

ECE 3300
Electrical Circuits: Laboratory
Experiment 7 Pre-Reading
Resistive Op-Amp Circuits

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In this experiment, the student will examine the properties of the operational amplifier (op-amp) and built and test resistive op-amp circuits.

Learning Objectives

By the end of this unit, the student should be able to experimentally:

- Use a DC power supply to bias an op-amp.
- Determine the saturation voltage of an op-amp.
- Determine the saturation current of an op-amp
- Determine if an op-amp is operating as a linear or a as a non-linear device.
- Build and verify the operation of a voltage comparator circuit.
- Build and verify the operation of a voltage follower.
- Build and verify the operation of an inverting amplifier.
- Build and verify the operation of a non-inverting amplifier.
- Build and verify the operation of an adder circuit.

Operational Amplifier Basics

The operational amplifier (op-amp) is an *active* circuit component. It is a device with two (voltage) inputs and a single (voltage) output. The op-amp is designed to work with other circuit components to perform useful signal-processing operations. Applications of op-amp circuits include voltage comparator, voltage amplification, analog signal addition, subtraction, multiplication, differentiation and integration.

In fact, the op-amp itself is a complex circuit of transistors, resistors and capacitors. The whole op-amp circuit fits on a very small integrated circuit and is packaged as an electronic chip with several input/output pins. Figure 1 depicts the commonly used general purpose LM741 op-amp chip.

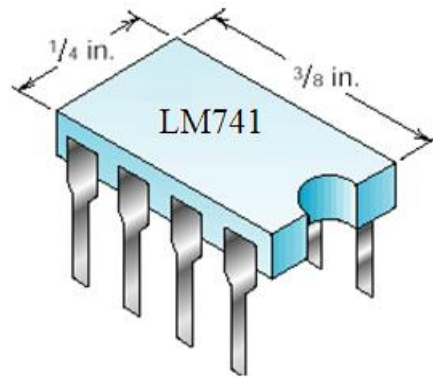


Figure 1. A depiction of the commonly used LM741 op-amp chip.

The pin diagram for the LM741 op-amp chip is shown in Figure 2. For our purpose, we need only consider the five pins 2-4, 6 and 7. Pins 2 and 3 are the op-amp input pins. Pin 6 represents the output pin. Pin 7 (V_+) and pin 4 (V_-) are the *bias pins*. Before the op-amp can be used in a circuit, its bias pins must be connected to a DC power supply. The V_+ pin is connected to a positive *bias voltage* V_s , and the V_- pin is connected to a $-V_s$ bias voltage. The bias voltage (which is typically less than 20V) is needed to “run” or “power up” the op-amp.

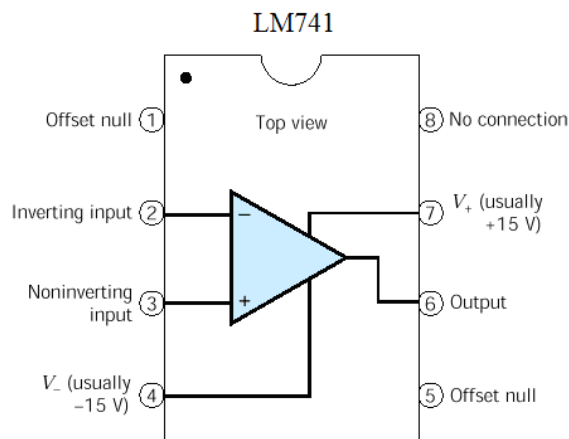


Figure 2. The LM741 op-amp pin diagram.

In circuits textbooks and in circuit diagrams, the op-amp is designated by the symbol shown in Figure 3 (typically, bias is assumed to have been applied and the bias pins are not shown). Here, v_1 is the inverting input, v_2 is the non-

inverting input and v_o is the op-amp output. The op-amp operation is governed by the formula:

$$v_o = -A(v_1 - v_2) \quad (1)$$

where A is the *open-loop voltage gain* of the op-ampr. The voltages v_1 , v_2 and v_o are measured with respect to a reference ground node. Typically, the open-loop voltage gain A is on the order of $10^5 - 10^6$ (the [LM741 op-amp](#) has $A = 200,000$). Therefore, and according to Eq. (1), the op-amp is basically a very high gain (linear) voltage amplifier that amplifies the difference of its input voltages.

