CHAPTER 1

Op Amp Basics

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Within Chapter 1, discussions are focused on the basic aspects of op amps. After a brief introductory section, this begins with the fundamental *topology* differences between the two broadest classes of op amps, those using *voltage feedback* and *current feedback*. These two amplifier types are distinguished more by the nature of their internal circuit topologies than anything else. The voltage feedback op amp topology is the classic structure, having been used since the earliest vacuum tube based op amps of the 1940s and 1950s, through the first IC versions of the 1960s, and includes most op amp models produced today. The more recent IC variation of the current feedback amplifier has come into popularity in the mid-to-late 1980s, when higher speed IC op amps were developed. Factors distinguishing these two op amp types are discussed at some length.

Details of op amp input and output *structures* are also covered in this chapter, with emphasis on how such factors potentially impact application performance. In some senses, it is logical to categorize op amp types into performance and/or application classes, a process that works to some degree, but not altogether.

In practice, once past those obvious application distinctions such as “high speed” versus “precision,” or “single” versus “dual supply,” neat categorization breaks down. This is simply the way the analog world works. There is much crossover between various classes, i.e., a high speed op amp can be either single or dual-supply, or it may even fit as a precision type. A low power op amp may be precision, but it need not necessarily be single-supply, and so on. Other distinction categories could include the input stage type, such as FET input (further divided into JFET or MOS, which, in turn, are further divided into NFET or PFET and PMOS and NMOS, respectively), or bipolar (further divided into NPN or PNP). Then, all of these categories could be further described in terms of the type of input (or output) stage used.

So, it should be obvious that categories of op amps are like an infinite set of analog gray scales; *they don’t always fit neatly into pigeonholes, and we shouldn’t expect them to*. Nevertheless, it is still very useful to appreciate many of the aspects of op amp design that go into the various structures, as these differences directly influence the optimum op amp choice for an application. Thus structure differences are application drivers, since we choose an op amp to suit the nature of the application—for example, single-supply.

In this chapter various op amp performance *specifications* are also discussed, along with those specification differences that occur between the broad distinctions of voltage or current feedback topologies, as well as the more detailed context of individual structures. Obviously, op amp specifications are also application drivers; in fact, they are the most important since they will determine system performance. We choose the best op amp to fit the application, based on the required bias current, bandwidth, distortion, and so forth.

Introduction

Walt Jung

As a precursor to more detailed sections following, this introductory chapter portion considers the most basic points of op amp operation. These initial discussions are oriented around the more fundamental levels of op amp applications. They include: *Ideal Op Amp Attributes*, *Standard Op Amp Feedback Hookups, The Non-Ideal Op Amp, Op Amp Common-Mode Dynamic Range(s),* the various *Functionality Differences of Single and Dual-Supply Operation*, and the *Device Selection* process.

Before op amp applications can be developed, some requirements are in order. These include an understanding of how the fundamental op amp operating modes differ, and whether dual-supply or single-supply device functionality better suits the system under consideration. Given this, then device selection can begin and an application developed.

First, an *operational amplifier* (hereafter simply op amp) is a differential input, single-ended output amplifier, as shown symbolically in Figure 1-1. This device is an amplifier intended for use with *external feedback elements*, where these elements determine the resultant function, or *operation*. This gives rise to the name "operational amplifier," denoting an amplifier that, by virtue of different feedback hookups, can perform a variety of operations.[1] At this point, note that there is no need for concern with any actual technology to implement the amplifier. Attention is focused more on the behavioral nature of this building block device.

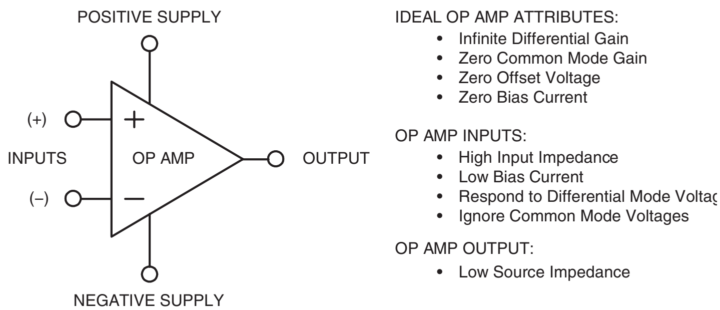

Figure 1-1: The ideal op amp and its attributes

An op amp processes small, differential mode signals appearing between its two inputs, developing a single-ended output signal referred to a power supply common terminal. Summaries of the various ideal op amp attributes are given in Figure 1-1. While real op amps will depart from these ideal attributes, it is very helpful for first-level understanding of op amp behavior to consider these features. Further, although these initial discussions talk in idealistic terms, they are also flavored by pointed mention of typical "real world" specifications—for a beginning perspective.

