

Amplifier Gain Error and Loop Gain Example

This is the schematic of an AC-amplifier. U_1 is the Apex PA441DF. Resistors R_2 and R_4 are 0.1% tolerance.

 $V_{IN} \bigotimes_{2.49k} R_{1}$ R_{2} R_{4} R_{5} R_{4} R_{4} R_{4} R_{4} R_{4} R_{5} R_{4} R_{4} R_{4} R_{5} R_{4} R_{4} R_{4} R_{5} R_{4} R_{4} R_{4} R_{5} R_{5} R_{6} R_{7} R_{8} R_{1} R_{2} R_{4} R_{4} R_{4} R_{5} R_{5} R_{6} R_{7} R_{8} R_{1} R_{2} R_{4} R_{4} R_{5} R_{5} R_{6} R_{7} R_{8} R_{1} R_{2} R_{4} R_{5} R_{5} R_{6} R_{7} R_{8} R_{1} R_{2} R_{4} R_{4} R_{5} R_{5} R_{7} R_{8} R_{1} R_{2} R_{4} R_{4} R_{5} R_{5} R_{6} R_{7} R_{8} R_{8} R_{1} R_{2} R_{4} R_{5} R_{5} R_{7} R_{8} R_{8} R_{9} R_{1} R_{2} R_{4} R_{5} R_{5} R_{7} R_{8} R_{8} R_{1} R_{2} R_{4} R_{5} R_{5} R_{7} R_{8} R_{1} R_{2} R_{4} R_{5} R_{5} R_{7} R_{8} R_{8} R_{1} R_{2} R_{3} R_{4} R_{5} R_{5} R_{7} R_{8} R_{8} R_{1} R_{2} R_{3} R_{4} R_{5} R_{5} R_{7} R_{8} R_{8} R_{8} R_{9} R_{1} R_{1} R_{2} R_{3} R_{4} R_{5} R_{5} R_{7} R_{8} R_{8} R_{1} R_{2} R_{3} R_{4} R_{5} R_{7} R_{8} R_{8} R_{1} R_{2} R_{3} R_{4} R_{5} R_{5} R_{7} R_{8} R_{8} R_{1} R_{2} R_{3} R_{4} R_{5} R_{5} R_{7} R_{8} R_{1} R_{2} R_{3} R_{4} R_{5} R_{5} R_{7} R_{8} R_{1} R_{2} R_{3} R_{4} R_{5} R_{5} R_{7} R_{8} R_{9} R_{1} R_{1} R_{2} R_{3} R_{3} R_{4} R_{5} R_{7} R_{8} R_{1} R_{2} R_{3} R_{4} R_{5} R_{5} R_{7} R_{8} R_{1} R_{2} R_{3} R_{4} R_{5} R_{7} R_{8} R_{1} R_{2} R_{3} R_{4} R_{5} R_{7} R_{8} R_{1} R_{2} R_{3} R_{4} R_{5} R_{5} R_{7} R_{8} R_{8} R_{1} R_{2} R_{3} R_{4} R_{5} $R_$

Figure 1: AC - amplifier circuit based on PA441

Desired Performance Specifications:

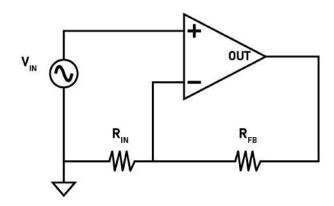
Frequency Response: 20Hz to 30kHz

Gain: 38dB ± 0.2dB

Maximum Output Voltage: 200Vp-p Maximum Output Current: 50mA

Basic feedback theory emphasizes the importance of a high dc open-loop gain as a requirement to maintain amplifier accuracy

Figure 2: Standard non-inverting op amp circuit



AN65



For the non-inverting ideal operational amplifier of Figure 2, A_{CL}, the closed-loop gain equation is:

$$A_{CL} = \frac{R_{FB}}{R_{IN}} + 1 = \frac{V_{OUT}}{V_{IN}}$$

The feedback factor or β is defined as:

$$\beta = \frac{R_{IN}}{R_{IN} + R_{FR}}$$

Then,

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

This is a good approximation, assuming that the open-loop gain, A_{OL} is much greater than the closed-loop gain, A_{CL} .