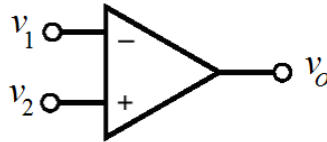


Figure 3. Op-amp symbol.

Op-Amp as a Comparator: Non-Linear Operation

It is important to note that Eq. (1) is only valid as long as the op-amp is operating in its linear range. The following conditions must be met in order for the op-amp to operate as a linear device:

$$\begin{aligned} |v_o| &\leq v_{sat} \\ |i_o| &\leq i_{sat} \\ \left| \frac{dv_o}{dt} \right| &\leq SR \end{aligned} \quad (2)$$

Where i_o is the op-amp output current, v_{sat} is a *saturation voltage*, i_{sat} is a *saturation current*, and SR is the *slew rate limit*. For the LM741 op-amp with $\pm V_s = \pm 15\text{V}$ (bias voltage), we have (approximately) $|v_{sat}| \cong |V_s| - 1 = 14\text{V}$, $i_{sat} \cong 25\text{ mA}$ and $SR \cong 500,000\text{ V/s}$.

The first condition in Eq. (2), when combined with Eq. (1), can be rewritten as $|v_o| = A|v_1 - v_2| \leq v_{sat}$, or

$$|v_1 - v_2| \leq \frac{v_{sat}}{A} \quad (3)$$

Since, in practice, A is about three orders of magnitude greater than v_{sat} , Eq. (3) implies that $|v_1 - v_2|$ must be very small (say less than $14/200,000 = 0.07$ mV) for the op-amp to maintain linear operation.

The second inequality in Eq. (2) is significant when the op-amp is connected to a circuit which draws a non-zero current i_o . Figure 4 shows an op-amp loaded by a resistor R_L . According to Ohms Law, $v_o = -R_L i_o$. Therefore, taking into account the restriction $|i_o| < i_{sat}$ and using Eq. (1), we may write: $|v_o| = A|v_1 - v_2| < R_L i_{sat}$, or

$$|v_1 - v_2| < \frac{R_L i_{sat}}{A} \quad (4)$$

The linearity condition in (4) is already satisfied if the inequality in Eq. (3) is satisfied, as long as $v_{sat}/A < R_L i_{sat}/A$, or $R_L > v_{sat}/i_{sat}$. For example, for the LM741 op-amp, if R_L is greater than $14\text{V}/25\text{mA} = 560\Omega$, then the condition in 94) is satisfied.

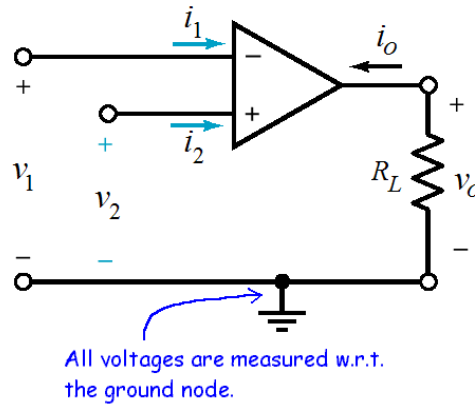


Figure 4. Op-amp comparator circuit showing input voltages, input currents, output voltage and output current.

What happens if $|v_1 - v_2|$ does not satisfy the inequalities in (3) or (4)? The answer is that the op-amp will no longer operate as a linear amplifier; here,

the LM741 op-amp output, v_o , will saturate at a voltage close to $-V_s$ (if $v_1 > v_2$) or a voltage close to $+V_s$ (if $v_1 < v_2$). In fact, this last observation forms the basis for an op-amp *comparator* circuit (shown in Figure 4); the comparator compares two voltages and produces a signal that indicates which voltage is greater. The following equation analytically captures the input/output relationship of an op-amp comparator:

$$v_o = \begin{cases} +v_{sat} & \text{if } v_1 < v_2 \\ -v_{sat} & \text{if } v_1 > v_2 \end{cases} \quad (5)$$

The third condition in Eq. (2) places an upper limit on the rate of change of the op-amp output. In fact, since linear behavior implies that v_o is proportional to v_{in} , then the rate condition also applies to the op-amp input signal; it implies that sharp transition in the input signal can compromise the linearity of the op-amp.

