PDHonline Course E272 (5 PDH)

Operational Amplifier Fundamentals and Design

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CHARACTERISTICS OF OP AMPS AND THEIR POWER SUPPLY REQUIREMENTS

The term *operational amplifier* refers to a high-gain dc amplifier that has a differential input (two input leads) and a single-ended output (one output lead). The signal output voltage V_o is larger than the differential input signal across the two inputs by the gain factor of the amplifier (see Fig. 2-1). Op Amps have characteristics such as high input resistance, low output resistance, high gain, etc., that make them highly suitable for many applications, a number of which are shown and discussed in later chapters. By examining some applications and comparing the characteristics of typical Op Amps, we will see that some types are apparently better than others. The overall most desirable characteristics that Op Amp manufacturers strive to obtain in their products are *ideal characteristics*. While some of these ideal characteristics are impossible to obtain, we often assume that they exist to develop circuits and equations that work perfectly on paper. These circuits and equations then work very well with practical Op Amps. Actual Op Amp characteristics are more or less ideal, relative to conditions external to the Op Amp: signal source resistance, load resistance, amount of feedback used, etc. Some of the more important characteristics, ideal and practical values, are given and defined in the following sections.

2.1 OPEN-LOOP VOLTAGE GAIN* A_{VOL}

The open-loop voltage gain A_{VOL} of an Op Amp is its *differential* gain under conditions where no negative feedback is used, as shown in Figs. 2-1 and 2-2.

*In industry, the open-loop voltage gain is referred to with a variety of symbols: A_{VOL}, A_d, A_{EOL}, A_{VD}, etc.

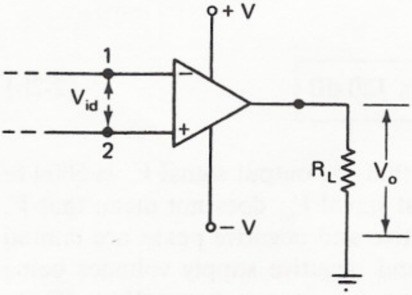

Figure 2-1 Typical Op Amp symbol. $+V$ is the positive dc power supply voltage; $-V$ is the negative dc power supply voltage; $A_{VOL} = V_o/V_{id}$.

Ideally, its value is infinite—that is, the ideal Op Amp has an open-loop voltage gain

$$\boxed{A_{VOL} = \frac{V_o}{V_{id}} = -\infty} \tag{2-1a}$$

or

$$\boxed{A_{VOL} = \frac{V_o}{V_1 - V_2} = -\infty} \tag{2-1b}$$

The negative sign means that the output V_o and the input V_{id} are out of phase. Of course, the concept of an infinite gain is theoretical. The important point to understand is that the Op Amp's output signal voltage V_o should be very much larger than its differential input signal V_{id}. To put it another way, the input V_{id} should be infinitesimal compared to any practical value of output V_o. Typical open-loop gains A_{VOL} range from about 5000 (about 74 dB) to 1,000,000 (about 120 dB)—that is,

$$5000 \leq A_{VOL} \leq 1{,}000{,}000 \tag{2-2a}$$

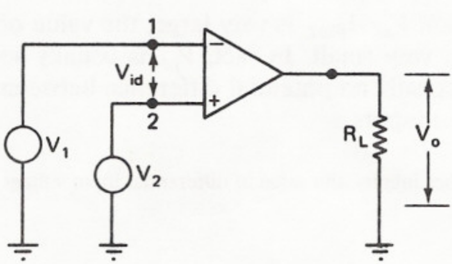

Figure 2-2 Op Amp with input voltages V_1 and V_2 whose difference is V_{id}. Power supply voltages $+V$ and $-V$ are assumed if not shown.

or

$$\boxed{74 \text{ dB} \leq A_{VOL} \leq 120 \text{ dB}} \tag{2-2b}$$

with popular types of Op Amps. The fact that the output signal V_o is 5000 to 10^6 times larger than the differential input signal V_{id} does not mean that V_o can actually be very large. In fact, its positive and negative peaks are limited to values a little less than the positive and negative supply voltages being used to power the Op Amp. Since the dc supply voltages of monolithic IC Op Amps are usually less than 20 V, the peaks of their output voltages V_o are less than 20 V. This fact, coupled with the large A_{VOL} of the typical Op Amp, makes the voltage V_{id} across its inputs 1 and 2 very small. Of course, the larger the open-loop gain A_{VOL}, the smaller V_{id} is in comparison to any practical value of output signal V_o. Thus, since

$$\boxed{A_{VOL} = \frac{V_o}{V_{id}}} \tag{2-3a}$$

or

$$\boxed{A_{VOL} = \frac{V_o}{V_1 - V_2},} \tag{2-3b}$$

then

$$\boxed{V_{id} = \frac{V_o}{A_{VOL}}}$$

and therefore,

as a limit, as A_{VOL} approaches infinity,
V_{id} approaches zero

Thus, if the gain A_{VOL} in the expression V_o/A_{VOL} is very large, the value of this expression, which is V_{id}, must be very small. In fact, V_{id} is usually so small that we can assume there is practically no potential difference between the inverting (−) and noninverting (+) inputs.

