14.3 BANDWIDTH LIMITATIONS

An op-amp's ability to amplify a signal is a direct function of the frequencies involved. The maximum frequency at which an op-amp provides useful performance can be characterized in multiple ways. Manufacturers provide a variety of related specifications to assist in this task. First, there is the *gain-bandwidth product* (GBW), also referred to as *bandwidth* (BW). As the name implies, GBW specifies a gain at a certain frequency. As the frequency of operation is decreased, the gain increases, and vice versa. Most op-amp data sheets provide either a bandwidth number, sometimes specified as the unity-gain bandwidth, or a chart that relates gain to frequency. The large-signal voltage gain of the LM741 remains relatively constant for frequencies only under 10 Hz (not kHz!). It is called "large-signal," because the response is essentially at DC; "small-signal" would denote practical operating frequencies that are typically orders of magnitude higher. Near 10 Hz, the gain rolls off at the rate of –20 dB per decade and reaches unity gain, 0 dB, near 1 MHz. Above 1 MHz, the LM741's gain rapidly drops off. Keep in mind, however, that this is the LM741's open-loop response. When a closed-loop circuit is formed, the gain is substantially lowered, thereby increasing the circuit's usable bandwidth over which the gain remains constant.

Figure 14.16 shows an approximate gain versus frequency curve for an older bipolar op-amp such as the LM741. The gain of the open-loop op-amp is approximately 100 dB below 10 Hz. Observe that, if the closed-loop gain is set at 10 (20 dB), the constant gain portion of the curve drops by approximately 80 dB, which correlates to four decades of frequency. Therefore, the closed-loop bandwidth increases to 10 Hz multiplied by four decades, or 100 kHz. Put another way, 100 dB equals 100,000. The gain-bandwidth product is approximately $100{,}000 \times 10$ Hz = 1 MHz. If a closed-loop gain of 10 is used, the bandwidth is 1 MHz $\div$ 10 = 100 kHz.

Two other interrelated frequency metrics are *slew rate* and *full-power bandwidth*. These specifications enable an engineer to determine whether a signal will be distorted by the op-amp based on the signal's frequency and amplitude. Slew rate defines the rate at which the op-amp can change its output voltage. The LM741's specified slew rate is 0.5 V/μs. If the desired output signal has a component that changes voltage faster than the slew rate, the op-amp will not be able to fully reproduce the signal and is said to be *slew-rate limited*. An example of slew-rate limiting is shown in Fig. 14.17, where the desired sine wave output, a pure signal with a single frequency, is converted to a triangle waveform that transitions at the op-amp's maximum slew rate.

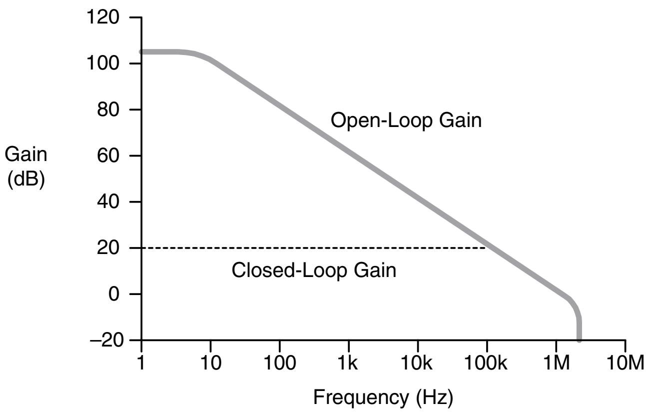

FIGURE 14.16 Typical gain vs. frequency curve.

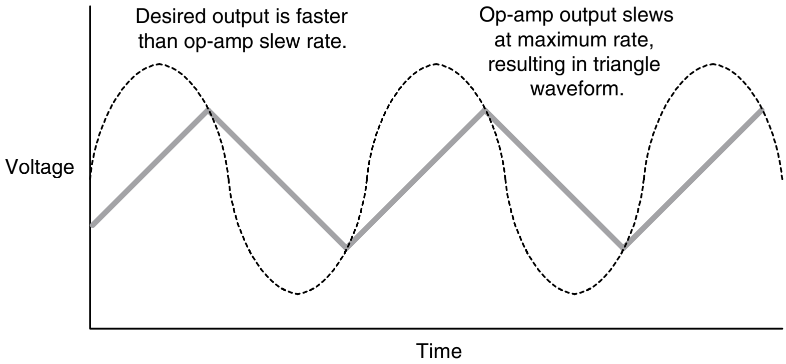

FIGURE 14.17 Slew-rate-limited output.

Higher output frequencies are possible when output amplitudes are reduced, because the slew rate is a function of both time (frequency) and amplitude. For a sine wave of amplitude V_{MAX}, its slew rate is determined by computing the maximum value of its first-derivative, which is equal to $2\pi f V_{MAX}$. Therefore, the op-amp's slew rate, SR, can be combined with this expression to calculate the highest output frequency that will not be slew-rate limited.

$$f_{MAX} = \frac{SR}{2\pi V_{MAX}}$$

Manufacturers may specify an op-amp's full-power bandwidth, which is calculated with this equation by using the device's slew rate and maximum rated output voltage swing. In the case of the LM741, which is rated at ±14 V of typical output swing, its full-power bandwidth is approximately 5.7 kHz, indicating that it can reproduce a 5.7 kHz sine wave at its full output range. Op-amps with lower operating voltages and higher slew-rates resulting from modern semiconductor process improvements can achieve full-power bandwidths in the tens of megahertz.

Each type of op-amp has different frequency, noise, and power characteristics. Op-amps are well behaved at DC and low frequencies. General-purpose op-amps are well suited to applications in the kilohertz range such as processing audio signals or transducer signals with limited bandwidths. Newer op-amps have much improved high-frequency characteristics, enabling them to be used for video and other more demanding applications. The gain-bandwidth product and slew-rate (or full-power bandwidth) specifications can be used to determine if a particular op-amp will handle signals of the desired frequency and amplitude. If this important first hurdle is passed, an op-amp's data sheet should be more carefully inspected to quantify the degradations in such characteristics as input impedance and CMRR resulting from frequency.

14.4 INPUT RESISTANCE

Op-amps are often used to amplify, or buffer, weak electrical signals that are generated by transducers such as a microphone or photodiode. These transducers often have very high output impedances that translate into an inability to drive even light loads. Current drive capability may range from a few milliamps down to nanoamps. When trying to buffer a signal that is measured in nanoamps, the