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FACULTY OF ELECTRICAL ENGINEERING AND INFORMATICS

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Lecture 12

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Applied Informatics

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8

IDEAL OPERATIONAL AMPLIFIERS

8.0 Introduction

In Chapter 7, we introduced op-amps in the context of a study of the discrete circuits that make up an operational amplifier. The current chapter is the first of two devoted exclusively to a detailed study of the op-amps. We have discussed some overall aspects of op-amps, including packaging and specifications on data sheets. We now idealize this important IC and explore its use in design. The inverting amplifier and the noninverting amplifier are studied. A procedure is presented, which permits a general approach toward designing an amplifier that is configured to form a weighted sum of any number of input voltages. We then explore a variety of useful op-amp applications, including negative resistance circuits, integrators, and impedance converters.

In Chapter 9 we modify the ideal op-amp mathematical model of the current chapter by recognizing the changes required to the model to make it more closely coincide with the real op-amp.

8.1 Ideal Op-Amps

This section uses a *systems* approach to present the fundamentals of ideal op-amps [21]. As such, we consider the op-amp as a block with input and output

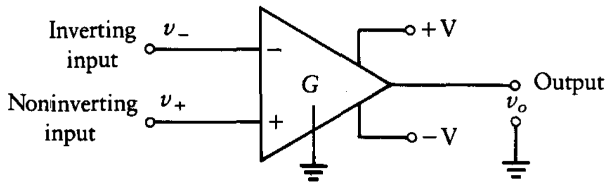


Figure 8.1 Symbol for ideal op-amp.

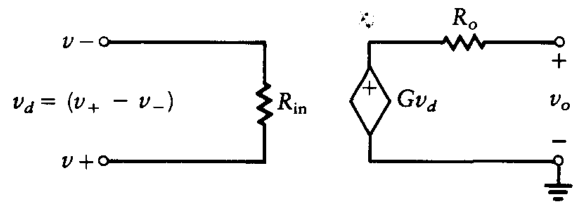


Figure 8.2 Equivalent circuit of op-amp.

terminals. We are not currently concerned with the electronic devices within the op-amp.

An op-amp is a high-gain direct-coupled amplifier, which is often powered by both a positive and a negative supply voltage. This allows the output voltage to swing both above and below ground. The op-amp finds wide application in many linear electronic systems.

The name *operational amplifier* is derived from one of the original uses of op-amp circuits; to perform mathematical operations in analog computers. Early op-amps used a single inverting input. A positive voltage change at the input caused a negative change at the output.

Figure 8.1 presents the symbol for the op-amp, and Figure 8.2 shows its equivalent circuit. The model contains a dependent voltage source, whose voltage depends upon the input voltage. The output impedance is represented in the figure as a resistance of value R_o. The amplifier is driven by two input voltages, v_+ and v_-. The two input terminals are known as the *noninverting* and *inverting* inputs, respectively. Ideally, the output of the amplifier depends not on the magnitudes of the two input voltages but upon the difference between them. We designate a new input voltage as this difference,

$$v_d = v_+ - v_-$$

where v_d is the *differential input voltage*. The input impedance of the op-amp is represented as a resistance in Figure 8.2. The output voltage is proportional to the input voltage, and we designate the ratio as the open loop gain, G. Thus, the output voltage is

$$v_o = G(v_+ - v_-) \tag{8.1}$$

As an example, an input of $E \sin \omega t$ (E is usually a small amplitude) applied to the inverting input with the noninverting terminal grounded, produces $-G(E \sin \omega t)$ at the output. When the same source signal is applied to the noninverting input, with the inverting terminal grounded, the output is $+G(E \sin \omega t)$.

The ideal operational amplifier is characterized as follows:

1. Input resistance, $R_{in} \to \infty$
2. Output resistance, $R_o = 0$
3. Open-loop voltage gain, $G \to \infty$
4. Bandwidth $\to \infty$
5. $v_o = 0$ when $v_+ = v_-$ (i.e., the common-mode gain is zero and the CMRR approaches infinity)

Let us explore the implication of the open-loop gain being infinite. If we rewrite equation (8.1) as

$$v_+ - v_- = \frac{v_o}{G}$$

and let G approach infinity, we see that

$$v_+ - v_- = 0$$

Hence, *the voltage between the two input terminals is zero,* or

$$v_+ = v_-$$

Since the input resistance, R_{in}, is infinite, *the current into each input, inverting and noninverting, is zero.*

Practical op-amps have high voltage gain (typically 10^5 at low frequency), but this gain varies with frequency. For this reason, an op-amp is not normally used in the form shown in Figure 8.1. This configuration is known as *open loop* because there is no feedback from output to input. We see later that the open-loop configuration is useful for *comparator* applications. The more common configuration for linear applications is the *closed-loop* circuit with *feedback.*

External elements are used to feed back a portion of the output signal to the input. If the feedback elements are placed between the output and the inverting input, the *closed-loop gain, or transfer ratio,* is decreased, since a portion of the output subtracts from the input. Feedback not only decreases the overall gain, but it also makes that gain less sensitive to the value of G. With feedback, the closed-loop gain depends upon the feedback circuit elements and not upon the basic op-amp voltage gain, G. Thus, the closed-loop gain is independent of the value of G and depends only upon values of the external circuit elements.

