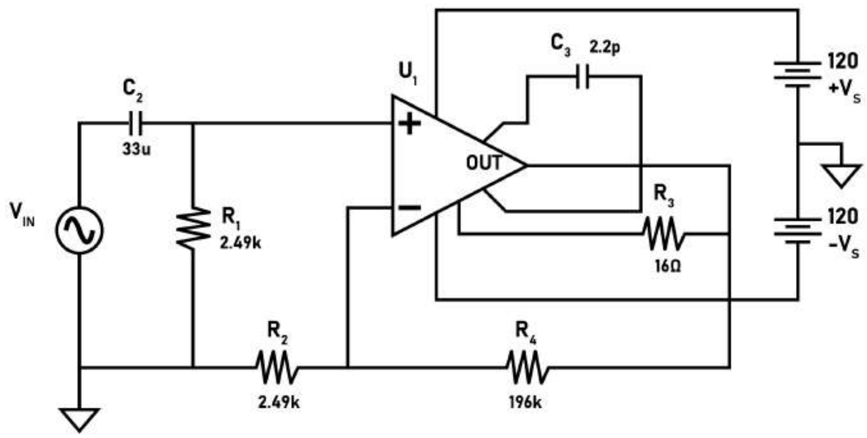
Amplifier Gain Error and Loop Gain Example

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

Figure 1: AC - amplifier circuit based on PA441

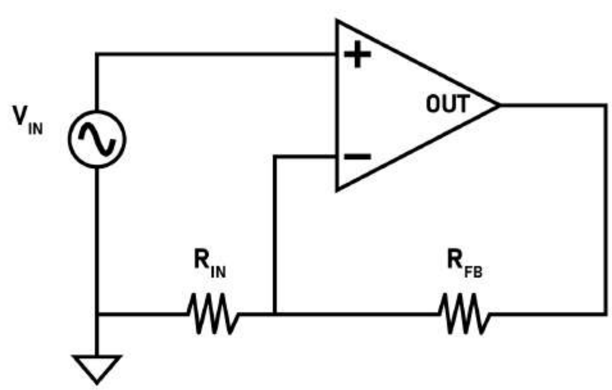


Desired Performance Specifications:

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



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:

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

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/β 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:

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

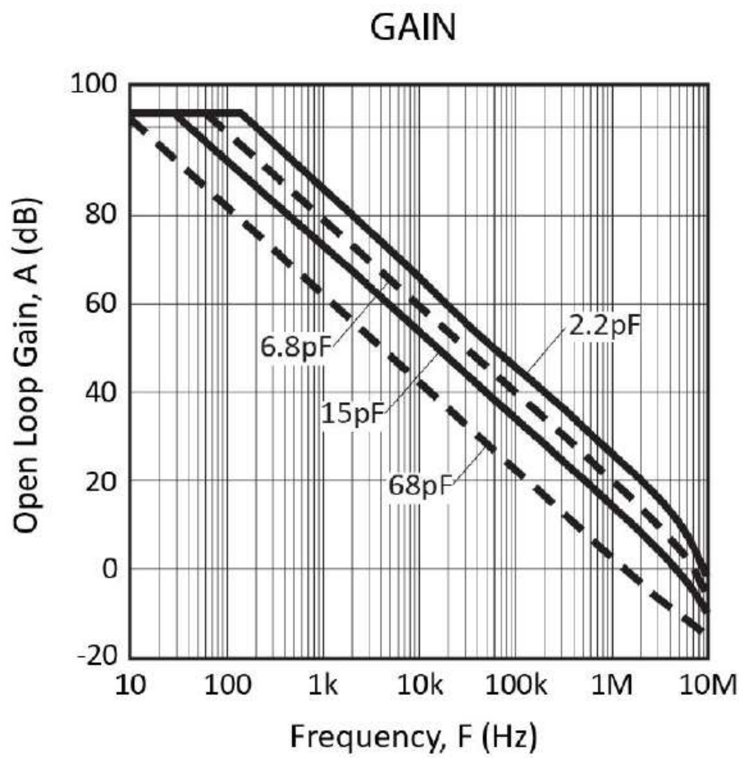
Notice that as the value of A_{OL} approaches infinity, the equation for A_{CL} reduces to:

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

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

Parameter	Test Conditions	Min	Typ	Max	Units
Open Loop at 15 Hz	R_L = 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=2.49kΩ, R_2=2.49kΩ, R_4=196kΩ, C_2=33µF

