Matching operational amplifier bandwidth with applications

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Introduction
Selecting the correct op amp for an application requires investigation of many different parameters. Voltage offset, bias currents and similar parameters are easy to evaluate because they are DC parameters that do not vary with frequency. Accuracy, on the other hand, is hard to specify and comply with because it is a function of frequency; hence, accuracy specifications involve the knowledge of frequency-dependent feedback circuits that are bandwidth-dependent.

The bandwidth (BW) problem is complicated by the op amp’s feedback because it hides decreasing BW until accuracy problems become apparent. If op amps had a constant open-loop gain, the accuracy of an op amp circuit would remain constant. The open-loop gain of any op amp decreases with increasing frequency. Except for a phenomenon called “peaking,” all op amps lose accuracy at high frequencies. The designer’s problem is selecting an op amp that has an acceptable accuracy loss at the frequencies of interest. Proper analysis of this problem requires an understanding of feedback, loop gain, and frequency dependence.

Preserving the signal integrity or accuracy during amplification is an essential part of the design, but in order to preserve the signal one must define the signal. Defining the signal sounds like a simple task, but it is complicated and must be performed in several different ways. Various methods used for defining the frequency content of the signal are examined in detail in this article because no single method works for every case.

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

$$V_{OUT} = EA$$

$$E = V_{IN} - \beta V_{OUT} = V_{IN} - \beta EA$$

The accuracy equation (Equation 3) is obtained by combining Equations 1 and 2.

$$\frac{E}{V_{IN}} = -\frac{1}{1 + A\beta}$$

Equation 4, which is the circuit gain, is also obtained from Equations 1 and 2 and is shown for completeness.

$$\frac{V_{OUT}}{V_{IN}} = \frac{A}{1 + A\beta}$$

The quantity $A\beta$ 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 occurs when $A\beta = -1$), and it determines the 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 position (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 is the same.

Three op amp circuits are shown in Figure 2, and the loop gain for all circuits is given in Equation 5.

$$A\beta = \frac{aR_G}{R_I + R_G}$$

The parameter “$a$” is the open-loop gain of the op amp, and it is often confused with the forward gain, “$A$.” The op amp open-loop gain decreases with frequency, hence the error increases with frequency, as Equation 3 illustrates.

A more in-depth analysis of stability and feedback is found in References 1, 2, and 3.

Defining a signal to determine its BW
The simplest case exists when the amplifier circuit specifications are included in the system specifications or given to the amplifier designer. A good amplifier specification shows the low-frequency gain at one frequency and the high-frequency gain at a second frequency. Sometimes the rate of the gain decrease (gain roll-off) is specified in dB/decade.

When a complex signal is applied to the amplifier input, and only a distortion or fidelity specification is given, the systems designer has passed the signal definition problem to the circuit designer. The circuit designer must determine what portion of the signal can be sacrificed because of loop gain reduction (“$a$” decreases with frequency) while meeting the distortion or fidelity specification. The first step in this procedure is to divide the signal into segments and analyze each segment using a Fourier series. An arbitrary maximum frequency is chosen; frequencies exceeding the maximum frequency are discarded, and the signal is reconstructed from the remnants. If the signal meets the specification,
the maximum frequency equals the BW requirement. If the signal does not meet the specification, a new maximum frequency is chosen and this procedure is repeated until the required distortion or fidelity specification is met.

Computer programs best implement the Fourier series procedure, but the procedure is complicated and laborious, so many engineers take the easy path of looking at test results. It is common for engineers to use the video screen or data error rate to evaluate amplifiers. They will solder the test units into working circuit boards and evaluate the video op amp performance by observing the screen. Likewise, data transmission amplifiers are often evaluated by in-circuit testing. The Fourier procedure must be used in many designs because in-circuit testing does not allow for manufacturing tolerances, it is not as accurate as the Fourier procedure, and it is hard to use where the results are not easily observable.

At this point it may seem that the easiest and safest path is to select an op amp with a BW much larger than required, but that isn’t an option in most cases because extra BW is costly and amplifies noise. The extra cost is prohibitive in multiple op amp or high-volume applications; thus, in-circuit testing or Fourier series analysis is used to evaluate the BW requirements of op amps. Extra BW can’t multiply the signal, and “Murphy’s Law” guarantees that it will multiply noise. When the only op amp that fits the BW requirement has extra BW, the designer should consider putting a passive filter in the signal chain to limit the noise passed by the system.

There is an extra requirement imposed on op amps that are used in active filter circuits. These op amp must have adequate BW to support the signal and to function as an active filter at noise frequencies. Often active filter op amps have their BW set by the noise frequencies rather than by the signal frequencies. Circuit designers must predict the highest noise frequency by calculation, measurement, or experience if they want to design good workable filters.

**Voltage feedback op amps**

The gain versus frequency plot of a typical voltage feedback amplifier (VFA) is shown in Figure 3. The loop gain plus one separates the closed-loop gain and forward gain plots. The closed-loop gain is down 3 dB at the intersection point. The loop gain decreases at –20 dB/decade beginning at low frequencies. The error increases as the frequency increases.

