Frequency response errors in voltage feedback op amps

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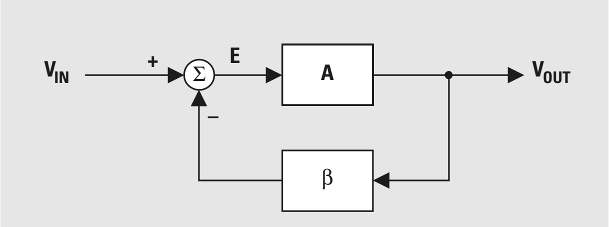
Introduction

An article entitled “Matching operational amplifier bandwidth with applications” appeared in the February 2000 issue of *Analog Applications Journal*. It attempted to analyze errors incurred when op amps are operated on the decreasing portion of the bandwidth curve, but a small mistake confused the explanation. This article focuses on the error analysis, so each equation is analyzed in detail. Further, the error analysis is completed for the inverting and non-inverting op amp configurations; thus the error function is analyzed as a function of circuit configuration as well as frequency.

Figure 1. Basic feedback loop



Feedback theory

The basic feedback circuit is shown in Figure 1, where E is the error voltage, β is the feedback factor, and A is the forward gain. Equations 1 and 2 govern the circuit performance.

$$V_{OUT} = EA \quad (1)$$

$$E = V_{IN} - \beta V_{OUT} \quad (2)$$

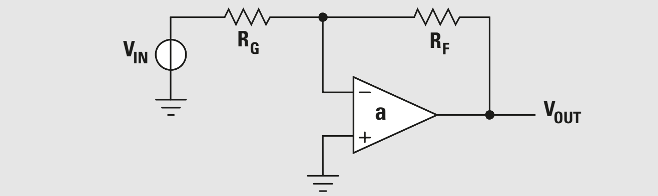
The accuracy equation (Equation 3) and closed-loop gain equation (Equation 4) are obtained by combining Equations 1 and 2.

$$\frac{E}{V_{IN}} = \frac{1}{1 + A\beta} \quad (3)$$

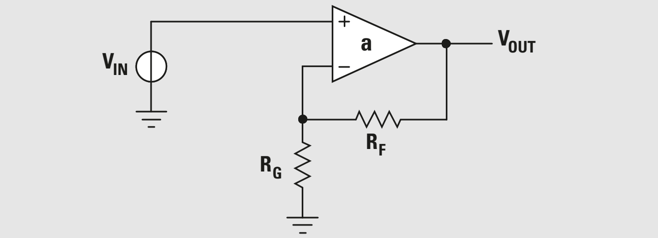
$$\frac{V_{OUT}}{V_{IN}} = \frac{A}{1 + A\beta} \quad (4)$$

The quantity Aβ appears in both equations and is called loop gain because it has a special significance in feedback circuits. The loop gain determines the stability of a feedback circuit as shown in Equation 4 (instability or oscillation occurs when $A\beta = -1$), and it determines accuracy as shown in Equation 3. Accuracy and stability are inversely related—i.e., stability decreases as accuracy increases, and vice versa. The loop gain is calculated with the voltage inputs grounded (current inputs open), so the input signal and its insertion point (plus or minus input) have no effect on the loop gain. This means that the loop gain for a non-inverting, inverting, or differential op amp circuit is the same. Three op amp circuits are shown in Figure 2, and the loop gain for all three circuits is given in Equation 5.

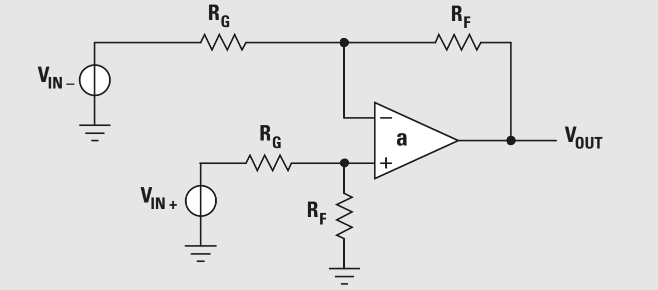
Figure 2. Op amp circuits



(a) Inverting Op Amp



(b) Non-inverting Op Amp



(c) Differential Op Amp

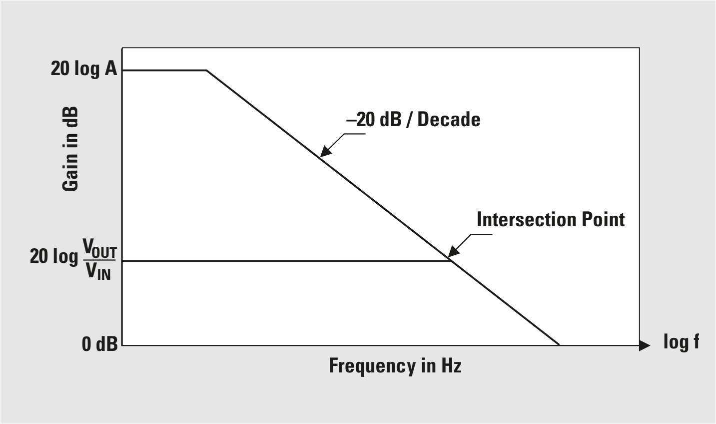
$$A\beta = \frac{aR_G}{R_F + R_G} \tag{5}$$

