Chapter 8

Amplifiers: Specifications and External Characteristics

The most important functional blocks found in electronic systems are amplifiers. Basically, amplifiers are used to increase the amplitudes of electrical signals. For example, the signals from most sensors (such as strain gauges used in mechanical engineering or flow meters used in chemical processes) are small in amplitude and need to be amplified before they can be utilized.

Section 8.1 Basic Amplifier Concepts

In this chapter we consider the external characteristics of amplifiers that are important in selecting an amplifier for instrumentation applications. After introducing the basic concepts of amplifiers, we consider several nonideal properties of real amplifiers. To avoid errors when working with electronic instrumentation in your field, you need to be familiar with these amplifier imperfections. The internal operation of amplifier circuits is treated in Chapters 9, 10, and 11.

8.1 BASIC AMPLIFIER CONCEPTS

Ideally, an amplifier produces an output signal with identical waveshape as the input signal but with a larger amplitude. The concept is illustrated in Figure 8.1. The signal source produces a voltage \( v_i(t) \) that is applied to the input terminals of the amplifier, which generates an output voltage

\[
v_o(t) = A_v v_i(t)
\]

across a load resistance \( R_L \) connected to the output terminals. The constant \( A_v \) is called the voltage gain of the amplifier. Often, the voltage gain is much larger than unity, but we will see later that useful amplification can take place even if \( A_v \) is less than unity.

An example of a signal source is a microphone which typically produces a signal of 1-mV peak as we speak into it. This small signal can be used as the input to an amplifier with a voltage gain of 10,000 to produce an output signal with a peak value of 10 V. If this larger output voltage is applied to a loudspeaker, a much louder version of the sound entering the microphone results. This is the principle of operation for the electronic megaphone.

Sometimes, \( A_v \) is a negative number, so the output voltage is an inverted version of the input, and the amplifier is then called an inverting amplifier. On the other hand, if \( A_v \) is a positive number, we have a noninverting amplifier. A typical input waveform and the corresponding output waveforms for a noninverting amplifier and for an inverting amplifier are shown in Figure 8.2.
For monaural audio signals, it does not matter whether the amplifier is inverting or noninverting because the sounds produced by the loudspeaker are perceived the same either way. However, in a stereo system, it is important that the amplifiers for the left and right channels are the same (i.e., either both inverting or both noninverting), so the signals applied to the two loudspeakers have the proper phase relationship. If video signals are inverted, a negative image with black and white interchanged results, so it is important whether video amplifiers are inverting or noninverting.

### 8.1.1 Common Ground Node

Often, one of the amplifier input terminals and one of the output terminals are connected to a common ground. Notice the ground symbol shown in Figure 8.1.
Typically, the ground terminal consists of the metal chassis that contains the circuit as well as circuit-board conductors. This common ground serves as the return path for signal currents and, as we will see later, the dc power-supply currents in electronic circuits.

You may be familiar with the concept of electrical grounds in automobile wiring. Here the ground conductor consists of the frame, fenders, and other conductive parts of the car. For example, current is carried to the taillights by a wire but (in many automobile designs) returns through the ground conductors, consisting of the fenders and frame. Similarly, residential 60-Hz power distribution systems are grounded, often to a cold-water pipe. However, in this case, return currents are not intended to flow through the ground conductors because that could pose safety hazards.

Sometimes, but not always, the chassis ground is connected through the line cord to the 60-Hz power-system ground. Always be careful in working with electrical circuits. In some types of electronic circuits, the chassis ground can be at 120 V ac with respect to the power-system ground. Touching the chassis while in contact with the power-system ground (through a water pipe or a damp concrete floor for example) can be fatal.

**EXERCISE 8.1** A certain noninverting amplifier has a voltage gain magnitude of 50. The input voltage is $v_i(t) = 0.1 \sin(2000\pi t)$. (a) Find an expression for the output voltage $v_o(t)$. (b) Repeat for an inverting amplifier.

