Matching operational amplifier bandwidth with applications

By Ron Mancini

Senior Application Specialist, Operational Amplifiers

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.

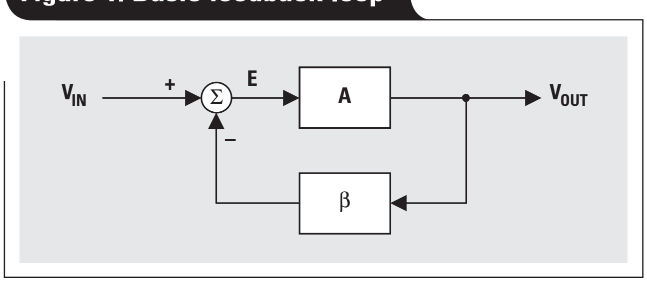
Feedback and accuracy

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

$$V_{OUT} = EA \tag{1}$$

$$E = V_{IN} - \beta V_{OUT} = V_{IN} - \beta EA \tag{2}$$

Figure 1. Basic feedback loop



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

$$\frac{E}{V_{IN}} = \frac{1}{1 + A\beta} \tag{3}$$

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

$$\frac{V_{OUT}}{V_{IN}} = \frac{A}{1 + A\beta} \tag{4}$$

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 occurs when Aβ = –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.

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

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 amps 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.

$$\frac{E}{V_{IN}} = \frac{1}{1+A\beta} = \frac{1}{1+\dfrac{aR_G}{R_F+R_G}} \tag{6}$$

Continued on next page

Figure 2. Op amp circuits

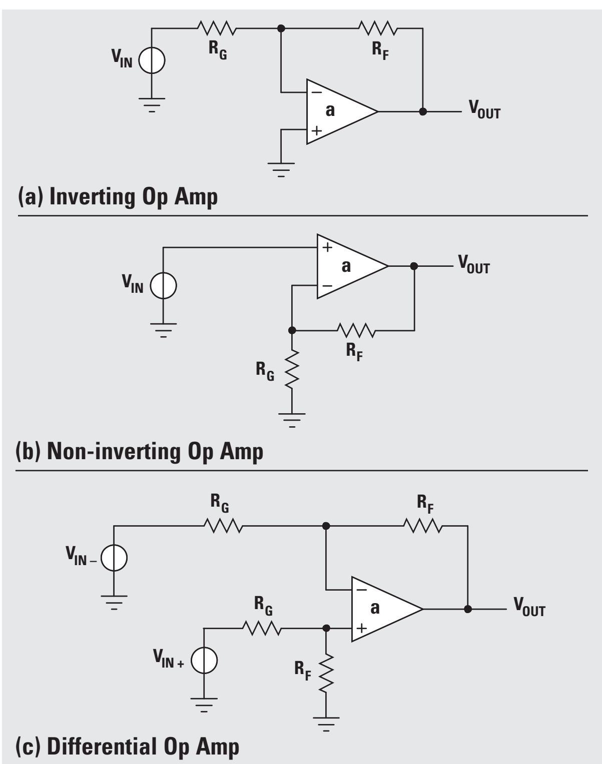


Figure 3. Plot of op amp equation

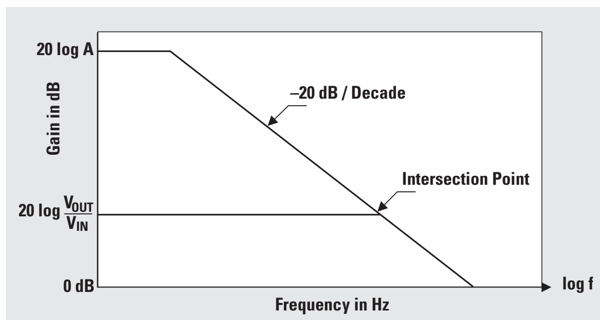
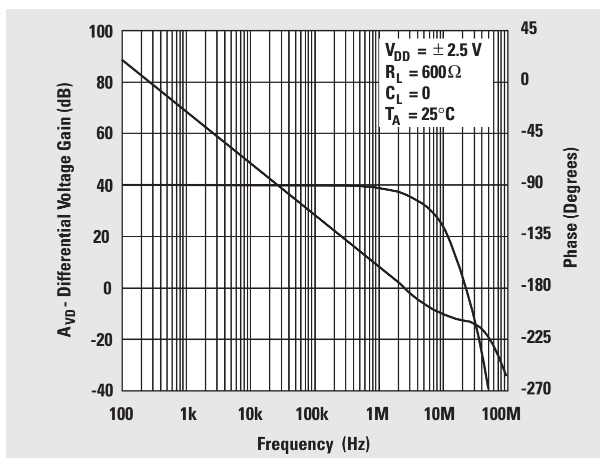


Figure 4. Open-loop gain plot of the TLV247x



Continued from previous page

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.

$$A\beta = \frac{Z}{R_F\left(1+\frac{Z_B}{R_F+R_G}\right)} \tag{7}$$

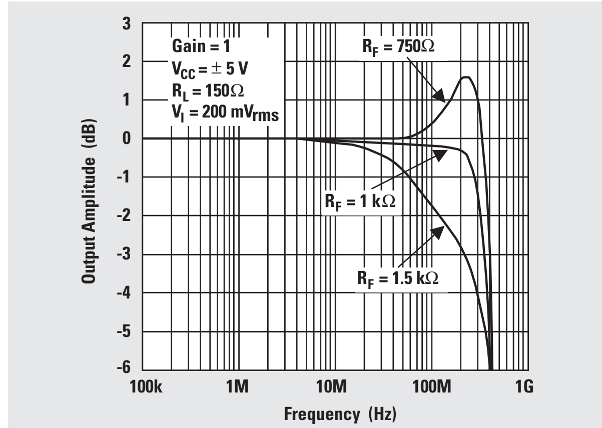
The input buffer's output impedance is made very small by design, and when it is neglected, Equation 8 results.

$$A\beta = \frac{Z}{R_F} \tag{8}$$

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 Ω) 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.