Op-Amp Linear Operation: Ideal Op-Amp model

When all three conditions in Eq. (2) are met, the op-amp will operate as a linear device. The circuit in which the op-amp is placed, and the amplitude of the input voltage, will ultimately determine whether those conditions are satisfied. In many applications, the op-amp is used in a circuit where negative feedback is applied: A direct connection (through a short circuit or through a resistor) is made between the output node of an op-amp and its *inverting terminal*. In a negative feedback system, an increase in the algebraic value of the output (more positive or less negative) yields a decrease in the algebraic value of the input. Because the output voltage is proportional to the input voltage difference, the output voltage is also decreased, and the op-amp is forced to operate in its linear region.

Practical op-amps are designed to have very high input resistance (the resistance at the input terminal pair). For example, the LM741 op-amp has a $2\text{M}\Omega$ input resistance. The high input resistance leads to very small input currents, i_1 and i_2 (typically, these currents are on the order of μA).

In practice, and for the purpose of circuit analysis and design, a high-gain op-amp (operating as a linear device) can be modeled as an *ideal op-amp* with the following voltage and current characteristics:

$$v_1 = v_2 \text{ and } i_1 = i_2 = 0 \quad (6)$$

The following are examples of useful linear op-amp circuits that employ negative feedback.

Voltage Follower (Buffer Circuit)

A voltage follower circuit is shown in Figure 5. It employs negative feedback whereby the inverting input is set equal to the output voltage v_o . This makes the op-amp net input $v_1 - v_2 = v_o - v_{in}$. Substituting this net input in Equation (1) leads to: $v_o = -A(v_o - v_{in})$. Solving for v_o gives us:

$$v_o = \frac{A}{1 + A} v_{in} \quad (7)$$

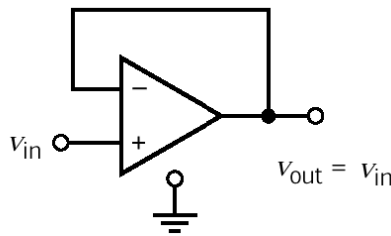


Figure 5. Voltage follower (buffer) circuit.

For an op-amp with very high gain (such as the LM741), Equation (7) reduces to $v_o = v_{in}$. Since the op-amp input resistance is very high, the voltage follower can then be used as a *buffer* that connects two circuits together (refer to Figure 6). Here, the circuit on the left of the buffer sees a high resistance load and therefore its operation is not affected. Without the buffer, the operation of the first circuit would be altered by the current that is drained by the second (loading) circuit; when the buffer is used, the op-amp will supply the current.