**Ans.** (a) $5 \sin(2000\pi t)$; (b) $-5 \sin(2000\pi t)$.

### 8.1.2 Voltage-Amplifier Model

Amplification can be modeled by a controlled source as illustrated in Figure 8.3. Because real amplifiers draw some current from the signal source, a realistic model of an amplifier must include a resistance $R_e$ across the input terminals. Furthermore, a resistance $R_e$ must be included in series with the output terminals to account for the fact that the output voltage of a real amplifier is reduced when load current flows. The complete amplifier model shown in Figure 8.3 is called the **voltage-amplifier model**. Later we will see that other models can be used for amplifiers.

The **input resistance** $R_i$ of the amplifier is the equivalent resistance seen when looking into the input terminals. As we will find later, the input circuitry can sometimes include capacitive or inductive effects, and we would then refer to the **input impedance**. For example, the input amplifiers of typical oscilloscopes have an input impedance consisting of a $100\Omega$ resistance in parallel with a 47-pF capacitance. In this chapter we assume that the input impedance is purely resistive unless stated otherwise.

The resistance $R_o$ in series with the output terminals is known as the **output resistance**. Real amplifiers are not able to deliver a fixed voltage to an arbitrary load resistance. Instead, the output voltage becomes smaller as the load resistance becomes smaller, and the output resistance accounts for this reduction. When the
load draws current, a voltage drop occurs across the output resistance, resulting in a reduction of the output voltage.

The voltage-controlled voltage source models the amplification properties of the amplifier. Notice that the voltage produced by this source is simply a constant $A_v$ times the input voltage $v_i$. If the load is an open circuit, there is no drop across the output resistance, and then $v_o = A_v v_i$. For this reason, $A_v$ is called the open-circuit voltage gain.

To summarize, the voltage-amplifier model includes the input impedance, the output impedance, and the open-circuit voltage gain in an equivalent circuit for the amplifier.

### 8.1.3 Current Gain

As shown in Figure 8.3, the input current $i_i$ is the current delivered to the input terminals of the amplifier, and the output current $i_o$ is the current flowing through the load. The current gain $A_i$ of an amplifier is the ratio of the output current to the input current:

$$A_i = \frac{i_o}{i_i} \quad (8.2)$$

The input current can be expressed as the input voltage divided by the input resistance, and the output current is the output voltage divided by the load resistance. Thus we can find the current gain in terms of the voltage gain and the resistances as

$$A_i = \frac{i_o}{i_i} = \frac{v_o / R_L}{v_i / R_i} = A_v \frac{R_i}{R_L} \quad (8.3)$$

in which

$$A_v = \frac{v_o}{v_i}$$

is the voltage gain with the load resistance connected. Usually, $A_v$ is smaller in magnitude than the open-circuit voltage gain $A_v$ because of the voltage drop across the output resistance.
8.1.4 Power Gain

The power delivered to the input terminals by the signal source is called the input power \( P_i \), and the power delivered to the load by the amplifier is the output power \( P_o \). The power gain \( G \) of an amplifier is the ratio of the output power to the input power:

\[
G = \frac{P_o}{P_i}
\]  

(8.4)

Because we are assuming that the input impedance and load are purely resistive, the average power at either set of terminals is simply the product of the root-mean-square (rms) current and rms voltage. Thus we can write

\[
G = \frac{P_o}{P_i} = \frac{V_o I_o}{V_i I_i} = A_v A_i = (A_i)^2 \frac{R_i}{R_L}
\]  

(8.5)

Notice that we have used uppercase symbols, such as \( V_o \) and \( I_o \), for the rms values of the currents and voltages. We use lowercase symbols, such as \( v_i \) and \( i_i \), for the instantaneous values. Of course, since we have assumed so far that the instantaneous output is a constant times the instantaneous input, the ratio of the rms voltages is the same as the ratio of the instantaneous voltages, and both ratios are equal to the voltage gain of the amplifier.