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

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

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

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

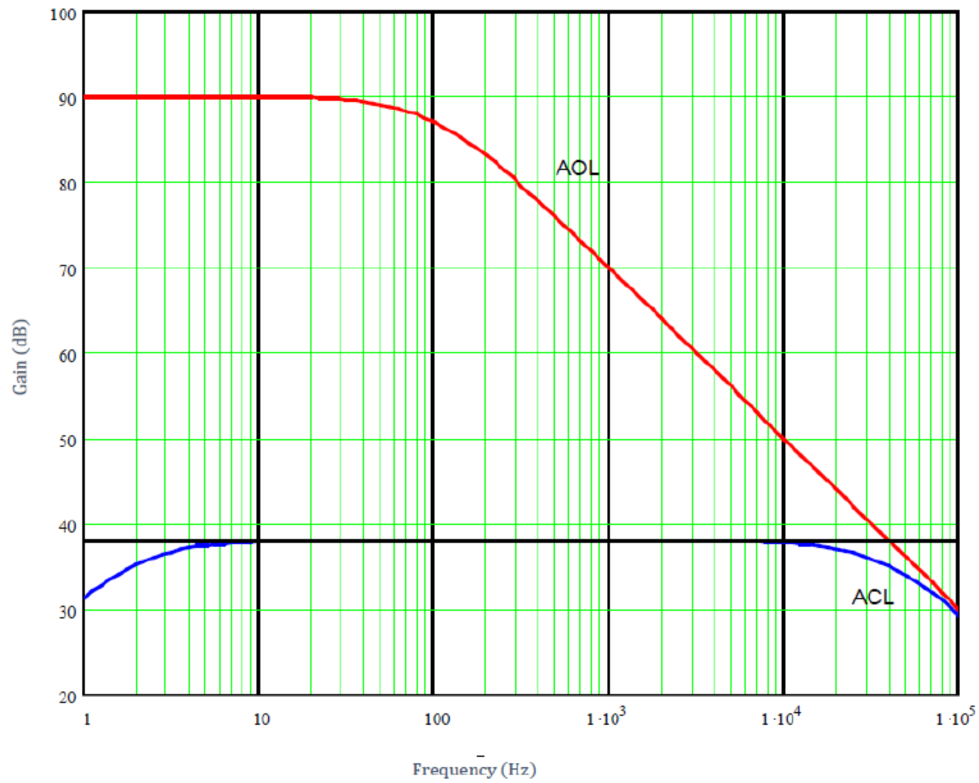
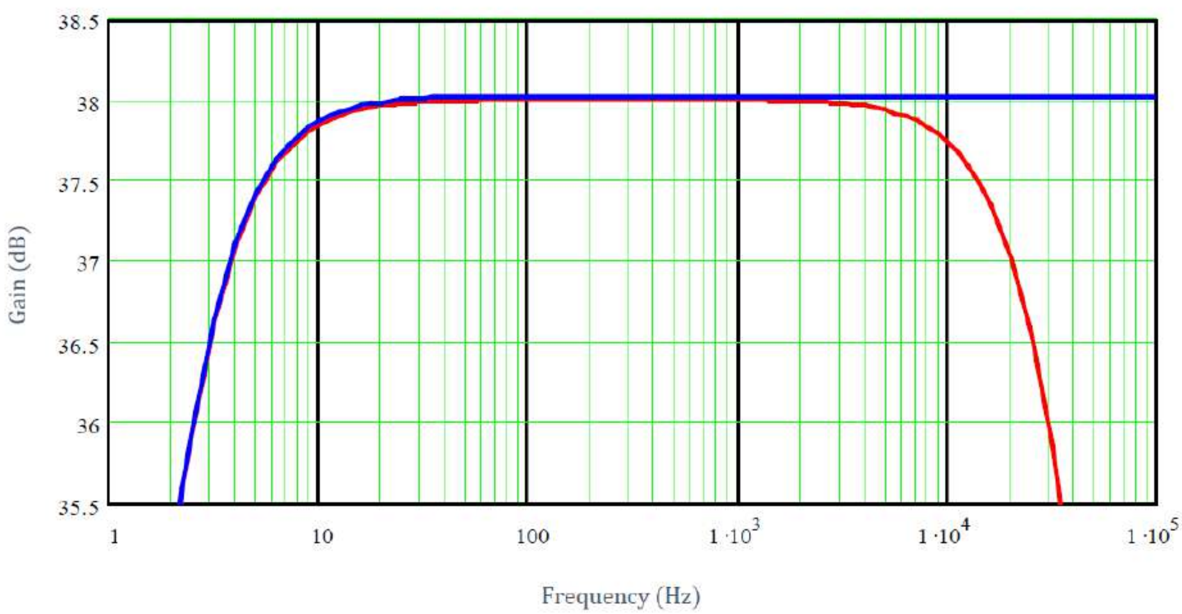


Figure 4 is a plot of the ideal amplifier response versus the predicted result based on the actual A_{OL}, A_{CL} compared to 1/β.

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:

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

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.

