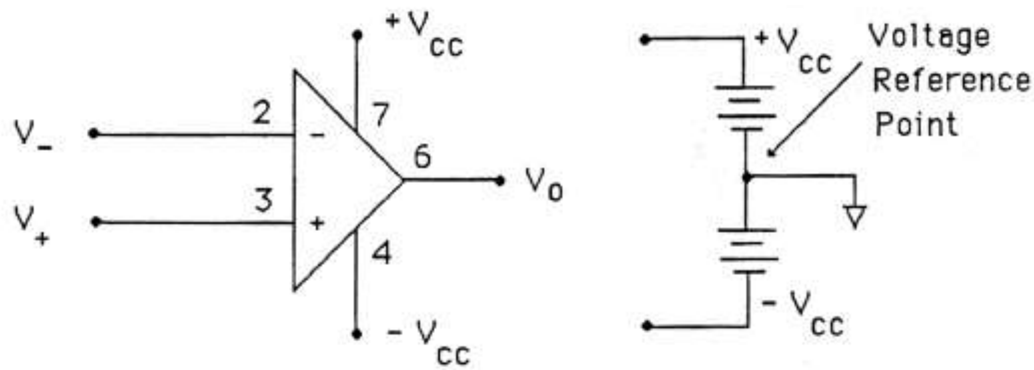

Figure 2.1 The symbol for an Operational Amplifier.

The numbers on the diagram in Figure 1.1 refer to the pin numbers on the ‘741 integrated circuit (IC) Dual In-Line Package (DIP) shown in Figure 2.2. The pin numbers and the supply voltages are usually omitted in circuit diagrams as long as there is no ambiguity. Pin 8 is not used. Pins 1 and 5 do serve a useful purpose for input offset voltage nulling, but they will not be used in this lab.

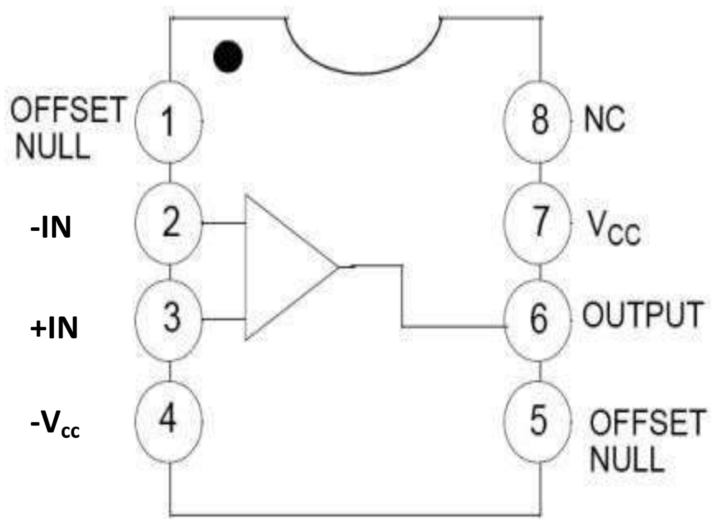

Figure 2.2 ‘741 Operational Amplifier integrated-circuit DIP package pin-outs

The ideal operational amplifier is characterized by the following three properties:

(1) The open-loop voltage gain a is very large.

   a. For frequencies below 8 Hz, our op amp has an a greater than 100,000 and for simple low frequency analyses, one may assume $a = \infty$.

(2) The input impedance R_i is very large and can be assumed to be infinite. This means no current flows into the op amp at the V_+ and V_- input ports.

(3) The output resistance R_o is negligibly small and can be assumed to be zero. This means that the output will drive any load without a decrease in output voltage.

Of course, there are limitations to the above characteristics, especially with regard to (1) and (3). The output voltage V_o is limited by the voltage available from the power supplies and the output current i_o is limited internally to about ±25mA so the device will not overheat and be destroyed. Nevertheless, for the voltages and currents used in this lab, the above 3 assumptions are very good approximations.

When designing circuits with op amps, one ***never*** uses the op amp by itself as a high-gain amplifier. The gain is usually much too large and the transfer characteristic too non-linear. Instead, one designs ***practical*** circuits using ***negative feedback*** connected from the output to the inverting input. This concept will be emphasized throughout this lab.

Figure 2.3 on the next page shows the input-output characteristic (or transfer characteristic) of a typical op amp. When the differential input voltage ($V_+ - V_-$) is in the range where the slope equals a, the output V_o will be equal to $a(V_+ - V_-)$. Otherwise, the output will saturate at $\pm V_{sat}$. The "trick" to designing linear op-amp circuits is to use negative feedback to force ($V_+ - V_-$) to be sufficiently small so that the amplifier operates within its linear region.