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[1] The actual *naming* of the operational amplifier occurred in the classic Ragazinni, et al paper of 1947 (see Reference 1). However, analog computations using op amps as we know them today began with the work of the Clarence Lovell-led group at Bell Labs, around 1940 (acknowledged generally in the Ragazinni paper).

It is also worth noting that this op amp is shown with five terminals, a number that happens to be a minimum for real devices. While some single op amps may have more than five terminals (to support such functions as frequency compensation, for example), none will ever have fewer. By contrast, those elusive ideal op amps don't require power, and symbolically function with just four pins.[2]

Ideal Op Amp Attributes

An ideal op amp has infinite gain for *differential* input signals. In practice, real devices will have quite high gain (also called *open-loop gain*) but this gain won't necessarily be precisely known. In terms of specifications, gain is measured in terms of V_{OUT}/V_{IN}, and is given in V/V, the dimensionless numeric gain. More often, however, gain is expressed in decibel terms (dB), which is mathematically dB = 20 • log (numeric gain). For example, a numeric gain of 1 million (10^6 V/V) is equivalent to a 120 dB gain. Gains of 100 dB – 130 dB are common for precision op amps, while high speed devices may have gains in the 60 dB – 70 dB range.

Also, an ideal op amp has zero gain for signals *common* to both inputs, that is, *common-mode* (CM) signals. Or, stated in terms of the rejection for these common-mode signals, an ideal op amp has infinite *CM rejection* (CMR). In practice, real op amps can have CMR specifications of up to 130 dB for precision devices, or as low as 60 dB–70 dB for some high speed devices.

The ideal op amp also has zero *offset voltage* ($V_{OS} = 0$), and draws zero *bias current* ($I_B = 0$) at both inputs. Within real devices, actual offset voltages can be as low as 1 µV or less, or as high as several mV. Bias currents can be as low as a few fA, or as high as several µA. This extremely wide range of specifications reflects the different input structures used within various devices, and is covered in more detail later in this chapter.

The attribute headings within Figure 1-1 for INPUTS and OUTPUT summarize the above concepts in more succinct terms. In practical terms, another important attribute is the concept of *low source impedance*, at the output. As will be seen later, low source impedance enables higher useful gain levels within circuits.

To summarize these idealized attributes for a signal processing amplifier, some of the traits might at first seem strange. However, it is critically important to reiterate that op amps simply are never intended for use without overall feedback. In fact, as noted, the connection of a suitable *external* feedback loop defines the *closed-loop* amplifier's gain and frequency response characteristics.

Note also that all real op amps have a positive and negative power supply terminal, but rarely (if ever) will they have a separate ground connection. In practice, the op amp output voltage becomes referred to a power supply common point. *Note: This key point is further clarified with the consideration of typically used op amp feedback networks.*

The basic op amp hookup of Figure 1-2 applies a signal to the (+) input, and a (generalized) network delivers a fraction of the output voltage to the (–) input terminal. This constitutes *feedback*, with the op amp operating in *closed-loop* fashion. The feedback network (shown here in general form) can be resistive or reactive, linear or nonlinear, or any combination of these. More detailed analysis will show that the circuit gain characteristic as a whole follows the inverse of the feedback network transfer function.

The concept of feedback is both an essential and salient point concerning op amp use. With feedback, the net closed-loop gain characteristics of a stage such as Figure 1-2 become primarily dependent upon a set of *external components* (usually passive). Thus behavior is less dependent upon the relatively unstable amplifier open-loop characteristics.

[2] Such an op amp generates its own power, has two input pins, an output pin, and an output common pin.

