Designing an anti-aliasing filter for ADCs in the frequency domain

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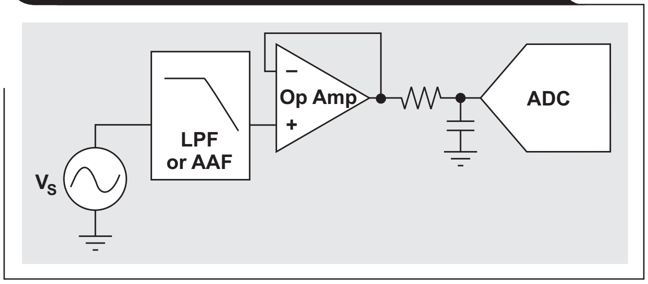
Introduction

Data acquisition (DAQ) systems are found across numerous applications where there is an interest to digitize a real-world signal. These applications can range from measuring temperatures to sensing light. When developing a DAQ system, it is usually necessary to place an anti-aliasing filter before the analog-to-digital converter (ADC) to rid the analog system of higher-frequency noise and signals. Figure 1 shows the general circuit diagram for this type of application.

Figure 1. Basic topology of a DAQ circuit



The DAQ system starts with a signal, such as a waveform from a sensor, V_S. Next is the low-pass filter (LPF) or anti-aliasing filter (AAF) and the operational amplifier (op amp) configured as a buffer. At the output of the buffer amplifier is a resistor/capacitor pair that drives the ADC's input. The ADC is a successive-approximation-converter ADC (SAR ADC).

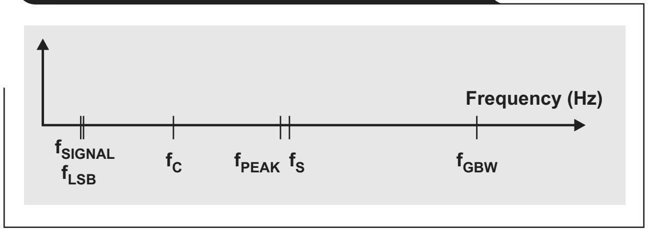
Typically, evaluations of this type of circuit consist of the offset, gain, linearity, and noise. Another perspective in evaluation involves the placement of events in the frequency domain.

There are six frequencies that impact the design of this system:

1. f_{SIGNAL} – Input signal bandwidth
2. f_{LSB} – Filter frequency with a tolerated gain error that has a desired number of least significant bits (LSBs). It is preferable that f_{LSB} is equal to f_{SIGNAL}
3. f_C – LPF corner frequency
4. f_{PEAK} – Amplifier maximum full-scale output versus frequency
5. f_S – ADC sampling frequency
6. f_{GBW} – Amplifier gain bandwidth frequency

Figure 2 shows the general relationship between these frequencies.

Figure 2. Basic relationship of f_S, f_{GBW}, f_{PEAK}, and f_C



For the following evaluation, the example system uses the following throughout:

- Input signal bandwidth of 1 kHz (f_{SIGNAL})
- Low-pass filter corner frequency of 10 kHz (f_C)
- SAR-ADC sampling frequency of 100 kHz (f_S)
- Dual operational amplifier, single-supply OPA2314

Determine maximum signal frequency (f_{SIGNAL}, f_{LSB}) and acceptable gain error

The first action is to determine the bandwidth of the input signal (f_{SIGNAL}). Next, determine the magnitude of the acceptable gain error from the LPF or AAF[1]. This gain error does not occur instantaneously at the frequency that is chosen to be measured. Actually, at DC, this gain error is zero. The LPF gain error progressively gets larger with frequency. An LSB error in dB equals

$$20 \times \log\left[(2^N - \text{err})/2^N\right],$$

where N is the number of converter bits and the whole number, err, is the allowable bit error. This error is found by examining the SPICE closed-loop gain curve.

In this example, the signal bandwidth is 1 kHz and acceptable gain error is equal to one code, which is equivalent to 1 LSB. For a 12-bit ADC where err equals 1 and N equals 12, the gain error equals –2.12 mdB.

Using a TINA-TI™ SPICE model to analyze a fourth-order, 10-kHz low-pass Butterworth filter, the closed-loop gain response is shown in Figures 3 and 4. In both figures, the location of the "b" cursor identifies the point where gain error is –2 mdB ($f_{1\text{-LSB}}$ = 1.04 kHz).

In Figure 3, the measurement window shows that the marker at "b" is at 1.04 kHz. The window also shows the –2 mdB[2] difference between frequency markers "a" and "b" on the y-axis.