**Example 8.1**

A source with an internal voltage of \( V_i = 1 \text{ mV} \) rms and an internal resistance of \( R_i = 1 \text{ M} \Omega \) is connected to the input terminals of an amplifier having an open-circuit voltage gain of \( A_{vo} = 10^4 \), an input resistance of \( R_i = 2 \text{ M} \Omega \), and an output resistance of \( R_o = 2 \text{ } \Omega \). The load resistance is \( R_L = 8 \text{ } \Omega \). Find the voltage gains \( A_{vi} = V_o/V_i \) and \( A_v = V_o/V_i \). Also, find the current gain and power gain.

**Solution**

A model of the source, amplifier, and load is shown in Figure 8.4. We can apply the voltage-divider principle to the input circuit to write

\[
V_i = \frac{R_i}{R_i + R_o} V_o = 0.667 \text{ mV} \text{ rms}
\]

The voltage produced by the voltage-controlled source is given by

\[
A_{vo} V_i = 10^4 V_i = 6.67 \text{ V rms}
\]

Next, the output voltage can be found by using the voltage-divider principle, resulting in

\[
V_o = A_{vo} V_i \frac{R_L}{R_o + R_L} = 5.33 \text{ V rms}
\]

Now, we can find the required voltage gains:

\[
A_v = \frac{V_o}{V_i} = A_{vo} \frac{R_L}{R_o + R_L} = 8000
\]

and

\[
A_{vi} = \frac{V_o}{V_i} = A_{vo} \frac{R_i}{R_i + R_o} \frac{R_L}{R_o + R_L} = 5333
\]
Using Equations 8.3 and 8.5, the current gain and power gain can be found as

\[ A_i = A_v \frac{R_i}{R_L} = 2 \times 10^9 \]

\[ G = A_v A_i = 16 \times 10^{12} \]

Notice that the current gain is very large, because the high input resistance allows only a small amount of input current to flow, whereas the relatively small load resistance allows the output current to be relatively large.

8.1.5 Loading Effects

Notice that not all of the internal voltage of the source appears at the input terminals of the amplifier in Example 8.1. This is because the finite input resistance of the amplifier allows current to flow into the input terminals, resulting in a voltage drop across the internal resistance \( R_i \) of the source. Similarly, the voltage produced by the controlled source does not all appear across the load. These reductions in voltage are called \textit{loading effects}. Because of loading effects, the voltage gains (\( A_v \) or \( A_{ve} \)) realized are less than the internal gain \( A_{vo} \) of the amplifier.

**EXERCISE 8.2** An amplifier has an input resistance of 2000 \( \Omega \), an output resistance of 25 \( \Omega \), and an open-circuit voltage gain of 500. The source has an internal voltage of \( V_i = 20 \text{ mV} \) and a resistance of \( R_i = 500 \ \Omega \). The load resistance is \( R_L = 75 \ \Omega \). Find the voltage gains \( A_v = V_o/V_i \) and \( A_{ve} = V_o/V_i \). Find the current gain and the power gain.

\textbf{Ans.} \( A_v = 375 \), \( A_{ve} = 300 \), \( A_i = 10^4 \), \( G = 3.75 \times 10^6 \).

**EXERCISE 8.3** Assume that we can change the load resistance in Exercise 8.2. What value of load resistance maximizes the power gain? What is the power gain for this load resistance?