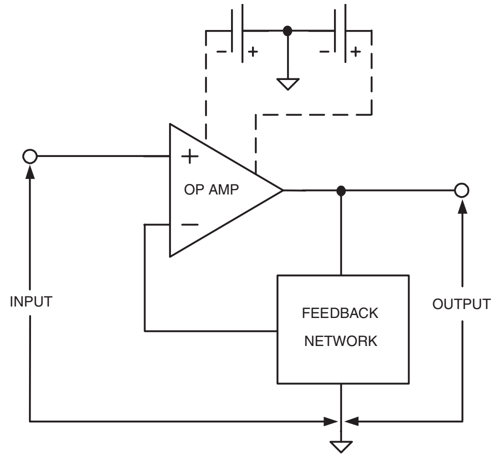

Figure 1-2: A generalized op amp circuit with feedback applied

Note that within Figure 1-2, the input signal is applied between the op amp (+) input and a *common* or *reference point*, as denoted by the ground symbol. It is important to note that this reference point is also common to the output and feedback network. By definition, the op amp stage's output signal appears between the output terminal/feedback network input, and this common ground. This single relevant fact answers the "Where is the op amp grounded?" question so often asked by those new to the craft. The answer is simply that it is grounded *indirectly*, by virtue of the commonality of its input, the feedback network, and the power supply, as is shown in Figure 1-2.

To emphasize how the input/output signals are referenced to the power supply, dual supply connections are shown dotted, with the ± power supply midpoint common to the input/output signal ground. But do note, while all op amp application circuits may not show full details of the power supply connections, every *real* circuit will always use power supplies.

Standard Op Amp Feedback Hookups

Virtually all op amp feedback connections can be categorized into just a few basic types. These include the two most often used, *noninverting* and *inverting* voltage gain stages, plus a related *differential* gain stage. Having discussed above just the attributes of the ideal op amp, at this point it is possible to conceptually build basic gain stages. Using the concepts of infinite gain, zero input offset voltage, zero bias current, and so forth, standard op amp feedback hookups can be devised. For brevity, a full mathematical development of these concepts isn't included here (but this follows in a subsequent section). The end-of-section references also include such developments.

The Noninverting Op Amp Stage

The op amp noninverting gain stage, also known as a *voltage follower with gain*, or simply *voltage follower*, is shown in Figure 1-3.

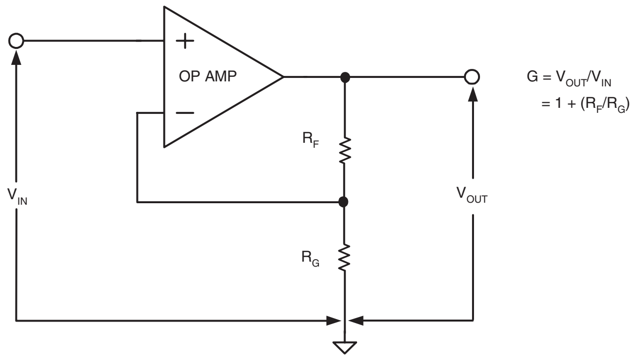

Figure 1-3: The noninverting op amp stage (voltage follower)

This op amp stage processes the input V_{IN} by a gain of G, so a generalized expression for gain is:

$$G = \frac{V_{OUT}}{V_{IN}} \qquad \text{Eq. 1-1}$$

Feedback network resistances R_F and R_G set the stage gain of the follower. For an ideal op amp, the gain of this stage is:

$$G = \frac{R_F + R_G}{R_G} \qquad \text{Eq. 1-2}$$

For clarity, these expressions are also included in the figure. Comparison of this figure and the more general Figure 1-2 shows R_F and R_G here as a simple feedback network, returning a fraction of V_{OUT} to the op amp (–) input. *(Note that some texts may show the more general symbols Z_F and Z_G for these feedback components—both are correct, depending upon the specific circumstances.)*

In fact, we can make some useful general points about the network $R_F – R_G$. We will define the transfer expression of the network as seen from the top of R_F to the output across R_G as β. Note that this usage is a general feedback network transfer term, *not* to be confused with bipolar transistor forward gain. β can be expressed mathematically as:

$$\beta = \frac{R_G}{R_F + R_G} \qquad \text{Eq. 1-3}$$

So, the feedback network returns a fraction of V_{OUT} to the op amp (–) input. Considering the ideal principles of zero offset and infinite gain, this allows some deductions on gain to be made. The voltage at the (–) input is forced by the op amp's feedback action to be equal to that seen at the (+) input, V_{IN}. Given this relationship, it is relatively easy to work out the ideal gain of this stage, which in fact turns out to be simply the inverse of β. This is apparent from a comparison of Eqs. 1-2 and 1-3.