Figure 4 zooms in on the y-axis of the Butterworth filter's action before the filter passes through its corner frequency (f_C). The first observation of this response is that the gain curve has a slight up-shoot before it begins to slope downwards. This upward peak reaches a magnitude of approximately +38 mdB. This is a fundamental characteristic of a fourth-order, Butterworth low-pass filter.

If a higher gain error is acceptable, Table 1 shows the change in f_{LSB}, versus the LSB value.

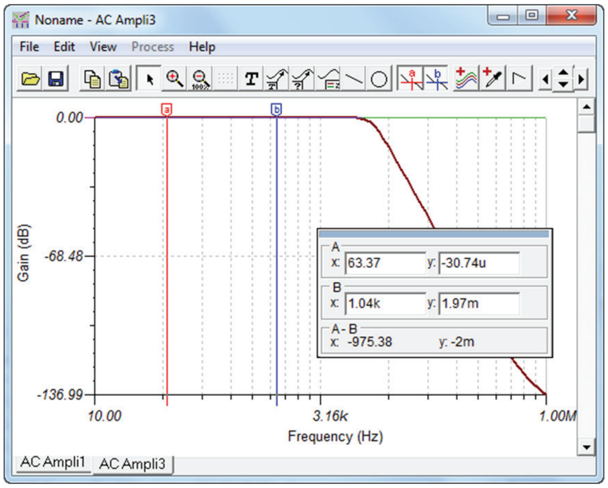
Table 1. LSB error versus f_{LSB}

LSB error (LSB)	LSB error (dB)	f_{LSB}
1	–0.002	1.04 kHz
2	–0.004	1.47 kHz
3	–0.006	1.82 kHz
4	–0.008	2.11 kHz

Filter corner frequency (f_C)

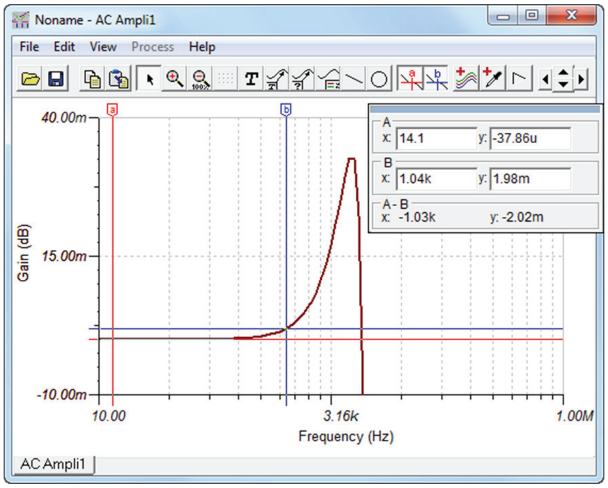
Note that the corner frequency (f_C) of the low-pass filter at the frequency where the attenuation of closed-loop frequency response is –3 dB. If a fourth-order LPF is chosen, f_C is approximately ten times higher than f_{1LSB}. SPICE simulations with the WEBENCH® Filter Designer allows this value to be determined quickly. When designing a single-supply filter in the filter designer, select the multiple-feedback (MFB) topology, which exercises the amplifiers with a static DC common-mode voltage that is at mid-supply. Figure 5 shows a circuit diagram of this fourth-order, 10-kHz Butterworth LPF.

Figure 3. Gain error at 1.04 kHz equals –2 mdB of a fourth-order, 10-kHz Butterworth LPF



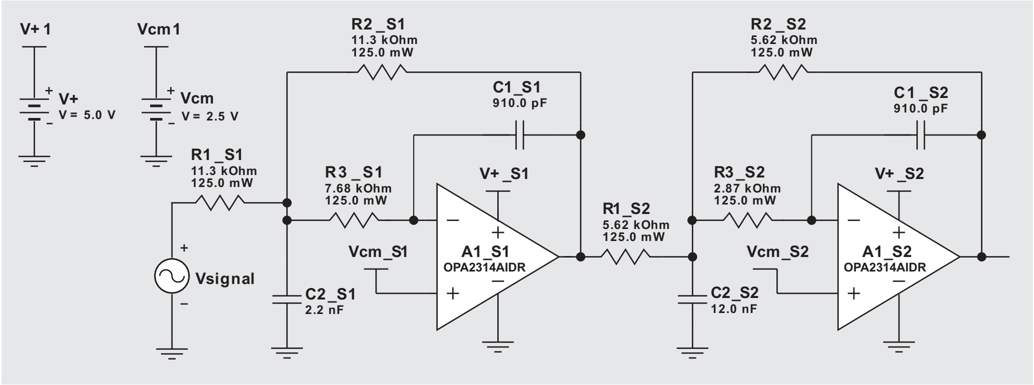
A
x: 63.37 y: -30.74u
B
x: 1.04k y: 1.97m
A - B
x: -975.38 y: -2m