Figure 8.3 illustrates a single negative-feedback op-amp circuit. We analyze this circuit later. For now, note that a single resistor, R_F, is used to connect the output voltage, v_o, to the inverting input, v_-. Another resistor is connected from the inverting input, v_-, to the input voltage.

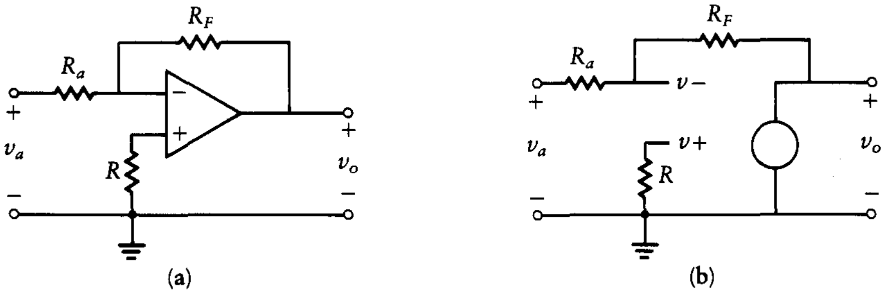


Figure 8.3
Op-amp circuit.

Circuits using op-amps, resistors, and capacitors can be configured to perform many useful operations, such as summing, subtracting, integrating, filtering, comparing, and amplifying.

8.1.1 *Analysis Method*

We use two important ideal op-amp properties:

1. The voltage between v_+ and v_- is zero, or $v_+ = v_-$.
2. The current into both the v_+ and v_- terminal is zero.

We develop a step-by-step procedure to analyze any ideal op-amp circuit as follows:

1. Write the Kirchhoff node equation at the noninverting terminal, v_+.
2. Write the Kirchhoff node equation at the inverting terminal, v_-.
3. Set $v_+ = v_-$ and solve for the desired closed-loop gains.

When performing the first two steps, remember that the current into both the v_+ and v_- terminal is zero.

8.2 The Inverting Amplifier

Figure 8.3(a) illustrates an inverting amplifier with feedback, and Figure 8.3(b) shows the equivalent-circuit form of this inverting amplifier. We wish to solve for the output voltage, v_o, in terms of the input voltage, v_a. Let us follow the step-by-step procedure of Section 8.1.1.

1. Kirchhoff's node equation at v_+ yields

$$v_+ = 0$$

2. Kirchhoff's node equation at v_- yields

$$\frac{v_a - v_-}{R_a} + \frac{v_o - v_-}{R_F} = 0$$

3. Setting $v_+ = v_-$ yields
$$v_+ = v_- = 0$$

We now solve for the closed-loop gain as

$$\frac{v_o}{v_a} = \frac{-R_F}{R_a}$$

Notice that the closed-loop gain, v_o/v_a, is dependent upon the ratio of two resistors, R_F/R_a, and is independent of the open-loop gain, G. This desirable result is caused by the use of feedback of a portion of the output voltage to subtract from the input voltage. The feedback from output to input through R_F serves to drive the differential voltage, $v_i = v_+ - v_-$, to zero. Since the noninverting input voltage, v_+, is zero, the feedback has the effect of driving v_- to zero. Hence, at the input of the op-amp,

$$v_+ = v_- = 0$$

and there is a *virtual ground* at v_-. The term *virtual* means that the voltage, v_-, is zero (ground potential), but no current actually flows into this short circuit since no current can flow into either the inverting or noninverting op-amp terminal.

No matter how complex the ideal op-amp circuit may be, by following this procedure the engineer can quickly begin to analyze (and soon design) op-amp systems.