The actual A_{CL} will differ from the ideal value of $1/\beta$ due to the finite value of A_{OL} . The influence of A_{OL} may result in a substantial gain error in the actual closed-loop gain, A_{CL} . Although it is possible to adjust the elements of the feedback network to compensate for the gain error, the uncertainty of A_{OL} places a practical limitation on the resulting accuracy achievable by this approach. The gain equation must include the contribution of the finite A_{OL} of the op amp to achieve the expected A_{CL} . The A_{CL} equation including the effect of A_{OL} becomes:

$$A_{CL} = \frac{A_{OL}}{1 + A_{OL}\beta}$$

Notice that as the value of A_{OL} approaches infinity, the equation for A_{CL} reduces to:

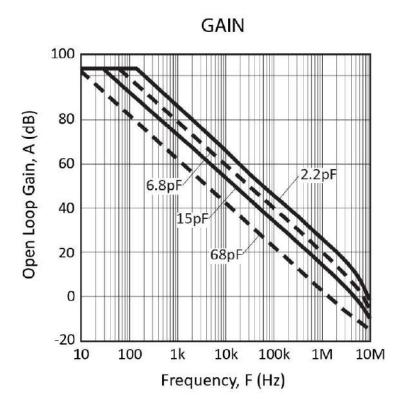
$$A_{CL} = \frac{1}{\beta}$$

The PA441 open-loop gain plot and gain specifications are shown below:

Parameter	Test Conditions	Min	Тур	Max	Units
Open Loop at 15 Hz	RL = 5 kΩ	90	103		dB
Bandwidth, gain bandwidth product	@ 1 MHz		10		MHz
Power Bandwidth	280V p-p		35		kHz



Gain (A_{OL}) plot of PA441



The A_{OL} of the PA441 is shown in the Gain plot. The A_{OL} value remains flat for a frequency of DC to approximately 100Hz. At frequencies greater than 100Hz the A_{OL} decreases at a rate of -20dB per decade indicating a dominant pole at approximately 100Hz. The minimum A_{OL} is specified at 90dB at a frequency of 15Hz.

The component values for the amplifier circuit of Figure 1:

 R_1 =2.49 $k\Omega$, R_2 =2.49 $k\Omega$, R_4 =196 $k\Omega$, C_2 =33 μF

$$\beta = \frac{R_2}{R_2 + R_4}$$

$$A_{CL} = \frac{A_{OL}}{1 + A_{OL}\beta} \left(\frac{sR_1C_2}{sR_1C_2 + 1} \right)$$



Figure 3 plot shows the relationships between $A_{\mbox{\scriptsize OL}}$ and $A_{\mbox{\scriptsize CL}}$ in dB for the AC-Amplifier of Figure 1.

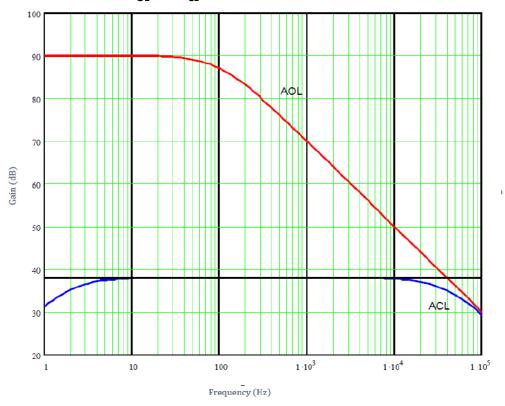


Figure 3: ${\rm A_{OL}}$ and ${\rm A_{CL}}$ curves for the AC-amplifier in Figure 1

Figure 4 is a plot of the ideal amplifier response versus the predicted result based on the actual A_{OL} , A_{CL} compared to $1/\beta$.

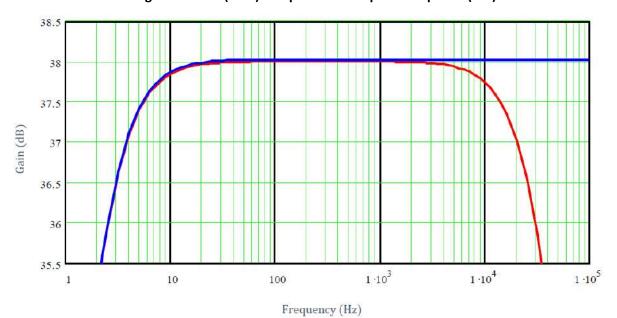


Figure 4: Ideal (blue) and predicted amplifier response (red)



The frequency response does not meet the desired specification of 20Hz to 30kHz at a gain of 38dB ±0.2dB. The gain at frequencies above approximately 8kHz is clearly out of spec and dips to 36dB at 30kHz.