The parameter "a" is the open-loop gain of the op amp and is often confused with the forward gain "A" in the basic feedback circuit (see Figure 1). The op amp's open-loop gain, a, decreases with frequency and is included in the forward gain, A; hence the error increases with frequency, as indicated by Equation 3. A more in-depth analysis of stability and feedback is found in References 1 and 2.

Equation 6 is the log of Equation 4 and is plotted in Figure 3.

$$20\log\left(\frac{V_{OUT}}{V_{IN}}\right) = 20\log(A) - 20\log(1 + A\beta) \tag{6}$$

Figure 3. Plot of op amp equation



The plot of Equation 6 assumes that one pole is contained in the forward gain; thus the forward gain rolls off with a slope of –20 dB/decade. If more poles are included in the forward gain, the curve rolls off faster. The closed-loop gain is constant until it intersects the forward-gain curve, then it follows the forward-gain curve down at a –1 slope (–20 dB/decade). The closed-loop gain is down –3 dB at the apparent intersection of the curves shown in Figure 3, but we never work close to the intersection because the error is too big at the intersection frequency. The difference between curves in Figure 3 is 20 log(1+Aβ) as defined in Equation 6. The β portion of the loop gain does not vary with a frequency change because it is resistive (at least in this example), but the op amp gain contains a pole making it responsible for the gain roll-off. Setting the input signal equal to 1 V normalizes the error voltage at E = 1/ (1+Aβ); and, under these conditions, the loop gain determines the error caused by the decreasing amplifier gain.

The open-loop gain plot of the TLV247x op amp is shown in Figure 4. This is a plot of the op amp's typical open-loop gain characteristics. In an attempt to relate this curve to a data-sheet specification, we will calculate the dc intercept of the differential voltage gain (DVG). The typical DVG curve given in the data sheet does not show the low-frequency data; thus we must reconstruct the curve at its dc intercept. From Figure 4 we observe that the DVG at 100 Hz is approximately 87 dB; the slope in the linear portion of the curve is –20 dB/decade (–6 dB/octave); and, if we back up one decade to 10 Hz, the DVG is 87 + 20 = 107 dB. If we now back up an octave to 5 Hz, the DVG is 107 + 6 = 113 dB. The large signal differential voltage amplification (AVD) is specified on the data sheet as 116 dB typical at dc. The two specifications match up fairly well because DVG = 113 dB at 5 Hz, so we accept the data-sheet typical value of op amp open-loop gain equal to 116 dB. The AVD guaranteed minimum specification is 90 dB; hence the typical curve is reduced by 116 dB – 90 dB = 26 dB to turn Figure 4 into a guaranteed curve—i.e., 107 – 26 = 81 dB at f = 10 Hz. The data for the new curve is given in Table 1.