Thus an ideal noninverting op amp stage gain is simply equal to 1/β, or:

$$G = \frac{1}{\beta} \qquad \text{Eq. 1-4}$$

This noninverting gain configuration is one of the most useful of all op amp stages, for several reasons. Because V_{IN} sees the op amp's high impedance (+) input, it provides an ideal interface to the driving source. Gain can easily be adjusted over a wide range via R_F and R_G, with virtually no source interaction.

A key point is the interesting relationship concerning R_F and R_G. Note that to satisfy the conditions of Eq. 1-2, only their *ratio* is of concern. In practice this means that stable gain conditions can exist over a range of actual $R_F - R_G$ values, so long as they provide the same ratio.

If R_F is taken to zero and R_G open, the stage gain becomes unity, and V_{OUT} is then exactly equal to V_{IN}. This special noninverting gain case is also called a *unity gain follower*, a stage commonly used for buffering a source.

Note that this op amp example shows only a simple resistive case of feedback. As mentioned, the feedback can also be reactive, i.e., Z_F, to include capacitors and/or inductors. In all cases, however, it must include a dc path, if we are to assume the op amp is being biased by the feedback (which is usually the case).

To summarize some key points on op amp feedback stages, we paraphrase from Reference 2 the following statements, which will always be found useful:

> *The* summing point *idiom is probably the most used phrase of the aspiring analog artificer, yet the least appreciated. In general, the inverting (−) input is called the* summing point, *while the noninverting (+) input is represented as the* reference terminal. *However, a vital concept is the fact that, within linear op amp applications,* the inverting input (or summing point) assumes the same absolute potential as the noninverting input or reference (within the gain error of the amplifier). *In short, the amplifier tries to servo its own summing point to the reference.*

The Inverting Op Amp Stage

The op amp inverting gain stage, also known simply as the *inverter*, is shown in Figure 1-4. As can be noted by comparison of Figures 1-3 and 1-4, the inverter can be viewed as similar to a follower, but with a transposition of the input voltage V_{IN}. In the inverter, the signal is applied to R_G of the feedback network and the op amp (+) input is grounded.

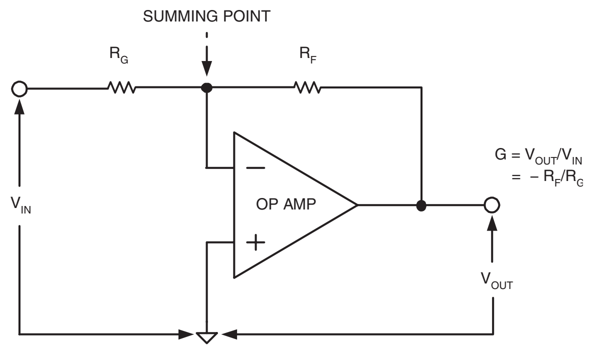

Figure 1-4: The inverting op amp stage (inverter)

The feedback network resistances R_F and R_G set the stage gain of the inverter. For an ideal op amp, the gain of this stage is:

$$G = -\frac{R_F}{R_G} \qquad \text{Eq. 1-5}$$

For clarity, these expressions are again included in the figure. Note that a major difference between this stage and the noninverting counterpart is the input-to-output sign reversal, denoted by the minus sign in Eq. 1-5. Like the follower stage, applying ideal op amp principles and some basic algebra can derive the gain expression of Eq. 1-5.

The inverting configuration is also one of the more useful op amp stages. Unlike a noninverting stage, however, the inverter presents a relatively low impedance input for V_{IN}, i.e., the value of R_G. This factor provides a finite load to the source. While the stage gain can in theory be adjusted over a wide range via R_F and R_G, there is a practical limitation imposed at high gain, when R_G becomes relatively low. If R_F is zero, the gain becomes zero. R_F can also be made variable, in which case the gain is linearly variable over the dynamic range of the element used for R_F. As with the follower gain stage, the gain is ratio dependent, and is relatively insensitive to the exact R_F and R_G values.

The inverter's gain behavior, due to the principles of infinite op amp gain, zero input offset, and zero bias current, gives rise to an effective node of zero voltage at the (–) input. The input and feedback currents sum at this point, which logically results in the term *summing point*. It is also called a *virtual ground*, because of the fact it will be at the same potential as the grounded reference input.