\textbf{Ans.} \( R_L = 25 \ \Omega \), \( G = 5 \times 10^6 \).
Section 8.2 Casceded Amplifiers

8.2 Casceded Amplifiers

Sometimes we connect the output of one amplifier to the input of another as shown in Figure 8.5. This is called a cascade connection of the amplifiers. The overall voltage gain of the cascade connection is given by

$$A_v = \frac{v_{o2}}{v_{i1}}$$

Multiplying and dividing by $v_{o1}$, this becomes

$$A_v = \frac{v_{o1}}{v_{i1}} \times \frac{v_{o2}}{v_{o1}}$$

However, referring to Figure 8.5, we see that $v_{i2} = v_{o1}$. Therefore, we can write

$$A_v = \frac{v_{o1}}{v_{i1}} \times \frac{v_{o2}}{v_{i2}}$$

However, $A_{v1} = v_{o1}/v_{i1}$ is the gain of the first stage, and $A_{v2} = v_{o2}/v_{i2}$ is the gain of the second stage, so we have

$$A_v = A_{v1}A_{v2} \quad (8.6)$$

Thus the overall voltage gain of cascaded amplifier stages is the product of the voltage gains of the individual stages. (Of course, it is necessary to include loading effects in computing the gain of each stage. Notice that the input resistance of the second stage loads the first stage.)

Similarly, the overall current gain of a cascade connection of amplifiers is the product of the current gains of the individual stages. Furthermore, the overall power gain is the product of the individual power gains.

Example 8.2 Consider the cascade connection of the two amplifiers shown in Figure 8.6. Find the current gain, voltage gain, and power gain of each stage and for the overall cascade connection.

![Figure 8.5 Cascade connection of two amplifiers.](image)
**Solution**

Considering loading by the input resistance of the second stage, the voltage gain of the first stage is

\[ A_{v1} = A_{vo1} \frac{R_{i2}}{R_{i2} + R_{o1}} = 150 \]

where we have used the fact that \( A_{vo1} = 200 \), as indicated in Figure 8.6. Similarly,

\[ A_{v2} = A_{vo2} \frac{R_L}{R_L + R_{o2}} = 50 \]

The overall voltage gain is

\[ A_v = A_{v1} A_{v2} = 7500 \]

Because \( R_{i2} \) is the load resistance for the first stage, we can find the current gain of the first stage by use of Equation 8.3.

\[ A_{i1} = A_{v1} \frac{R_{i1}}{R_{i2}} = 10^5 \]

Similarly, the current gain of the second stage is found as

\[ A_{i2} = A_{v2} \frac{R_{i2}}{R_L} = 750 \]

The overall current gain is

\[ A_i = A_{i1} A_{i2} = 75 \times 10^6 \]

Now the power gains can be found as

\[ G_1 = A_{v1} A_{i1} = 1.5 \times 10^7 \]

\[ G_2 = A_{v2} A_{i2} = 3.75 \times 10^4 \]

and

\[ G = G_1 G_2 = 5.625 \times 10^{11} \]
8.2.1 Simplified Models for Cascaded Amplifier Stages

Sometimes we will want to find a simplified model for a cascaded amplifier. The input resistance of the cascade is the input resistance of the first stage, and the output resistance of the cascade is the output resistance of the last stage. The open-circuit voltage gain of the cascade is computed with an open-circuit load on the last stage. However, loading effects of each stage on the preceding stage must be considered. Once the open-circuit voltage gain of the overall cascade connection is found, a simplified model can be drawn.

**Example 8.3**

Find the overall simplified model for the cascade connection of Figure 8.6.

**Solution**

The voltage gain of the first stage, accounting for the loading of the second stage, is

\[ A_{v1} = A_{vo1} \frac{R_s}{R_s + R_o1} = 150 \]

With an open-circuit load, the gain of the second stage is

\[ A_{v2} = A_{vo2} = 100 \]

The overall open-circuit gain is

\[ A_{vo} = A_{v1}A_{v2} = 15 \times 10^3 \]

The input resistance of the cascade amplifier is

\[ R_i = R_{i1} = 1 \text{ M}\Omega \]

and the output resistance is

\[ R_o = R_{o2} = 100 \Omega \]

The simplified model for the cascade is shown in Figure 8.7.

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**Figure 8.7** Simplified model for the cascaded amplifiers of Figure 8.6. See Example 8.3.