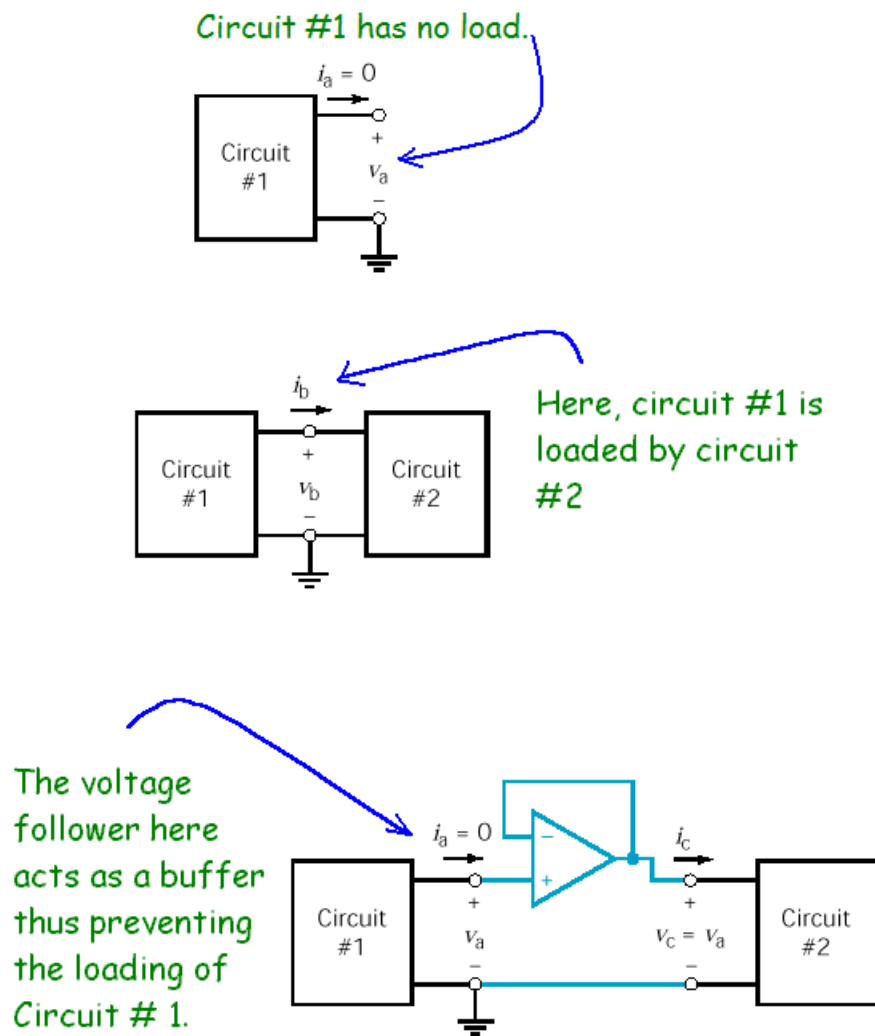


Figure 6. An application of a voltage followers as a buffer.

The linear range of operation of the voltage follower is guaranteed as long as: (1) $-v_{sat} < v_{in} < +v_{sat}$ and (2) the voltage follower load resistance (if present) satisfies $R_L > |v_o/i_{sat}|$ or (since $v_o = v_{in}$) $R_L > |v_{in}/i_{sat}|$ (an $R_L \geq 1k\Omega$ should satisfy this condition). The input/output relation for a practical voltage follower is depicted in Figure 6 (recall that the LM741 has $|v_{sat}| \cong |V_s| - 1$).

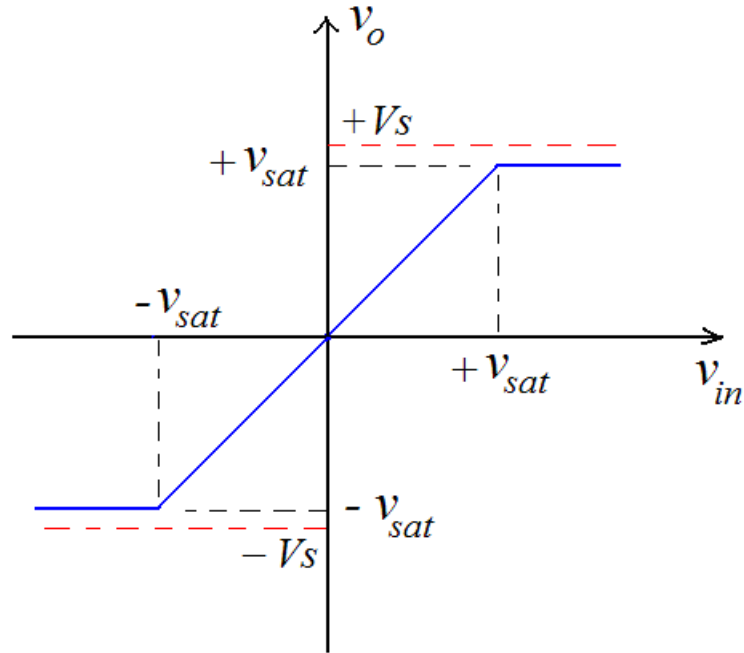


Figure 7. A plot of the output voltage versus the input voltage for a voltage follower.

Inverting Amplifier

The op-amp-based inverting amplifier circuit is shown in Figure 8. This circuit operates according to the following linear input/output equation:

$$v_o = -\frac{R_f}{R} v_{in} \quad (8)$$

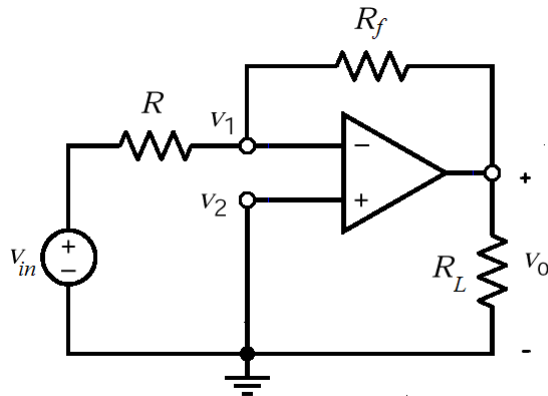


Figure 8. Inverting amplifier circuit.