Note that, technically speaking, *all* op amp feedback circuits have a summing point, whether they are inverters, followers, or a hybrid combination. The summing point is always the feedback junction at the (–) input node, as shown in Figure 1-4. However in follower type circuits this point isn't a virtual ground, since it follows the (+) input.

A special gain case for the inverter occurs when $R_F = R_G$, which is also called a *unity gain inverter*. This form of inverter is commonly used for generating complementary V_{OUT} signals, i.e., $V_{OUT} = -V_{IN}$. In such cases it is usually desirable to match R_F to R_G accurately, which can readily be done by using a well-specified matched resistor pair.

A variation of the inverter is the *inverting summer*, a case similar to Figure 1-4, but with input resistors R_{G2}, R_{G3}, etc (not shown). For a summer individual input resistors are connected to additional sources V_{IN2}, V_{IN3}, and so forth, with their common node connected to the summing point. This configuration, called a *summing amplifier*, allows linear input current summation in R_F.[3] V_{OUT} is proportional to an inverse sum of input currents.

The Differential Op Amp Stage

The op amp differential gain stage (also known as a *differential amplifier*, or *subtractor*) is shown in Figure 1-5.

Paired input and feedback network resistances set the gain of this stage. These resistors, R_F–R_G and R_F'–R_G', *must be matched as noted,* for proper operation. Calculation of individual gains for inputs V_1 and V_2 and their linear combination derives the stage gain.

[3] The very first general-purpose op amp circuit is described by Karl Swartzel in Reference 3, and is titled "Summing Amplifier." This amplifier became a basic building block of the M9 gun director computer and fire control system used by Allied Forces in World War II. It also influenced many vacuum tube op amp designs that followed over the next two decades.

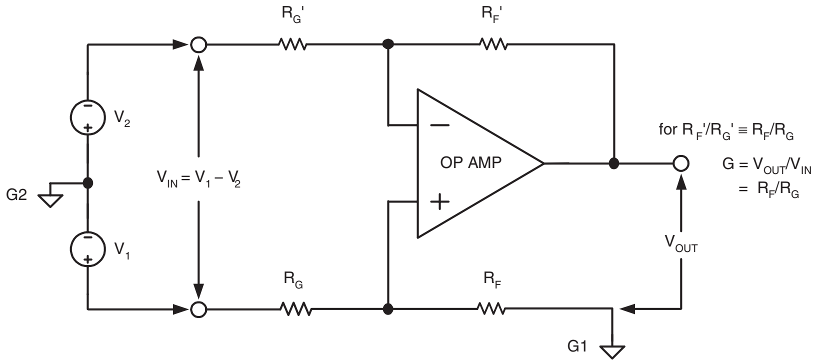

Figure 1-5: The differential amplifier stage (subtractor)

Note that the stage is intended to amplify the *difference* of voltages V_1 and V_2, so the net input is $V_{IN} = V_1 – V_2$. The general gain expression is then:

$$G = \frac{V_{OUT}}{V_1 - V_2} \qquad \text{Eq. 1-6}$$

For an ideal op amp and the resistor ratios matched as noted, the gain of this differential stage from V_{IN} to V_{OUT} is:

$$G = \frac{R_F}{R_G} \qquad \text{Eq. 1-7}$$

The great fundamental utility that an op amp stage such as this allows is the property of rejecting voltages *common* to $V_1–V_2$, i.e., common-mode (CM) voltages. For example, if noise voltages appear between grounds G1 and G2, the noise will be suppressed by the common-mode rejection (CMR) of the differential amp. The CMR however is only as good as the matching of the resistor ratios allows, so in practical terms it implies precisely trimmed resistor ratios are necessary. Another disadvantage of this stage is that the resistor networks load the $V_1–V_2$ sources, potentially leading to additional errors.

The Nonideal Op Amp—Static Errors Due to Finite Amplifier Gain

One of the most distinguishing features of op amps is their staggering magnitude of dc voltage gain. Even the least expensive devices have typical voltage gains of 100,000 (100 dB), while the highest performance precision bipolar and chopper stabilized units can have gains as high as 10,000,000 (140 dB), or more. Negative feedback applied around this much voltage gain readily accomplishes the virtues of closed-loop performance, making the circuit dependent only on the feedback components.