Figure 4. Open-loop gain plot of the TLV247x

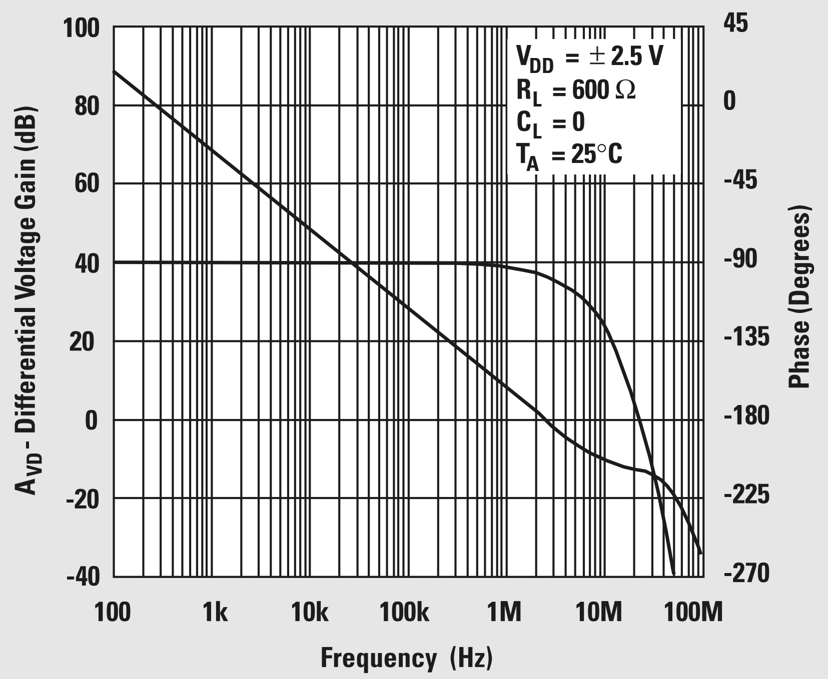


Table 1. Guaranteed minimum bandwidth of TLV247x

FREQUENCY (Hz)	GAIN (dB)
10	81
100	61
1000	41
10,000	21
100,000	01

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Non-inverting op amp

The non-inverting closed-loop gain is

$$\frac{V_{OUT}}{V_{IN}} = \frac{A}{1+A\beta} = \frac{a}{1+\frac{aR_G}{R_F+R_G}}. \tag{7}$$

When the op amp is used in the non-inverting circuit configuration, the forward gain, A, equals the op amp open-loop gain, a. In Equation 8, 20 log(1+Aβ) is calculated for the following conditions: the closed-loop gain is 2 (6 dB), the input signal is 10 Hz, and 20 log(a) = 81 dB. The error is calculated in Equation 9; notice that 1 is negligible compared to a very high aβ, and 20 log(1+Aβ) = 20 log(1+aβ).

$$\begin{aligned} 20\log(1+a\beta) &= 20\log(a) - 20\log\left(\frac{V_{OUT}}{V_{IN}}\right) \\ &= 81\text{ dB} - 6\text{ dB} = 75\text{ dB} \end{aligned} \tag{8}$$

$$E = \frac{1}{1+a\beta} = \frac{1}{10^{\frac{dB}{20}}} = \frac{1}{10^{\frac{75}{20}}} = \frac{1}{5623.4} = 0.1778\text{ mV} \tag{9}$$

If the closed-loop gain is changed to 10 (20 dB) for an input signal of 10 Hz, then 20 log(1+Aβ) = 61 dB, and the error is 0.89 mV. Notice that the error, E, increases as the closed-loop gain increases because the loop gain decreases when the closed-loop gain increases. When the closed-loop gain is kept constant at 20 dB and the input signal frequency is increased to 1000 Hz, the error increases to 89.1 mV. Notice that the error increases as the signal frequency increases because the op amp gain decreases with increasing frequency. If oscilloscope probes are placed across the inputs of an op amp, the differential voltage observed is the error voltage, and one can observe the error voltage increase as the signal frequency is increased.

Inverting op amp

The inverting closed-loop gain is

$$\frac{V_{OUT}}{V_{IN}} = \frac{A}{1+A\beta} = \frac{\frac{-aR_F}{R_F+R_G}}{1+\frac{aR_G}{R_F+R_G}}. \tag{10}$$

The inverting op amp circuit's forward gain does not equal the op amp open-loop gain; rather, it is modified by a combination of the gain setting resistors. When the closed-loop gain is 2 (6 dB), $R_F = 2R_G$. The circuit's forward gain, A, is

$$|A| = \left|\frac{aR_F}{R_F+R_G}\right| = \left|\frac{a2R_G}{2R_G+R_G}\right| = \frac{2a}{3}. \tag{11}$$

The op amp open-loop gain at f = 10 Hz is

$$a = 10^{\frac{81}{20}} = 10^{4.05} = 11{,}220.2. \tag{12}$$

The op amp open-loop gain is reduced by the two-thirds factor to obtain the forward gain:

$$A = \frac{2a}{3} = \frac{2(11{,}220.2)}{3} = 7480.1. \tag{13}$$

Then the forward gain is converted back to dB:

$$A = 20\log(7480.1) = 77.48\text{ dB}. \tag{14}$$

Equation 6 is repeated in Equation 15, where 20 log(1+Aβ) is calculated for a closed-loop gain of 2 (6 dB) and an input signal of 10 Hz.

$$20\log(1+A\beta) = 77.48\text{ dB} - 6\text{ dB} = 71.48\text{ dB}. \tag{15}$$

The error is given by

$$E = \frac{1}{1+A\beta} = \frac{1}{10^{\frac{dB}{20}}} = \frac{1}{10^{\frac{71.48}{20}}} = \frac{1}{3749.7} = 0.266\text{ mV}. \tag{16}$$

Because the forward gain is decreased by the closed-loop gain, the error for the inverting op amp—at the same closed-loop gain and input signal frequency—is higher than it is for the non-inverting op amp. The error is calculated for a closed-loop gain of 10 (20 dB and $R_F = 10R_G$); and an input signal of 10 Hz is calculated in the following equations.