The equation to find the % gain error is:

% Gain error=
$$\frac{1}{A_{OL}\beta}$$

What is the gain error necessary to achieve the required minimum gain specification of 38dB -0.2dB or 37.8dB?

The nominal gain of 38dB relates to the gain of 79.4 V/V. The lower limit of 37.8dB corresponds to a gain of approximately 77.6 and the approximate value of β = 0.0125.

The A_{OL} of 90dB corresponds to the value of 31600 V/V.

% Gain error=
$$\frac{1}{31600(0.0125)} \times 100 = 0.25\%$$

This gain error is valid for frequencies less than 100Hz where A_{OL} equals 90dB. At higher frequencies the percent gain error equation is:

% Gain error =
$$\left(\frac{1}{A_{OI}\beta}\right)^2 \times 100$$

The actual percent gain error allowed can be calculated as shown:

% Actual Gain error=
$$\frac{79.4 - 77.6}{79.4} \times 100 = 2.3\%$$

Then solving for the required A_{OI} :

$$A_{OL} = \sqrt{\frac{1}{\text{Gain error } \times \beta^2}} = \sqrt{\frac{1}{0.023(0.0125^2)}} = 528$$

Converting the gain to dB gives A_{OL} of approximately 54dB. Therefore, the A_{OL} at 30kHz must be greater than 54dB to satisfy the gain requirement of 38dB \pm 0.2dB.

Loop gain is defined as the product, $A_{OL} \times \beta$ and the difference between A_{OL} and A_{CL} . The loop gain may be thought of as the gain around the loop formed by the amplifier and its feedback network. The accuracy of the closed-loop gain, A_{CL} , is limited by the amount of loop gain available. Applying this technique gives us the required loop gain of 16dB: (54dB - 38dB = 16dB).

A less accurate and more intuitive approach can be used for a first order approximate solution. The plots of Figures 3 and 4 show that A_{OL} must be greater than 53dB to achieve a gain error of less than -0.2dB. For frequencies above 8kHz, the corresponding A_{OL} is less than 53dB causing the gain error to drop below the -0.2dB lower limit. The loop gain at 8kHz is approximately 15dB. This means that a loop gain exceeding 15dB is necessary to maintain the required gain error at 30kHz. The minimum A_{OL} at DC must be at least 90dB + 15dB. Therefore, the DC- A_{OL} must be greater than 105dB to achieve less than the 2.3% gain error at 30kHz. The minimum required loop gain is, LG_{reg} = 53dB - 38dB = 15dB.



The plot of Figure 5 shows the loop gain and indicates that the required gain is within the specification for a loop gain value greater than 15dB up to the frequency of approximately 8kHz. The plot also shows that at the frequency of 30kHz, the loop gain is just slightly greater than 0dB.

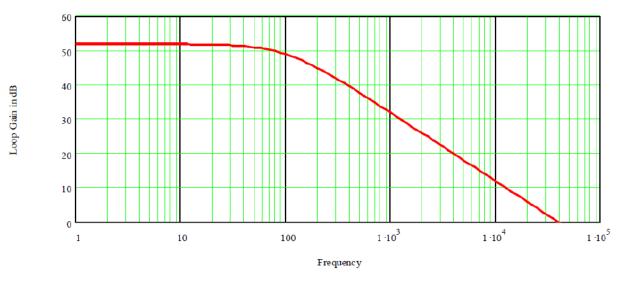


Figure 5: Loop gain (A_{OL} - A_{CL})

In general, the loop gain should be at least 20dB to achieve reasonable gain accuracy. For relatively high-gain amplifier applications, a multi-stage amplifier should be considered.

The proposed alternative circuit of Figure 6 is a two-stage amplifier consisting of the Apex PA443DF dual operational amplifier. The first stage is operating at an inverting gain of 20 followed by the second stage operating at an inverting gain of 4. The PA443DF consists of two PA441 operational amplifiers housed in the same package as the single PA441DF. Resistors R2, R4, R7 and R8 are 0.1% tolerance.