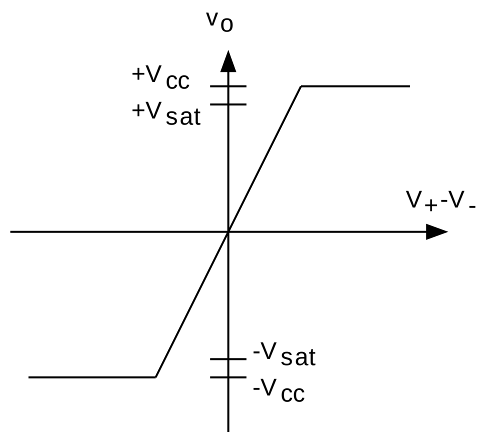

Figure 2.3 Ideal op amp input-output characteristic

There is a simple algorithm for the analysis of an ideal op amp circuit. This algorithm is valid when there is a path from V_o to V_- (i.e., negative feedback) to force the op amp to operate within its linear region at low frequencies.

(1) Assume that the currents into the op amp inputs are zero.

(2) Assume that the output voltage V_o always adjusts itself to force the differential input voltage (V_+ - V_-) to be zero. This is a consequence of assuming infinitely large voltage gain a.

(3) If for whatever reason (2) cannot be satisfied, then the output voltage is $\pm V_{sat}$, depending upon the polarity of the differential input.

Let's apply this algorithm to the op amp circuit shown in Figure 2.4, called the unity-gain buffer, or the Voltage Follower.

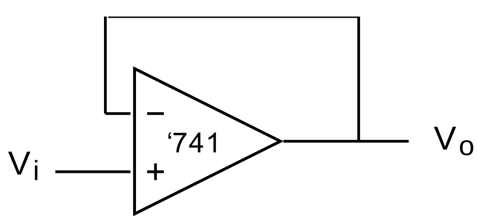

Figure 2.4 Operational amplifier connected as a Unity-Gain Buffer

The input voltage is V_i. The very large voltage gain a forces V_- to be equal to V_+ and thereby $V_o = V_i$. Hence, this circuit is termed the Unity-Gain Buffer, or Voltage Follower.

Now, you may think this circuit serves no useful function since the output voltage merely equals the input voltage. However, the circuit provides a very large ***current*** gain. Hence, the input signal at V_i may have large impedance (i.e., low current such as nanoamps) and be incapable of providing significant power to a load; for example, a microphone or guitar pick-up driving another amplifier or an audio speaker. Here the signal V_i supplies very little power. Instead, it is the op amp which provides current (i.e., milliamps) and therefore power to the load, in such a way that $V_o = V_i$. Of course, this power is ultimately derived from the power supplies via $\pm V_{CC}$.

In this laboratory you will assemble and test an Inverting Negative Feedback Amplifier built around the ‘741 operational amplifier. The following 2 sections contain general information on assembling op amp circuits. Read them carefully before building anything!

3.0 Supplies

- 1 Solderless Breadboard
- 1 ‘741 Operational Amplifier
- 1 ea. 1kΩ, 100kΩ, and 200Ω Resistors
- 2 Male Banana-to-Female BNC Adaptors
- 1 BNC Tee Connector
    - Connect to Oscilloscope Channel 1
- 3 BNC Cables
    - Connect from Function Generator to Tee
    - Connect from Tee to Breadboard Input
    - Connect from Breadboard Output to Oscilloscope Channel 2
- 1 Red, 1 Black, and 2 Gray short banana leads

- One 5” Black jumper wire
- One 3” Red jumper wire
- One 3” Orange jumper wire
- One 3” Blue jumper wire
- Two 3” Green jumper wire

3.1 Preliminary Circuit Assembly

The ‘741 op amp can be inserted into the fixture for building op-amp circuits. Insert it so the pins straddle the center horizontal gap in the solderless wiring fixture with Pin 1 on the DIP to the left. The pins are numbered 1 through 8, counter-clockwise beginning with Pin 1 next to the dot. Do not turn on the power supplies until after you have made the following connections.

All operational amplifiers require external power supplies to operate. The ‘741 requires two equal-voltage power supplies, one positive and one negative. These will not be shown on subsequent diagrams, but it is always assumed. Use the left-hand power supply for +15V, and the right-hand for -15V. Connect the negative (Black) terminal on the left-hand power supply to ground, and connect the positive (Red) terminal on the right-hand power supply to ground. Use a red banana cable to connect the left hand power supply to the breadboard. Use a black banana cable to connect the right power supply to the breadboard.

The ground to the op amp will be provided by the ground terminal of the BNC cables, which is denoted by the GND rectangle on one side of the adaptor. Then, connect +15V (Red Banana Cable) to Pin 7 and the -15V (Black Banana Cable) to Pin 4 of the op amp using jumper wires.