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

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

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

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

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

Then solving for the required A_{OL}:

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

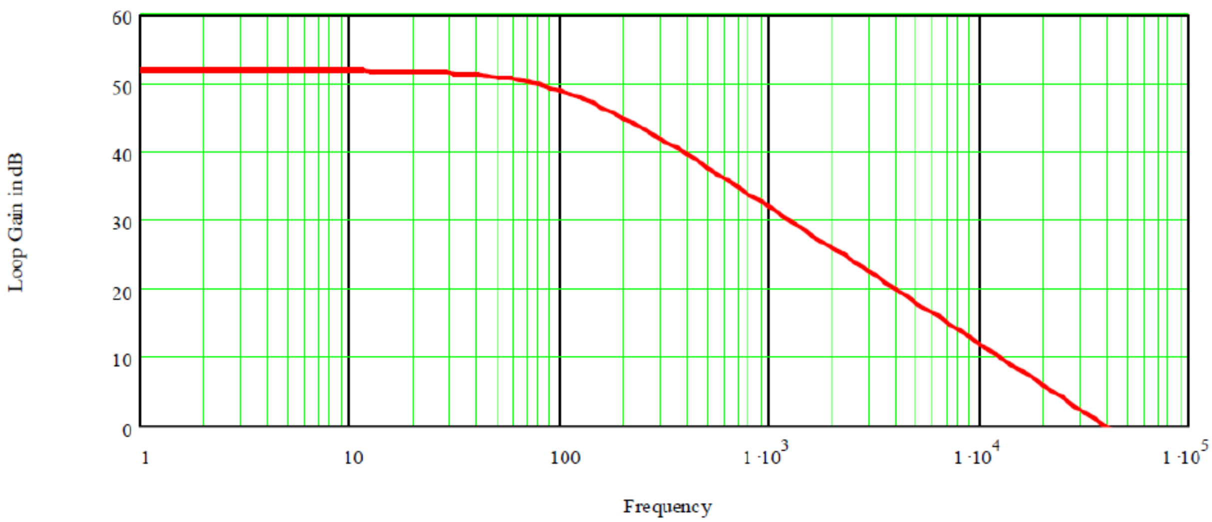
Converting the gain to dB gives A_{OL} of approximately 54dB. Therefore, the A_{OL} at 30kHz must be greater than 54dB to satisfy the gain requirement of 38dB ± 0.2dB.

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_{req} = 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

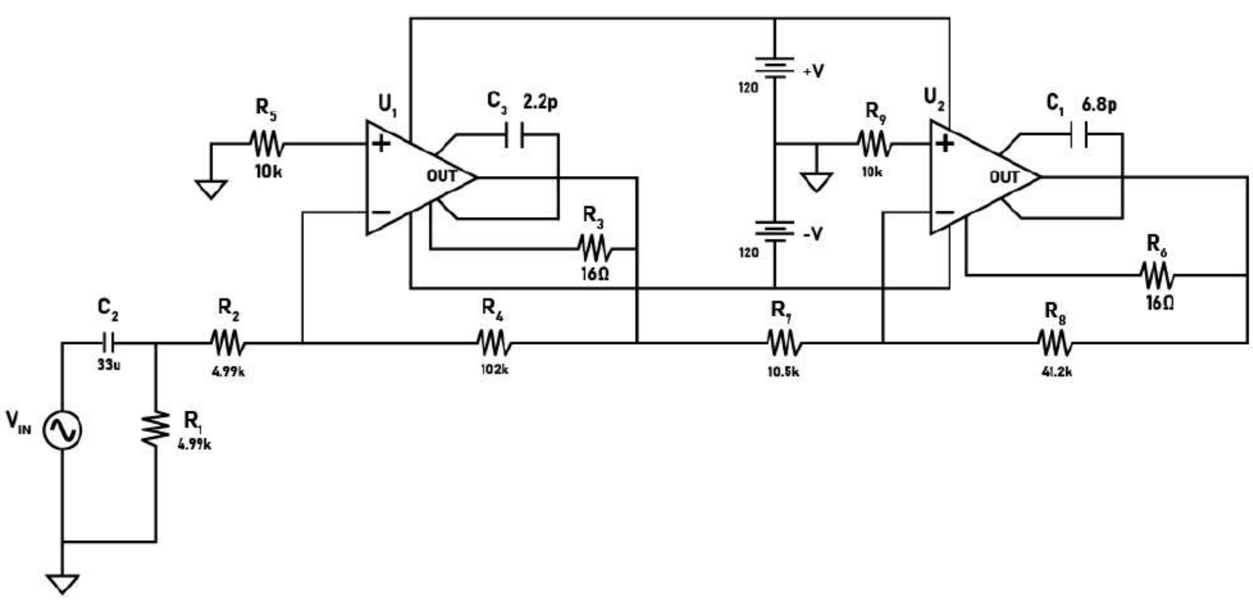


Figure 7 shows the results of a Spice simulation for the circuit of Figure 1. The device model is based on the typical A_{OL} value of 103dB. This analysis assumes the minimum A_{OL} value of 90dB. This is the reason for the slightly improved gain shown in this plot compared to Figure 4.