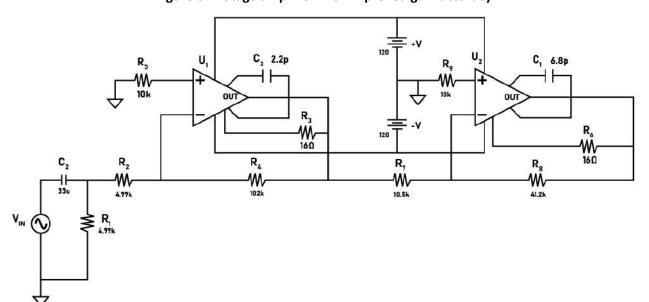


Figure 6: 2-Stage amplifier with improved gain accuracy



Figure 7 shows the results of a Spice simulation for the circuit of Figure 1. The device model is based on the typical A_{OL} value of 103dB. This analysis assumes the minimum A_{OL} value of 90dB. This is the reason for the slightly improved gain shown in this plot compared to Figure 4.

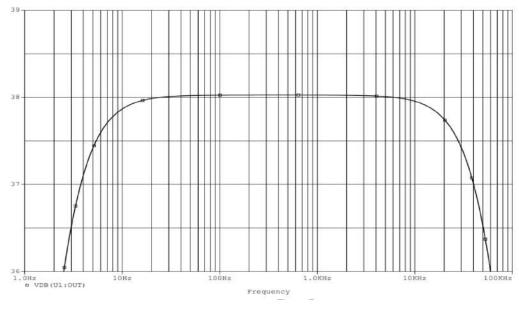


Figure 7: AC simulation result of Figure 1 circuit

Figure 8 shows results of Spice simulation for the circuit of Figure 6. The gain is essentially flat from 20Hz to 30kHz allowing for additional errors introduced by A_{OL} variation, feedback component shifts and temperature effects.

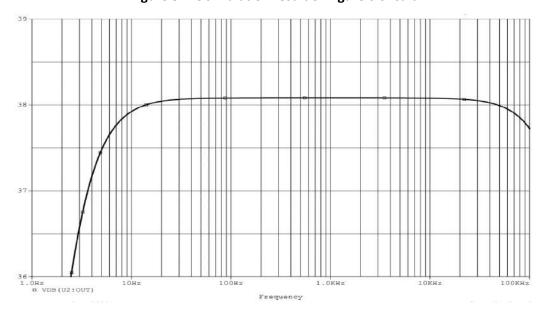


Figure 8: AC simulation result of Figure 6 circuit



NEED TECHNICAL HELP? CONTACT APEX SUPPORT!

For all Apex Microtechnology product questions and inquiries, call toll free 800-546-2739 in North America. For inquiries via email, please contact apex.support@apexanalog.com. International customers can also request support by contacting their local Apex Microtechnology Sales Representative. To find the one nearest to you, go to www.apexanalog.com

IMPORTANT NOTICE

Apex Microtechnology, Inc. has made every effort to insure the accuracy of the content contained in this document. However, the information is subject to change without notice and is provided "AS IS" without warranty of any kind (expressed or implied). Apex Microtechnology reserves the right to make changes without further notice to any specifications or products mentioned herein to improve reliability. This document is the property of Apex Microtechnology and by furnishing this information, Apex Microtechnology grants no license, expressed or implied under any patents, mask work rights, copyrights, trademarks, trade secrets or other intellectual property rights. Apex Microtechnology owns the copyrights associated with the information contained herein and gives consent for copies to be made of the information only for use within your organization with respect to Apex Microtechnology integrated circuits or other products of Apex Microtechnology. This consent does not extend to other copying such as copying for general distribution, advertising or promotional purposes, or for creating any work for resale.

APEX MICROTECHNOLOGY PRODUCTS ARE NOT DESIGNED, AUTHORIZED OR WARRANTED TO BE SUITABLE FOR USE IN PRODUCTS USED FOR LIFE SUPPORT, AUTOMOTIVE SAFETY, SECURITY DEVICES, OR OTHER CRITICAL APPLICATIONS. PRODUCTS IN SUCH APPLICATIONS ARE UNDERSTOOD TO BE FULLY AT THE CUSTOMER OR THE CUSTOMER'S RISK.

Apex Microtechnology, Apex and Apex Precision Power are trademarks of Apex Microtechnology, Inc. All other corporate names noted herein may be trademarks of their respective holders.