ANALOG edge[SM]

Expert tips, tricks, and techniques for analog designs

Vol. IV, Issue 10

DESIGN idea

Amplifier Closed-Loop Bandwidth Considerations in High Resolution A/D Converter Applications

By Jerry Freeman, Applications Engineer

Amplifier Bandwidth Limitations

Amplifier closed-loop bandwidth-limited accuracy considerations are critical when driving high resolution A/D Converters (ADCs). It is useful to be able to predict, for any closed loop gain, the required gain-bandwidth (GBW) product of an op amp to achieve a specified level of accuracy in terms of the minimum ADC resolution. Other sources of error include offset, noise, and distortion, which are beyond the scope of this article. A simple equation will be developed below that relates the minimum closed-loop bandwidth of an op amp to the resolution requirements of a given ADC.

Amplifier Response

Assuming a single pole roll-off, the frequency dependence of an amplifier's closed-loop gain, A_{CL}, is given by:

$$A_{CL} = \frac{A_{CLDC}}{\sqrt{1+\left(\frac{f}{f_{-3\ dB}}\right)^2}} \qquad \textit{Equation 1}$$

where A_{CLDC} is the amplifier's DC gain, and $f_{-3\ dB}$ is its corner frequency.

This equation describes the op amp's closed-loop gain at frequency ***f***, in terms of the amplifier's corner frequency.

The vast majority of op amps employ internal lag compensation with a single dominant pole that rolls off the open-loop gain, from its cut-off frequency, to unity gain (zero dB) at a 20 dB per decade rate. The frequency response of such an amplifier with feedback is therefore also the same as for an RC low-pass filter. The frequency where the open-loop gain crosses unity gain is routinely called the GBW product in op amp datasheets. The GBW product for an amplifier is the product of its open loop gain (constant for a given amplifier)

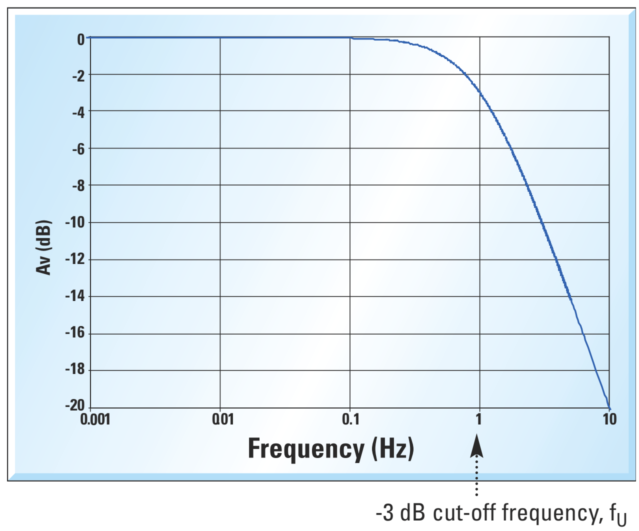

Figure 1. Normalized bandwidth curve for an op amp in unity gain (Curve assumes an open loop gain with a single pole roll-off.)

and its -3 dB bandwidth (GBW product = gain x -3 dB bandwidth). Given the GBW product and the open-loop gain roll-off of -20 dB per decade, the -3 dB bandwidth for any closed loop gain can be easily calculated, from

$$BW = GBW / A_{CL} \qquad \textit{Equation 2}$$

For example, the LMP2011 with a GBW product of 3 MHz will have a bandwidth of 300 kHz when configured with an A_{CL} of 10 V/V. However, at -3 dB the closed-loop gain has a 29.3% gain error. In reality, the gain expression starts rolling off long before the -3 dB pole frequency is reached. It is important to determine the frequency at which the closed-loop gain error increases above the maximum error allowed for a given data error. The maximum error in data

NEXT ISSUE:
Dithered Switching Frequency

Amplifier Closed-Loop Bandwidth Considerations in High Resolution A/D Converter Applications

converters is usually expressed in terms of the Least Significant Bit (LSB). Ideally, all error sources should be well below this level. An LSB of an ADC is defined as the finest resolution of which the ADC is capable. Quantitatively this is equal to the full scale voltage divided by the resolution of the ADC ($V_{FS}/2^N$) for one LSB, were N is the number of bits. Thus for an 8-bit converter, the error would be $V_{FS}/256$. If 1/2 LSB is set as the required system accuracy, the acceptable accuracy limit would be:

Accuracy (δ) = 100% - gain error (%),

where gain error = 1/2 ($1/2^N$) *100%, *Equation 3*

which gives δ **= 100% - 1/2 ($1/2^N$) *100%,** or 99.8%

The accuracy is calculated based on the -3 dB cut-off frequency at a particular close-loop gain. Approximating the frequency response of an op amp to that of a single pole filter, we get the frequency vs gain curve of such a system as shown in ***Figure 1.***

Because the curve is normalized to 1 for a frequency f_U (-3 dB at unity gain), the expression for this curve, for any ***f***, from ***Equation 1*** is

$$A_{CL} = \frac{1}{\sqrt{1+(f)^2}} \qquad \textit{Equation 4}$$

Solving for f gives

$$f = \sqrt{\frac{1}{(A_{CL})^2} - 1} \qquad \textit{Equation 5}$$

The question is now, for any ACL, what is the maximum signal frequency that does not exceed the specified error? From ***Equation 1, Equation 3,*** and ***Equation 5***, and the example for 8-bit accuracy, the normalized frequency, f_{MAX}, for an amplifier requiring 99.8% accuracy, is the frequency where the gain roll off is less than 1/2 LSB is expressed as

$$f_{max} = \sqrt{\frac{1}{(0.998)^2} - 1} \times f_U = 0.062 \times f_U \qquad \textit{Equation 6}$$

for the case of unity gain.

Thus, the maximum frequency at which it is still possible to get at least 99.8% (1/2 LSB) accuracy in an 8-bit system, is 0.062 of the op amp's -3 dB frequency. In the case of the LMP2011 example, the available bandwidth for 99.8% accuracy is

$$0.062 \times f_{-3\,dB}\ \text{kHz} = 0.062 \times 300\ \text{kHz} = 18.6\ \text{kHz}$$

In general, the normalized f_{MAX} for 1/2 LSB error for ADCs of various resolutions can be calculated as

$$\text{Normalized } f_{MAX} = \sqrt{\frac{1}{\left(1-\frac{1}{2^{n+1}}\right)^2} - 1} \qquad \textit{Equation 7}$$

Using this equation, a list of normalized bandwidths for system resolutions up to 16 bits have been calculated *(Table 1)*.

System Resolution	Normalized Bandwidth for <1/2 LSB Error
8-bit	0.062592
9-bit	0.044227
10-bit	0.031261
11-bit	0.022101
12-bit	0.015626
13-bit	0.011049
14-bit	0.007813
15-bit	0.005524
16-bit	0.003906

Table 1. Calculated maximum frequency with an error less than ½ LSB at the specified resolution

Conclusion

Obtaining dynamic performance compatibility between an amplifier and an ADC in data acquisition designs requires careful analysis of the amplifier's bandwidth capability. Choosing an amplifier that satisfies the bandwidth requirements of the system on the basis of its GBW product specification can introduce an excessive amount of error into the system. The amplifier must be chosen such that its closed-loop bandwidth matches the resolution needs of the ADC. This dictates the need for a much wider bandwidth amplifier than would be suggested by the specified signal bandwidth in the amplifier's datasheet. ■