*As the value of open-loop gain A_{VOL} approaches infinity, the value of differential input voltage V_{id} approaches zero if $V_o \neq 0$.

2.2 OUTPUT OFFSET VOLTAGE V_{oo}

The output offset voltage V_{oo} of an Op Amp is its output voltage to ground or common under conditions when its differential input voltage $V_{id} = 0$ V. Ideally $V_{oo} = 0$ V. In practice, due to imbalances and inequalities in the differential amplifiers within the Op Amp itself (see Fig. 1-12), some output offset voltage V_{oo} will usually occur even though the input $V_{id} = 0$ V. In fact, if the open-loop gain A_{VOL} of the Op Amp is high and if no feedback is used, the output offset is large enough to saturate the output. In such cases, the output voltage is either a little less than the positive source voltage $+V$ or the negative source $-V$. This is not as serious as it first appears because corrective measures are fairly simple to apply and because the Op Amp is seldom used without some feedback. When corrective action is taken to bring the output to 0 V, when the applied input signal is 0 V, the Op Amp is said to be *balanced* or *nulled*.

If both inputs are at the same finite potential, causing $V_1 - V_2 = V_{id} = 0$ V, and if the output $V_o = 0$ V as a result, the Op Amp is said to have an ideal *common-mode rejection* (CMR). Though most practical Op Amps have a good CMR capability, they do pass some *common-mode* (CM) voltage to the load R_L. Typically though, the load's common-mode output voltage V_{cmo} is hundreds or thousands of times *smaller* than the input common-mode voltage V_{cm}. A thorough discussion of the practical Op Amp's CMR capability and its applications is given in a later chapter.

2.3 INPUT RESISTANCE R_i

The Op Amp's input resistance R_i is the resistance seen looking into its inputs 1 and 2 as shown in Fig. 2-3. Ideally, $R_i = \infty\ \Omega$. Practical Op Amps' input resistances are not infinite but instead range from less than 5 kΩ to over 20 MΩ, depending on type. Though resistances in the low end of this range seem a bit small compared to the desired ideal ($\infty\ \Omega$), they can be quite large compared to the low internal resistances of some signal sources that commonly drive the inputs of Op Amps. Generally, if a high-resistance signal source is to drive an Op Amp, the Op Amp's input resistance should be relatively large. As we will see later, the *effective* input resistance $R_{i(\text{eff})}$ is made considerably larger than the manufacturer's specified R_i by use of

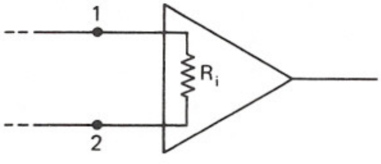

Figure 2-3 Input resistance R_i is the resistance seen looking into the inputs 1 and 2.

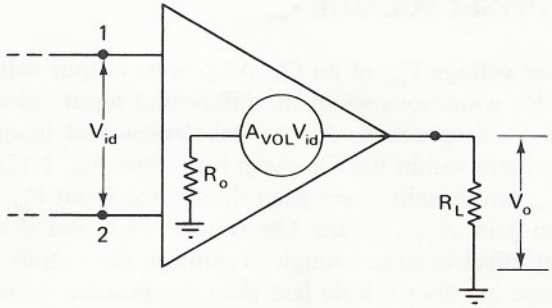

Figure 2-4 Output resistance R_o tends to reduce output voltage V_o.

negative feedback. Manufacturers usually specify their Op amps' input resistances as measured under open-loop conditions (no feedback). In most linear applications, Op Amps are wired with feedback and this improves (increases) the effective resistance seen by the signal source driving the Op Amp.