$$|A| = \left|\frac{aR_F}{R_F+R_G}\right| = \left|\frac{a10R_G}{10R_G+R_G}\right| = \frac{10a}{11} \tag{17}$$

$$A = \frac{10a}{11} = \frac{10(11{,}220.2)}{11} = 10020 \tag{18}$$

$$A = 20\ \log(10020) = 80.02\ \text{dB} \tag{19}$$

$$20\log(1+A\beta) = 80.02\text{ dB} - 20\text{ dB} = 60.02\text{ dB} \tag{20}$$

$$E = \frac{1}{1+A\beta} = \frac{1}{10^{\frac{dB}{20}}} = \frac{1}{10^{\frac{60.02}{20}}} = \frac{1}{1002.3} = 0.9977\text{ mV} \tag{21}$$

Again, the error increases as the closed-loop gain increases, and the error will increase when the input signal frequency increases.

Measurements

Error voltages are hard to measure at low frequencies because they are very small voltages, thus error measurements are taken at higher frequencies. When two error measurements are separated by a frequency decade they should have a voltage difference of 20 dB, and this voltage difference acts as a check on the measurement technique. Instrumentation is kept at a minimum in these measurements so they can be easily repeated.

Configure the subject op amp as an inverting amplifier as shown in Figure 2a, with a gain of one ($R_F = R_G$). Set the input voltage to 1 V, and measure the voltage from the inverting input to ground. The measured error voltages are E = 2.83 mV at f_{IN} = 10 kHz and E = 28.3 mV at f_{IN} = 100 kHz. The error voltages differ by a factor of 10; thus the slope of the forward-gain curve is –20 dB/decade. Obtaining the correct slope indicates that the error measurements are probably correct. Equation 22 calculates the quantity (1+Aβ) at the 100-kHz input frequency.

$$(1+A\beta) = \frac{1}{E} = \frac{1}{0.0283} = 35.33 \tag{22}$$

Equation 23 takes the log of Equation 22.

$$20\log(35.33) = 31\text{ dB} \qquad \textbf{(23)}$$

For very large values of A, $V_{OUT}/V_{IN} = 1/\beta$; thus $20\log(V_{OUT}/V_{IN}) = 20\log(1) = 0$. Equation 6 reduces to Equation 24 when $\beta = 1$ and A is very large.

$$20\log(A) = 20\log(1 + A\beta) = 31\text{ dB} \qquad \textbf{(24)}$$

Equation 25 relates the forward gain to the op amp gain.

$$A = \frac{aR_F}{R_F + R_G} = \frac{aR_F}{R_F + R_F} = \frac{a}{2} \qquad \textbf{(25)}$$

$$a = 2A = 2(31\text{ dB}) = 6\text{ dB} + 31\text{ dB} = 37\text{ dB} \qquad \textbf{(26)}$$

Three values for op amp open-loop gain (f_{IN} = 100 kHz) have been taken from a data-sheet curve, calculated, and measured; and these values are given in Table 2.

Table 2. Comparison of op amp open-loop gains

HOW OBTAINED	a (dB)
Data sheet curve	27
Worst-case calculation	01
Measurement and calculation	37

The measured data supports the data-sheet typical curves much better than does the calculated worst case data. The measured error voltages of several op amps ranged from 32 mV to 26 mV, so this batch of op amps has much higher than nominal gain (10 dB higher). Since this will not always be the case, it is prudent to design with the worst-case specifications developed in Table 1.

Conclusions

The first conclusion is that the error increases at higher input-signal frequencies. This is because the gain bandwidth is constant in voltage-feedback op amps.

The second conclusion is that the non-inverting circuit configuration has less error than the inverting circuit configuration, and the error difference is greater at low closed-loop gains.

The third conclusion is that the error in a differential amplifier circuit constructed with a single op amp is different for the inverting and non-inverting inputs. This difference causes some of the common-mode input voltage to feed through to the output as a differential error voltage. The inverting and non-inverting input impedances are different in a single op amp differential amplifier; and this, coupled with the single op amp error amplification, precludes use of the single op amp differential amplifier in demanding applications. Multiple op amp differential amplifiers or instrumentation amplifiers are used in the demanding applications.

There is phase shift associated with the amplifier gain, a, and these calculations have neglected that phase shift for clarity's sake. The error introduced by neglecting the feedback phase shift is small and usually negligible except near the intersection point (Figure 3), but the error at that point is so large that very few people operate an op amp there.

References

For TI information related to this article, you can download an Acrobat Reader file at www-s.ti.com/sc/techlit/*litnumber* and replace *"litnumber"* with the **TI Lit. #** for the following document.

Document Title	**TI Lit. #**
1. "Feedback Amplifier Analysis Tools," Application Report	sloa017
2. "Stability Analysis of Voltage-Feedback Op Amps Including Compensation Techniques," Application Report	sloa020
3. "Current Feedback Amplifier Analysis and Compensation," Application Report	sloa021

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