Figure 7: AC simulation result of Figure 1 circuit

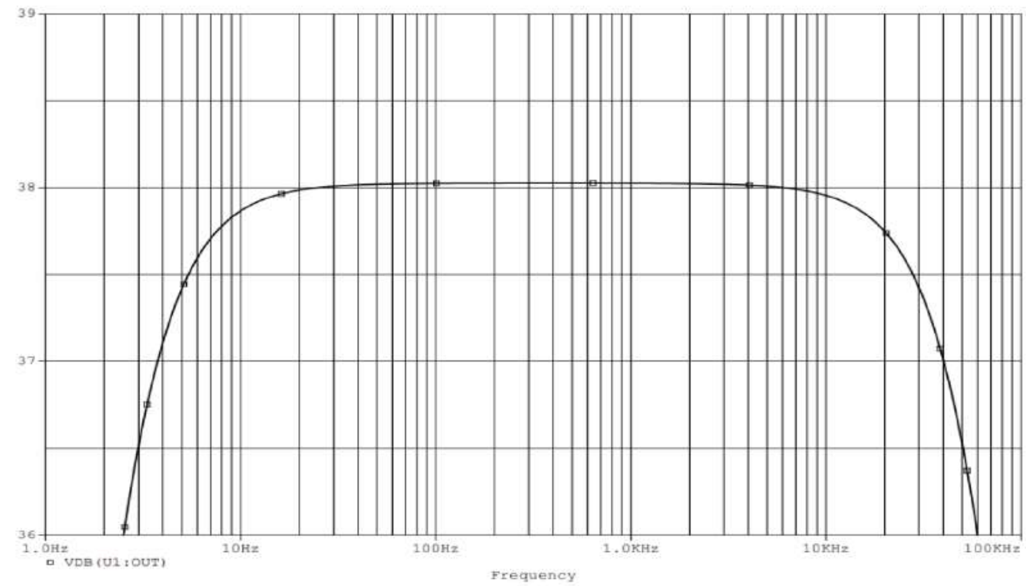
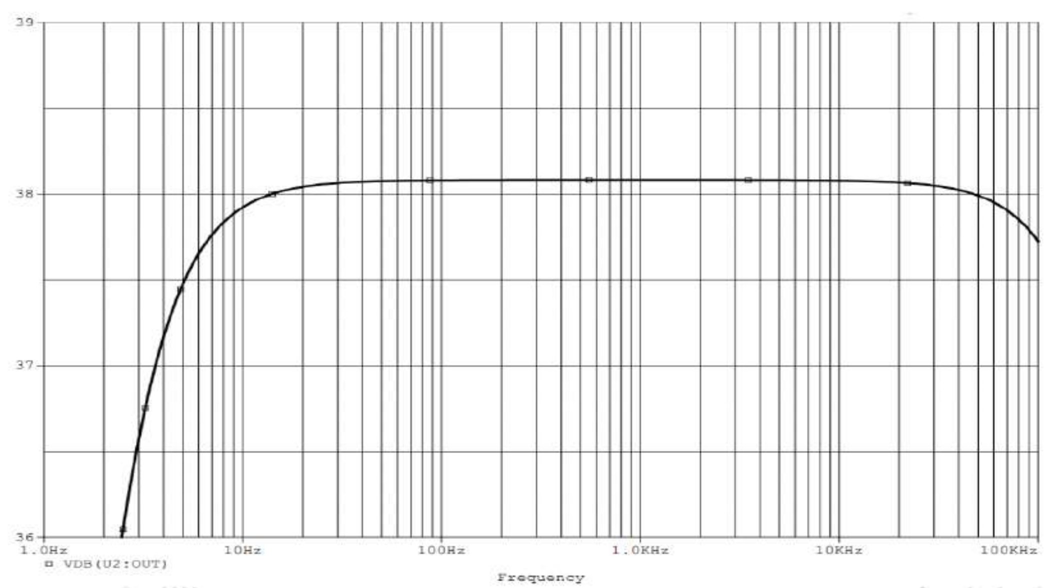


Figure 8 shows results of Spice simulation for the circuit of Figure 6. The gain is essentially flat from 20Hz to 30kHz allowing for additional errors introduced by A_{OL} variation, feedback component shifts and temperature effects.

Figure 8: AC simulation result of Figure 6 circuit



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