2.4 OUTPUT RESISTANCE R_o

With a differential input signal V_{id} applied, the Op Amp behaves like a signal generator as the load connected to the output sees it. As shown in Fig. 2-4, the Op Amp is equivalent to a signal source generating an open-circuit voltage of $A_{VOL}V_{id}$ and having an internal resistance of R_o. This R_o is the Op Amp's output resistance and ideally should be 0 Ω. Obviously, if $R_o =$ 0 Ω in the circuit of Fig. 2-4, all of the generated output signal $A_{VOL}V_{id}$ appears at the output and across the load R_L. Depending on the type of Op Amp, specified output resistance R_o values range from a few ohms to a few hundred ohms and are usually measured under open-loop (no feedback) conditions. Fortunately, the *effective* output resistance $R_{o(\text{eff})}$ is considerably smaller when the Op Amp is used with feedback. In fact, in most applications using feedback, the effective output resistance of the Op Amp is very nearly ideal (0 Ω). The effect feedback has on output resistance is discussed in more specific terms later.

2.5 BANDWIDTH BW

The *bandwidth* BW of an amplifier is defined as the range of frequencies at which the output voltage does not drop more than 0.707 of its maximum value while the input voltage *amplitude* is constant. Ideally, an Op Amp's bandwidth BW = ∞. An infinite bandwidth is one that starts with dc and extends to infinite cycles/second (Hz). It is indeed idealistic to expect such a bandwidth from any kind of amplifier. Practical Op Amps fall far short of this ideal. In fact, limited high-frequency response is a shortcoming of monolithic IC Op Amps. While some types of Op amps can be used to amplify signals up to a few megahertz, they require carefully chosen feedback and externally wired compensating components. Most general-purpose IC Op Amps are limited to less than 1-MHz bandwidth and more often are used with signals well under a few kilohertz, especially if any significant gain is expected of them. The limited high-frequency response of Op Amps is not a serious matter with most types of instrumentation in which Op Amps are used extensively. Chapter 6 discusses high frequency characteristics of Op Amps.

2.6 RESPONSE TIME

The response time of an amplifier is the time it takes the output of an amplifier to change after the input voltage changes. Ideally, response time = 0 seconds; that is, the output voltage should respond instantly to any change on the input. Figure 2-5 shows an Op Amp's typical output-voltage response to a step input voltage when wired for unity gain. Manufacturers also specify a *slew rate* that gives the circuit designer a good idea of how fast a given Op Amp responds to changes of input voltage. Note that the time scale in Fig. 2-5 is in microseconds (μs) and that the output voltage, when changing, overshoots the level it eventually settles at. Overshoot is the ratio of the amount of overshoot to the steady-state deviation expressed as a percentage. For example, if we observe the responding output voltage of Fig. 2-5 on an oscilloscope whose vertical deflection sensitivity is at 10 V/cm, and the amount of overshoot measures 0.2 cm, the percentage of overshoot is

$$\frac{\text{Amount of overshoot}}{\text{Steady-state deflection}} \times 100 = \frac{0.2\text{ cm}}{2\text{ cm}} \times 100 = 10\%.$$

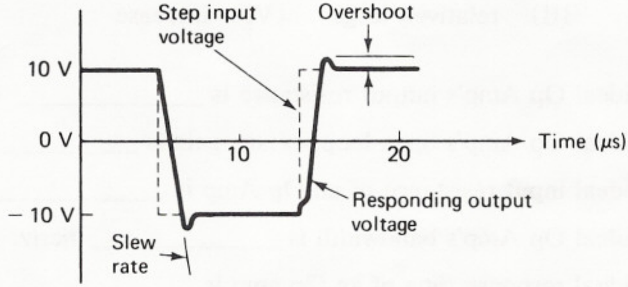

Figure 2-5 Typical Op Amp response to a step input voltage when wired as a voltage follower (unity gain).

From time to time we will refer to the various *ideal* characteristics, and here is a summary:

(1) Open-loop voltage gain $A_{VOL} = \infty$.
(2) Output offset voltage $V_{oo} = 0$ V.
(3) Input resistance $R_i = \infty\ \Omega$.
(4) Output resistance $R_o = 0\ \Omega$.
(5) Bandwidth BW $= \infty$ Hz.
(6) Response time $= 0$ s.

2.7 POWER SUPPLY REQUIREMENTS

In many applications, the Op Amp's output voltage V_o must be capable of swinging in both positive and negative directions. In such applications, the Op Amp requires two source voltages: one positive $(+V)$ and the other negative $(-V)$ with respect to ground or a common point. These dc source voltages must be well filtered and regulated; otherwise the Op amp's output voltage will vary with the power supply variations. The output voltage of an Op Amp varies more or less with power supply variations, depending on its closed-loop* voltage gain and sensitivity factor S which is usually specified on the manufacturer's data sheets. An ideal Op Amp has a sensitivity factor $S = 0$, which means that power supply voltage variations have no effect on its output. Practical Op Amps, however, are affected by changes in the supply voltages, and therefore regulated supplies are used to keep Op Amp outputs responsive to differential input voltages only.