As noted above in the discussion of ideal op amp attributes, the behavioral assumptions follow from the fact that negative feedback, coupled with high open-loop gain, constrains the amplifier input error voltage (and consequently the error current) to infinitesimal values. The higher this gain, the more valid these assumptions become.

In reality, however, op amps *do* have finite gain and errors exist in practical circuits. The op amp gain stage of Figure 1-6 will be used to illustrate how these errors impact performance. In this circuit the op amp is ideal except for the finite open-loop dc voltage gain, A, which is usually stated as A_{VOL}.

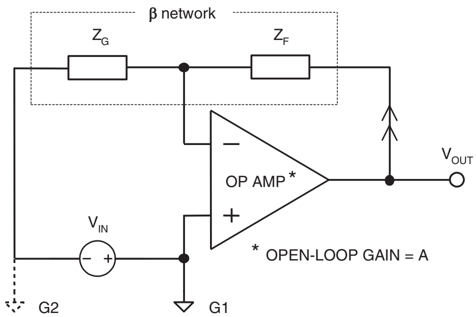

Figure 1-6: Nonideal op amp stage for gain error analysis

Noise Gain (NG)

The first aid to analyzing op amps circuits is to differentiate between *noise gain* and *signal gain*. We have already discussed the differences between noninverting and inverting stages as to their signal gains, which are summarized in Eqs. 1-2 and 1-4, respectively. But, as can be noticed from Figure 1-6, the difference between an inverting and noninverting stage can be as simple as where the reference ground is placed. For a ground at point G1, the stage is an inverter; conversely, if the ground is placed at point G2 (with no G1) the stage is noninverting.

Note, however, that in terms of the feedback path, *there are no real differences*. To make things more general, the resistive feedback components previously shown are replaced here with the more general symbols Z_F and Z_G, otherwise they function as before. The feedback attenuation, β, is the same for both the inverting and noninverting stages:

$$\beta = \frac{Z_G}{Z_G + Z_F} \qquad \text{Eq. 1-8}$$

Noise gain can now be simply defined as: *The inverse of the net feedback attenuation from the amplifier output to the feedback input*. In other words, the inverse of the β network transfer function. This can ultimately be extended to include frequency dependence (covered later in this chapter). Noise gain can be abbreviated as NG.

As noted, the inverse of β is the ideal noninverting op amp stage gain. Including the effects of finite op amp gain, a modified gain expression for the noninverting stage is:

$$G_{CL} = \frac{1}{\beta} \times \left[\frac{1}{1 + \frac{1}{A_{VOL}\beta}} \right] \qquad \text{Eq. 1-9}$$

where G_{CL} is the finite-gain stage's closed-loop gain, and A_{VOL} is the op amp open-loop voltage gain for loaded conditions.

It is important to note that this expression is identical to the ideal gain expression of Eq. 1-4, with the addition of the bracketed multiplier on the right side. Note also that this right-most term becomes closer and closer to unity, as A_{VOL} approaches infinity. Accordingly, it is known in some textbooks as the *error multiplier* term, when the expression is shown in this form.[4]

It may seem logical here to develop another finite gain error expression for an inverting amplifier, but in actuality there is no need. Both inverting and noninverting gain stages have a common feedback basis, which is the noise gain. So Eq. 1-9 will suffice for gain error analysis for both stages. Simply use the β factor as it applies to the specific case.

It is useful to note some assumptions associated with the rightmost error multiplier term of Eq. 1-9. For $A_{VOL}\beta >> 1$, one assumption is:

$$\frac{1}{1+\frac{1}{A_{VOL}\beta}} \approx 1-\frac{1}{A_{VOL}\beta} \qquad \text{Eq. 1-10}$$

This in turn leads to an estimation of the percentage error, ε, due to finite gain A_{VOL}:

$$\varepsilon(\%) \approx \frac{100}{A_{VOL}\beta} \qquad \text{Eq. 1-11}$$

Gain Stability

The closed-loop gain error predicted by these equations isn't in itself tremendously important, since the ratio Z_F/Z_G could always be adjusted to compensate for this error.