We now expand this result to the case of multiple inputs. The amplifier shown in Figure 8.4(a) produces an output that is a negative summation of several input voltages. The node equation at v_+ yields $v_+ = 0$. The node equation at the inverting input is given by

$$\frac{v_- - v_o}{R_F} + \frac{v_- - v_a}{R_a} + \frac{v_- - v_b}{R_b} + \frac{v_- - v_c}{R_c} = 0$$

Since $v_+ = v_-$, then $v_+ = 0 = v_-$, and we solve for v_o in terms of the inputs as follows:

$$v_o = -R_F\left(\frac{v_a}{R_a} + \frac{v_b}{R_b} + \frac{v_c}{R_c}\right)$$
$$= -R_F \sum_{j=a}^{c} \left(\frac{v_j}{R_j}\right) \tag{8.2}$$

The extension to n inputs is obvious.

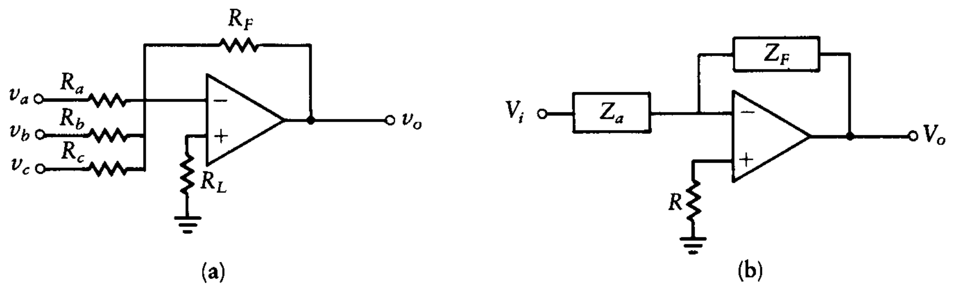


Figure 8.4
Op-amp circuit.

The relationship of equation (8.2) is easily extended to include nonresistive components if R_j is replaced by Z_j and R_F is replaced by Z_F. For a single input, as shown in Figure 8.4(b), the output reduces to

$$V_o = \frac{-Z_F V_i}{Z_A} \tag{8.3}$$

Since we are dealing in the ω-domain, we use uppercase letters for the voltages and currents, which represent the *complex amplitudes*.

One useful circuit based upon equation (8.3) is the *Miller integrator*. In this application, the feedback component is a capacitor, C, and the input component is a resistor, *R*, so

$$Z_F = \frac{1}{j\omega C}$$

and

$$Z_A = R$$

When we substitute these impedances into equation (8.3), we obtain

$$\frac{V_o}{V_i} = \frac{-1}{j\omega RC}$$

which has the form of an integral in the time domain:

$$v_o(t) = \left(\frac{-1}{RC}\right) \int_o^t v_i(\tau)\, d\tau$$

This is an *inverting integrator* because the expression contains a negative sign.

If the feedback element is a resistor and the input element is a capacitor, the input-output relationship becomes

$$\frac{V_o}{V_i} = -j\omega RC$$

and in the time domain, this becomes

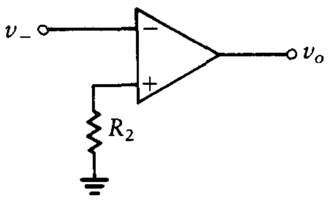
$$v_o(t) = -RC\frac{dv_i}{dt}$$

The circuit is operating as an *inverting differentiator.*

Drill Problems

Using the step-by-step procedure of Section 8.1.1, determine v_o in terms of the input voltages for the following circuits. (The answers are shown on the figures.)

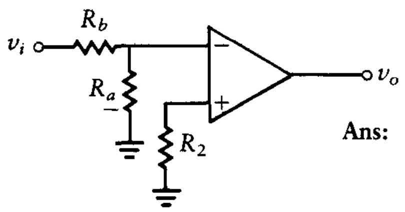
D8.1 Single inverting open loop



Ans: $v_o = -Gv_-$

Figure D8.1

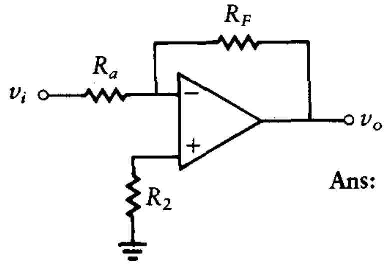
D8.2 Open-loop voltage divider



Ans: $v_o = -\dfrac{GR_a}{R_a + R_b}v_i$

Figure D8.2

D8.3 Inverter



Ans: $v_o = -\dfrac{R_F}{R_a}v_i$

Figure D8.3

8.3 The Noninverting Amplifier

The operational amplifier can be configured to produce either an inverted or noninverted output. In the previous section we analyzed the inverting amplifier, and in this section we repeat the analysis for the noninverting amplifier, which is shown in Figure 8.5. To analyze this circuit, we again follow the procedure of Section 8.1.1:

1. Write a node equation at the v_+ node to get

$$v_+ = v_i$$

2. Write a node equation at the v_- node to get

$$\frac{v_- - 0}{R_a} + \frac{v_- - v_o}{R_F} = 0$$

3. Set $v_+ = v_-$, and substitute for v_-, since

$$v_+ = v_i = v_-$$

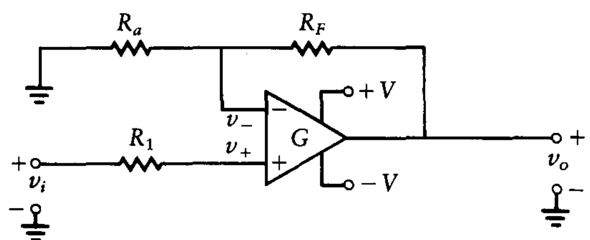
Then

$$\frac{v_i}{R_a} + \frac{v_i - v_o}{R_F} = 0$$

Solving for the gain, we obtain

$$\frac{v_o}{v_i} = 1 + \frac{R_F}{R_a} \tag{8.4}$$

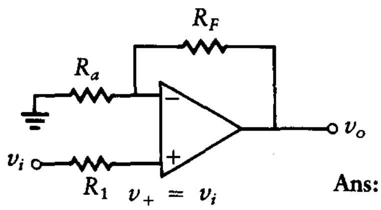
Figure 8.5 Noninverting amplifier.



Drill Problems

Using the ideal op-amp approximations, determine v_o in terms of the input voltages for the following six circuits. (The answers are shown directly on the figures.)

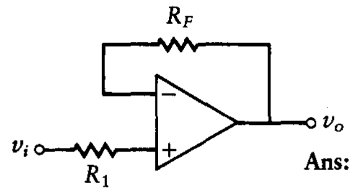
D8.8 Noninverting amplifier



Ans: $v_o = (1 + \frac{R_F}{R_a})\, v_i$

Figure D8.8

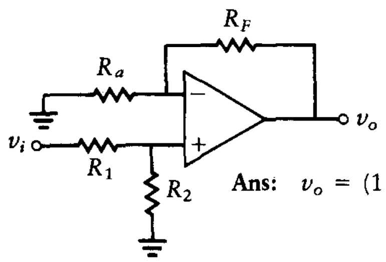
D8.9 Voltage follower



Ans: $v_o = v_i$

Figure D8.9

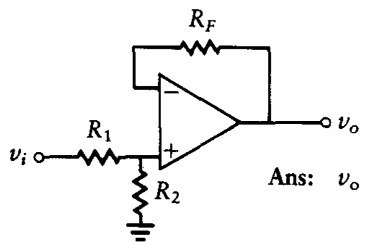
D8.10 Noninverting input with voltage divider



Ans: $v_o = (1 + \frac{R_F}{R_a})(\frac{R_2}{R_1 + R_2})\, v_i$

Figure D8.10

D8.11 Less than unity gain



Ans: $v_o = \frac{R_2}{R_1 + R_2}\, v_i$

Figure D8.11

9

PRACTICAL OPERATIONAL AMPLIFIERS

9.0 Introduction

This chapter expands upon the results of the previous two chapters. We reexamine many of the same op-amp circuits, but in this chapter, the op-amps are no longer assumed to be ideal. We begin by identifying the variations of a practical op-amp from the ideal and then develop an improved equivalent circuit, which more accurately models the actual op-amp characteristics. The improved model is then applied to the analysis of noninverting and inverting amplifiers. Since the practical op-amp is frequency-dependent, we spend time analyzing the frequency characteristics of the various circuits.

The chapter continues with an exploration of the sensitivity of op-amp circuits to changes in supply voltage. We conclude with a discussion of audio amplifiers.

9.1 Practical Op-Amps

Practical op-amps approximate their *ideal* counterparts but differ in some important respects. It is important for the circuit designer to realize the differences between actual op-amps and ideal op-amps, since these differences can adversely affect circuit performance.

Table 9.1 Parameter Values for Op-Amps.

	Ideal	General-Purpose 741	High Speed 715	Low Noise 5534
Voltage gain, G	∞	1×10^{5}*	3×10^{4}	10^{5}
Output impedance, Z_o	0	75 Ω	75 Ω	0.3 Ω
Input impedance, Z_{in} (open loop)	∞	2 MΩ	1 MΩ	100 kΩ
Offset current, I_{io}	0	20 nA	250 nA	300 nA
Offset voltage, V_{io}	0	2 mV	10 mV	5 mV
Bandwidth, BW	∞	1 MHz	65 MHz	10 MHz
Slew rate, SR	∞	0.7 V/ms	100 V/ms	13 V/ms

*The 741 op-amp has typical values of approximately 2 to 3 $\times$ 10^{5}; however in this text we use 10^{5}.