4.0 Inverting Negative Feedback Amplifier

Using the '741 op amp with power supplies connected as described above, assemble the circuit shown in Figures 4.1 and 4.2. This is, nominally, a 40 dB amplifier, i.e., the voltage gain is about $A = -100$, or equivalently $A = -\sqrt{10^{40dB/10}} = -\sqrt{10^4} = -100$.

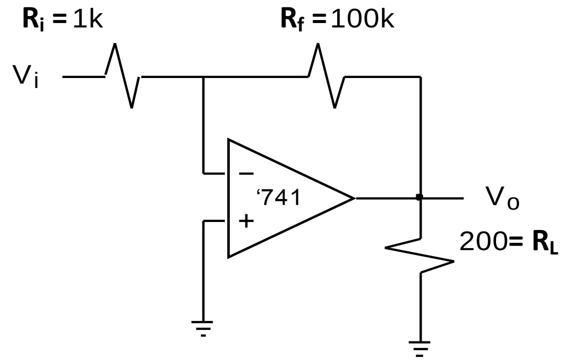

Figure 4.1 Inverting negative feedback amplifier circuit.

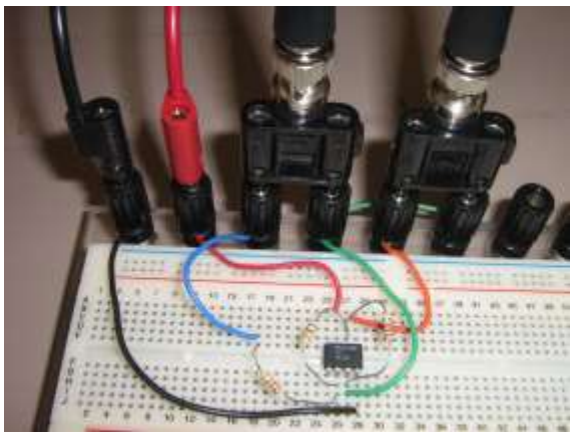

Figure 4.2 Physical representation of inverting negative feedback amplifier circuit

The input-output relationship for this circuit is given <u>ideally</u> by

$$V_o = (-R_f / R_i)V_i \qquad (4.1)$$

Before inserting resistors R_L, R_i, and R_f, measure and record their actual resistance values using the DMM. Note that R_L, R_i, and R_f represent the load resistance, the input resistance, and the feedback resistance, respectively. Create the circuit shown in Figure 4.1 above using the resistors and more jumper wires. Use the function generator to supply a 1 kHz, ±10 mV amplitude sine wave to the V_i input. Use oscilloscope Channel 1 to measure V_i and Channel 2 to measure V_o. Trigger the oscilloscope using Channel 1.

Power-up the power supplies and the instruments. Notice the phase inversion corresponding to the minus sign in Equation 4.1. Observe and record in an Excel spreadsheet the input and output voltages of the circuit using the oscilloscope for each of the frequencies. Carry out measurements from 10 Hz to 1 MHz in 1-2-5 sequence, i.e., 10 Hz, 20 Hz, 50 Hz, 100 Hz, 200 Hz, 500 Hz, etc. Calculate the voltage gain $A = V_o/V_i$ and compare your results to the prediction of Equation 4.1. Over what range of frequencies do your results agree with Equation 4.1 within 5%?

4.1 Inverting Negative Feedback Amplifier with Square Wave Input

Next, apply a ±50 mV amplitude square-wave input to the amplifier with frequencies from 1.0 to 50 kHz in a 1-2-5 sequence. Record the input and output voltages just as you did previously. Is the output waveform a precise replica of the input waveform but amplified by $A=-R_f/R_i$, or does it appear that a slew-rate limitation is occurring, especially at higher frequencies? Calculate the positive and negative-going slew rates SR+ and SR- at 1 kHz.

5.0 Report Checklist

- Include Introduction
- Include Procedure

Section 4.0

- Measured value of load resistance, R_L
- Measured value of input resistance, R_i
- Measured value of feedback resistance, R_f
- Table of data including frequency, V_i, V_o, and A
- Plot of $A=V_o/V_i$ versus frequency
- Plot of the fit of the experimental data to theoretical calculations of A using the Realistic Model of the Op Amp including R_i, R_f, r_{id}, r_o, and R_L.
- Explanation of the disagreement, if any, between the experimental and theoretical data
- Range of frequencies where experimental values of A agree with Equation 4.1 within 5%

Section 4.1

- Table of data including frequency, V_i, V_o, and A
- Plot of $A=V_o/V_i$ versus frequency
- Value of the positive -going slew rate, SR+
- Value of the negative-going slew rate, SR-
- Explanation of the distortion of the output voltage at high frequencies