But note however that closed-loop gain *stability* is a very important consideration in most applications. Closed-loop gain instability is produced primarily by variations in open-loop gain due to changes in temperature, loading, and so forth.

$$\frac{\Delta G_{CL}}{G_{CL}} \approx \frac{\Delta A_{VOL}}{A_{VOL}} \times \frac{1}{A_{VOL}\beta} \qquad \text{Eq. 1-12}$$

From Eq. 1-12, any variation in open-loop gain (ΔA_{VOL}) is reduced by the factor $A_{VOL}\beta$, insofar as the effect on closed-loop gain. This improvement in closed-loop gain stability is one of the important benefits of negative feedback.

Loop Gain

The product $A_{VOL}\beta$, which occurs in the above equations, is called *loop gain*, a well-known term in feedback theory. The improvement in closed-loop performance due to negative feedback is, in nearly every case, proportional to loop gain.

The term "loop gain" comes from the method of measurement. This is done by breaking the closed feedback loop at the op amp output, and measuring the total gain around the loop. In Figure 1-6 for example, this could be done between the amplifier output and the feedback path (see arrows). To a first

[4] Some early discussions of this finite gain error appear in References 4 and 5. Terman uses the open-loop gain symbol of A, as we do today. West uses Harold Black's original notation of μ for open-loop gain. The form of Eq. 1-9 is identical to Terman's (or to West's, substituting μ for A).

approximation, closed-loop output impedance, linearity error, and gain instability are all reduced by $A_{VOL}\beta$ with the use of negative feedback.

Another useful approximation is developed as follows. A rearrangement of Eq. 1-9 is:

$$\frac{A_{VOL}}{G_{CL}} = 1 + A_{VOL}\beta \qquad \text{Eq. 1-13}$$

So, for high values of $A_{VOL}\beta$,

$$\frac{A_{VOL}}{G_{CL}} \approx A_{VOL}\beta \qquad \text{Eq. 1-14}$$

Consequently, in a given feedback circuit the loop gain, $A_{VOL}\beta$, is approximately the numeric ratio (or difference, in dB) of the amplifier open-loop gain to the circuit closed-loop gain.

This loop gain discussion emphasizes that, indeed, loop gain is a very significant factor in predicting the performance of closed-loop operational amplifier circuits. The open-loop gain required to obtain an adequate amount of loop gain will, of course, depend on the desired closed-loop gain.

For example, using Eq. 1-14, an amplifier with A_{VOL} = 20,000 will have an $A_{VOL}\beta \approx 2000$ for a closed-loop gain of 10, but the loop gain will be only 20 for a closed-loop gain of 1000. The first situation implies an amplifier-related gain error on the order of ≈ 0.05%, while the second would result in about 5% error. Obviously, the higher the required gain, the greater will be the required open-loop gain to support an $A_{VOL}\beta$ for a given accuracy.

Frequency Dependence of Loop Gain

Thus far, it has been assumed that amplifier open-loop gain is independent of frequency. Unfortunately, this isn't the case. Leaving the discussion of the effect of open-loop response on bandwidth and dynamic errors until later, let us now investigate the general effect of frequency response on loop gain and static errors.

The open-loop frequency response for a typical operational amplifier with superimposed closed-loop amplifier response for a gain of 100 (40 dB), illustrates graphically these results in Figure 1-7. In these Bode plots, subtraction on a logarithmic scale is equivalent to normal division of numeric data.[5] Today, op amp open-loop gain and loop gain parameters are typically given in dB terms, thus this display method is convenient.

A few key points evolve from this graphic figure, which is a simulation involving two hypothetical op amps, both with a dc/low frequency gain of 100 dB (100 kV/V). The first has a gain-bandwidth of 1 MHz, while the gain-bandwidth of the second is 10 MHz.

- The open-loop gain A_{VOL} for the two op amps is noted by the two curves marked 1 MHz and 10 MHz, respectively. Note that each has a –3 dB corner frequency associated with it, above which the open-loop gain falls at 6 dB/octave. These corner frequencies are marked at 10 Hz and 100 Hz, respectively, for the two op amps.
- At any frequency on the open-loop gain curve, the numeric product of gain A_{VOL} and frequency, f, is a constant (10,000 V/V at 100 Hz equates to 1 MHz). This, by definition, is characteristic of a constant gain-bandwidth product amplifier. All *voltage feedback* op amps behave in this manner.

[5] The log-log displays of amplifier gain (and phase) versus frequency are called *Bode* plots. This graphic technique for display of feedback amplifier characteristics, plus definitions for feedback amplifier stability were pioneered by Hendrick W. Bode of Bell Labs (see Reference 6).