The gain G is determined by the resistor ratio $G = R_f/R$. The input voltage is amplified when $G > 1$. On the other hand, when $0 < G < 1$ the input voltage is attenuated. The negative sign causes the output voltage signal to be inverted (i.e., 180° out of phase) with respect to the input signal, thus the name “inverting.” When R_L is sufficiently large, the linear relationship in Eq. (8) holds as long as $-v_{sat} < v_o < +v_{sat}$ (i.e., $|v_o| < v_{sat}$) or $G < |v_{sat}/v_{in}|$. For example, if the LM741 is used with bias voltage $\pm 15\text{V}$ and $v_{in} = 10\text{ mV}$, then $G < 14/0.01 = 1400$. If v_{in} is a time-varying function $v_{in}(t)$, then employ the design constraint:

$$G = \frac{R_f}{R} < \frac{|v_{sat}|}{\max|v_{in}(t)|}$$

Non-Inverting Amplifier

The op-amp-based non-inverting amplifier circuit is shown in Figure 9. This circuit operates according to the following linear input/output function:

$$v_o = \left(1 + \frac{R_f}{R}\right) v_{in} \quad (9)$$

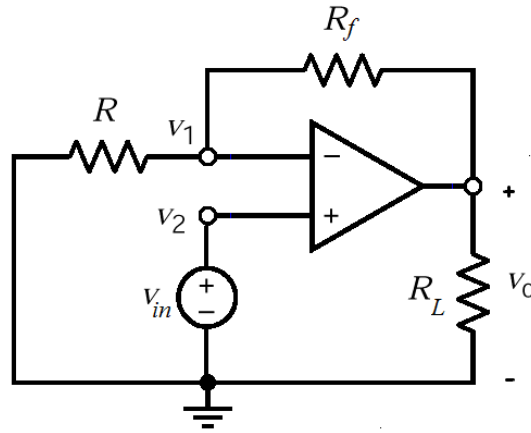


Figure 9. Non-inverting amplifier circuit.

Here, the gain G is equal to $1 + R_f/R$. The input voltage is always amplified since the gain is always greater than 1. When R_L is sufficiently large the linear relationship in Eq. (9) holds as long as $1 + R_f/R < |v_{sat}/v_{in}|$. For example, if the LM741 is used with bias voltage $\pm 15\text{V}$ and $v_{in} = 1\text{V}$, then $1 + R_f/R < 14/1$ or

$R_f/R < 13$. If v_{in} is a time-varying function, then the design constraint:
 $1 + \frac{R_f}{R} < \frac{|v_{sat}|}{\max|v_{in}(t)|}$ should be use.

Adder (Summing Amplifier)

The op-amp-based analog adder circuit is shown in Figure 10. This circuit adds the analog voltages $v_1, v_2, \dots, v_n$ and amplify the sum by $-R_f/R$. The output of this *summing amplifier* can be written as:

$$v_o = -\frac{R_f}{R}(v_1 + v_2 + \dots + v_n) \quad (10)$$

Again for proper operation, v_o must not exceed v_{sat} .

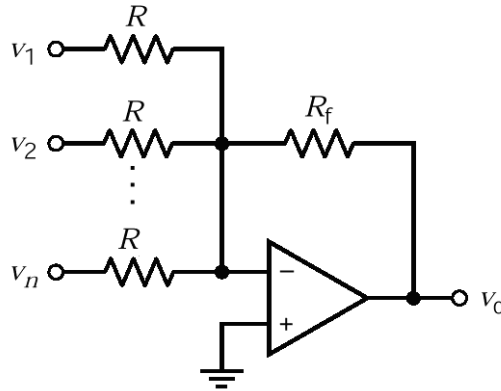


Figure 10. Op-amp-based analog adder.