The open-loop gain plot of the TLV2472 is shown in Figure 4. This plot defines the op amp open-loop gain, “a,” which is not necessarily the forward gain, “A.” The error equation for the op amp circuits shown in Figure 2 is given in Equation 6.

\[
\frac{E}{V_{IN}} = \frac{1}{1 + AB} = \frac{1}{1 + \frac{aR_G}{R_F + R_G}}
\]

(6)

**Figure 3. Plot of op amp equation**

**Figure 4. Open-loop gain plot of the TLV247x**
The loop gain equation contains the closed-loop gain equation; thus, the error is dependent on the closed-loop gain and the amplifier frequency response.

For a non-inverting circuit with a closed-loop gain of 2 (6 dB), the open-loop gain is approximately 61 dB at 1 kHz; therefore, the non-inverting circuit built with a TLV2472 op amp has about 0.18% error at 1 kHz. For a non-inverting circuit with a closed-loop gain of 10 (20 dB), the open-loop gain is approximately 43 dB at 1 kHz; therefore, the non-inverting circuit built with a TLV2472 op amp has about 7.9% error at 1 kHz.

For an inverting circuit with a closed-loop gain of 2 (6 dB), the open-loop gain is approximately 61 dB at 1 kHz; therefore, the non-inverting circuit built with a TLV2472 op amp has about 0.26% error at 1 kHz. For a non-inverting circuit with a closed-loop gain of 10 (20 dB), the open-loop gain is approximately 43 dB at 1 kHz; therefore, the non-inverting circuit built with a TLV2472 op amp has about 8.7% error at 1 kHz.

Although the advertised gain-BW product of the TLV2472 is 2.8 MHz, circuits built with this IC can show gain errors at much lower frequencies because the amplifier gain starts falling off at much lower frequencies.

Current feedback op amps

The loop gain for a current feedback amplifier (CFA) is given in Equation 7, where \( Z \) is the transimpedance (sometimes called transresistance) and \( Z_B \) is the input buffer’s output impedance. \( Z \) functions in a CFA like the amplifier gain, “\( a \),” does in a VFA. Both are very large quantities, so they are very hard to measure. Transimpedance measurements must be made at very high frequencies and in the presence of noise, so many manufacturers do not include transimpedance plots in their data sheets.

\[
A_B = \frac{Z}{R_F} \quad \frac{1}{1 + \frac{Z_B}{R_F + R_G}}
\]  

(7)

The input buffer’s output impedance is made very small by design, and when it is neglected, Equation 8 results.

\[
A_B = \frac{Z}{R_F}
\]  

(8)

The closed-loop gain is not contained in the loop gain; thus, the CFA BW and error are independent of closed-loop gain. The manufacturer seldom plots the transimpedance, hence open-loop gain plots cannot be used to calculate the error. The manufacturers do plot amplitude versus frequency as a function of feedback resistance, supply voltage, and closed-loop gain. These plots are used to determine the accuracy of the circuit.

Figure 5 is the closed-loop response plot of the THS3001; notice that the response can be peaked, flat, or rolled off. The peaked response (\( R_F = 750 \Omega \)) creates distortion in a perfect signal because it emphasizes the high-frequency components in the signal. Sometimes the peaked response is chosen because it compensates for high-frequency gain lost due to stray capacitances or cables. Some CFAs have external leads that enable peaking control so that the overall response can be made flat.

The rolled-off response (\( R_F = 1.5 \text{ k}\Omega \)) is used only when a less expensive op amp having the correct BW can’t be found. When the signal requires a 10-MHz BW, and a lower-cost op amp can’t be found, the designer often makes \( R_F = 1.5 \text{ k}\Omega \) or slightly more to roll off the gain so that the circuit cannot amplify high-frequency noise. The \( R_F = 1 \text{ k}\Omega \) response is usually chosen because it amplifies the signal with the best fidelity.

Conclusions

Determining the amplifier’s required BW can be as simple as in-circuit testing or as complicated as using Fourier series analysis. The VFA loop gain contains the closed-loop gain; thus, the error is related to the closed-loop gain and amplifier frequency response. Selecting the proper BW VFA consists of using the op amp open-loop gain plot to calculate the error at the operating frequency. Selecting the proper CFA consists of reviewing the closed-loop gain plots and calculating the error based on these plots. In either case, excess BW is detrimental to good circuit performance because it contributes to instability, increases cost, and amplifies noise.

References

For more information related to this article, visit the TI Web site at www.ti.com/ and look for the following materials by entering the TI literature number into the quick-search box.

- Document Title
  - TI Lit. #
  - 1. “Feedback Amplifier Analysis Tools” . . . . . . SLOA017
  - 3. “Current Feedback Amplifier Analysis and Compensation” . . . . . . SLOA021

Related Web sites

- amplifier.ti.com
- analog.ti.com

Get product data sheets at:

www.ti.com/sc/docs/products/analog/device.html

Replace \textit{device} with the IC number for the THS3001 or the TLV2472.
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