Our intent is to develop a detailed model of the practical op-amp—a model that takes into account the most significant characteristics of the nonideal device. We begin by defining the parameters used to describe practical op-amps. These parameters are specified in listings on data sheets supplied by the op-amp manufacturer.

Table 9.1 lists the parameter values for three particular op-amps, one of the three being the popular 741. As the various parameters are defined in the following sections, reference should be made to this table to find typical values.

The most significant difference between ideal and actual op-amps is in the voltage gain. The ideal op-amp has an infinite voltage gain. The actual op-amp has a finite voltage gain that decreases as the frequency increases. Most op-amps are frequency-compensated to provide a predictable voltage gain versus frequency characteristic. Some op-amps, like the 741, are internally compensated with a fixed capacitor. Other op-amps, like the 101, permit a capacitor to be added externally to the op-amp so the frequency characteristic can be changed.

9.1.1 *Open-Loop Voltage Gain (G)*

The *open-loop voltage gain* of an op-amp is the ratio of the change in output voltage to a change in the input voltage without feedback. Voltage gain is a dimensionless quantity. The symbol G is used to indicate the open-loop voltage gain. Op-amps have high voltage gain for inputs with frequencies in the range of dc to about 10 kHz. The op-amp specification lists the voltage gain in volts per millivolt or in decibels defined as $20 \log_{10}(v_o/v_i)$.

The open-loop voltage gain is frequency-dependent. Figure 9.1 illustrates this gain as a function of frequency for a typical op-amp. Note that the gain decreases with increasing frequency.

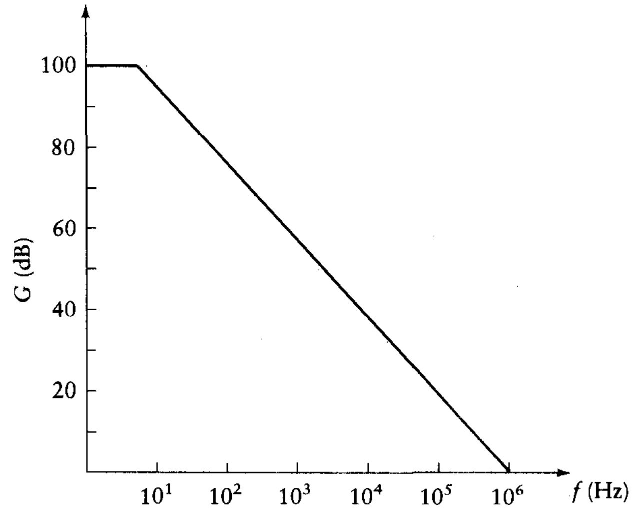


Figure 9.1
Voltage gain vs. frequency.

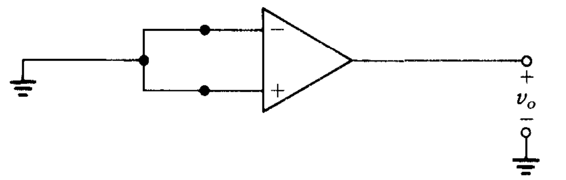


Figure 9.2
Technique for measuring V_{io}.

9.1.2 *Input Offset Voltage (V_{io})*

When the input voltage to an ideal op-amp is zero, the output voltage is also zero. This is not true for an actual op-amp. The ***input offset voltage, V_{io},*** is defined as the input voltage required to make the output voltage equal to zero. V_{io} is zero for the ideal op-amp. A typical value of V_{io} for the 741 op-amp is 2 mV. A nonzero value of V_{io} is undesirable, since the op-amp will amplify any input offset, thus causing a larger output dc error.

The following technique may be used to measure the input offset voltage. Rather than vary the input voltage in order to force the output to zero, the input is set equal to zero, as shown in Figure 9.2, and the output voltage is measured. The output voltage resulting from a zero input voltage is known as the *output dc offset voltage.* If this quantity is divided by the open loop gain of the op-amp, the input offset-voltage is obtained.

The effects of input offset voltage can be incorporated into the op-amp model, as shown in Figure 9.3. Note that in addition to including input offset voltage, the ideal op-amp model has been further modified by the addition of four resistances. R_o is the output resistance. The input resistance of the op-amp, R_i, is measured between the inverting and noninverting terminals. The model also contains a resistor between each of the two inputs and ground. These are the *common-mode resistances* and are each equal to $2R_{cm}$. If the