Figure 5. Closed-loop response plot of the THS3001



The rolled-off response (R_F = 1.5 kΩ) 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 kΩ or slightly more to roll off the gain so that the circuit cannot amplify high-frequency noise. The R_F = 1 kΩ 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
2. "Stability Analysis of Voltage Feedback Op Amps, Including Compensation Techniques" SLOA020
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 *device* with ths3001 or tlv2472

IMPORTANT NOTICE

Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, modifications, enhancements, improvements, and other changes to its products and services at any time and to discontinue any product or service without notice. Customers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All products are sold subject to TI's terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its hardware products to the specifications applicable at the time of sale in accordance with TI's standard warranty. Testing and other quality control techniques are used to the extent TI deems necessary to support this warranty. Except where mandated by government requirements, testing of all parameters of each product is not necessarily performed.

TI assumes no liability for applications assistance or customer product design. Customers are responsible for their products and applications using TI components. To minimize the risks associated with customer products and applications, customers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any TI patent right, copyright, mask work right, or other TI intellectual property right relating to any combination, machine, or process in which TI products or services are used. Information published by TI regarding third-party products or services does not constitute a license from TI to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. Reproduction of this information with alteration is an unfair and deceptive business practice. TI is not responsible or liable for such altered documentation.

Resale of TI products or services with statements different from or beyond the parameters stated by TI for that product or service voids all express and any implied warranties for the associated TI product or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

Following are URLs where you can obtain information on other Texas Instruments products and application solutions:

Products	
Amplifiers	**amplifier.ti.com**
Data Converters	**dataconverter.ti.com**
DSP	**dsp.ti.com**
Interface	**interface.ti.com**
Logic	**logic.ti.com**
Power Mgmt	**power.ti.com**
Microcontrollers	**microcontroller.ti.com**

Applications	
Audio	**www.ti.com/audio**
Automotive	**www.ti.com/automotive**
Broadband	**www.ti.com/broadband**
Digital control	**www.ti.com/digitalcontrol**
Military	**www.ti.com/military**
Optical Networking	**www.ti.com/opticalnetwork**
Security	**www.ti.com/security**
Telephony	**www.ti.com/telephony**
Video & Imaging	**www.ti.com/video**
Wireless	**www.ti.com/wireless**

TI Worldwide Technical Support

Internet

TI Semiconductor Product Information Center Home Page
support.ti.com

TI Semiconductor KnowledgeBase Home Page
support.ti.com/sc/knowledgebase

Product Information Centers

Americas

Phone	+1(972) 644-5580	Fax	+1(972) 927-6377
Internet/Email	support.ti.com/sc/pic/americas.htm		

Europe, Middle East, and Africa

Phone			
Belgium (English)	+32 (0) 27 45 54 32	Netherlands (English)	+31 (0) 546 87 95 45
Finland (English)	+358 (0) 9 25173948	Russia	+7 (0) 95 7850415
France	+33 (0) 1 30 70 11 64	Spain	+34 902 35 40 28
Germany	+49 (0) 8161 80 33 11	Sweden (English)	+46 (0) 8587 555 22
Israel (English)	1800 949 0107	United Kingdom	+44 (0) 1604 66 33 99
Italy	800 79 11 37		
Fax	+(49) (0) 8161 80 2045		
Internet	support.ti.com/sc/pic/euro.htm		

Japan

Fax			
International	+81-3-3344-5317	Domestic	0120-81-0036
Internet/Email			
International	support.ti.com/sc/pic/japan.htm		
Domestic	www.tij.co.jp/pic		

Asia

Phone			
International	+886-2-23786800		
Domestic	Toll-Free Number		Toll-Free Number
Australia	1-800-999-084	New Zealand	0800-446-934
China	800-820-8682	Philippines	1-800-765-7404
Hong Kong	800-96-5941	Singapore	800-886-1028
Indonesia	001-803-8861-1006	Taiwan	0800-006800
Korea	080-551-2804	Thailand	001-800-886-0010
Malaysia	1-800-80-3973		
Fax	886-2-2378-6808	Email	tiasia@ti.com
Internet	support.ti.com/sc/pic/asia.htm		ti-china@ti.com

C011905

Safe Harbor Statement: This publication may contain forward-looking statements that involve a number of risks and uncertainties. These “forward-looking statements” are intended to qualify for the safe harbor from liability established by the Private Securities Litigation Reform Act of 1995. These forward-looking statements generally can be identified by phrases such as TI or its management “believes,” “expects,” “anticipates,” “foresees,” “forecasts,” “estimates” or other words or phrases of similar import. Similarly, such statements herein that describe the company's products, business strategy, outlook, objectives, plans, intentions or goals also are forward-looking statements. All such forward-looking statements are subject to certain risks and uncertainties that could cause actual results to differ materially from those in forward-looking statements. Please refer to TI's most recent Form 10-K for more information on the risks and uncertainties that could materially affect future results of operations. We disclaim any intention or obligation to update any forward-looking statements as a result of developments occurring after the date of this publication.

Trademarks: All trademarks are the property of their respective owners.

Mailing Address: Texas Instruments
Post Office Box 655303
Dallas, Texas 75265