Figure 4. Closed-loop gain response of a fourth-order, 10-kHz Butterworth filter



A
x: 14.1 y: -37.86u
B
x: 1.04k y: 1.98m
A - B
x: -1.03k y: -2.02m

Figure 5. Fourth-order, Butterworth LPF with f_C = 10 kHz



Define the amplifier's gain bandwidth frequency (f_{GBW})

The low-pass filter's Q factor, gain (G), and corner frequency (f_C) determine the amplifier's minimum allowable gain bandwidth (f_{GBW}). When finding the Q factor, first identify the type of filter approximation (Butterworth, Bessel, Chebyshev, etc.) and the filter order[2]. As previously specified, the corner frequency is 10 kHz. In this example, the filter approximation is Butterworth and the gain is 1 V/V. Finally, this is a fourth-order filter. The determination of the gain bandwidth of the amplifier is:

$$f_{GBW} = 100 \times Q \times G \times f_C \qquad (1)$$

In this system, f_{GBW} must be equal to or greater than 1.31 MHz (as verified by WEBENCH Filter Designer). The gain bandwidth of the OPA2314 dual amplifier is 2.7 MHz.

Amplifier's maximum full-scale output

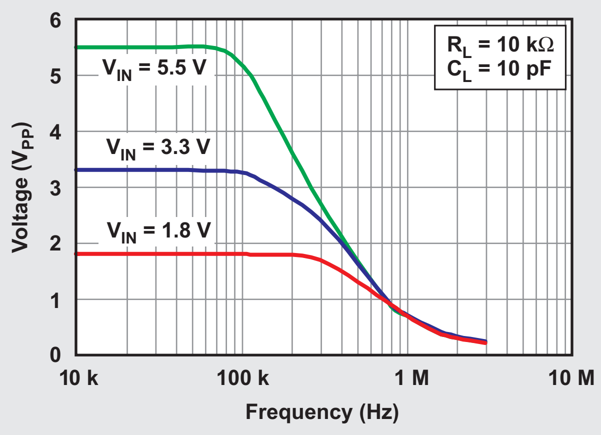
In most applications, it is imperative that the amplifier is capable of delivering its full-scale output. This may or may not be true. One check is to get a rough estimate from the amplifier's slew-rate specification.

A conservative definition of the maximum output voltage per frequency for an amplifier is equal to approximately $f_{PEAK} = SR/(V_{PP} \times \pi)$, where SR is the amplifier's datasheet slew rate and V_{PP} is the peak-to-peak specified output swing. Note that the amplifier's rise and fall times may not be exactly equal. So the slew-rate specification of the datasheet is an estimate.

The datasheet slew rate of the OPA2314 amplifier is 1.5 V/µs and in the 5.5-V system, V_{PP} equals 5.46 V. While the amplifier is in the linear region, the rail-to-rail output with a 5.5-V power supply is equal to 5.46 V. Figure 6 shows the tested behavior of the OPA2314 with an output range that goes beyond the linear region of the amplifier.

The calculated maximum output voltage of the OPA2314 occurs at approximately 87.5 kHz. However, in Figure 6, the maximum value with bench data is shown to be approximately 70 kHz. This discrepancy exists because of the mismatches between the amplifier rise and fall times and the responsivity of the amplifier at the peaks and valleys of the sinusoidal input voltage swing.

Figure 6. OPA2314 maximum output voltage



SAR-ADC sampling frequency

The challenge now is to identify the sampling frequency of the SAR ADC. Given a 1-kHz maximum input signal, it is imperative that the SAR ADC samples the signal more than one cycle per second. Actually, over ten times is preferable. This implies that a 10-kHz sampling ADC will work.

Additionally, it is important to eliminate signal-path noise when possible. If the SAR ADC is converting at higher frequencies above the corner frequency of the filter, that portion of the noise will not be aliased back into the system. Consequently, a 100-kHz sampling SAR ADC meets the requirements.

If the sampling frequency is 100 kHz, the Nyquist frequency is 50 kHz. At 50 kHz, the frequency response of the low-pass filter is down by approximately 50 dB. This level of attenuation limits the impact on noise going through the system.

Conclusion

The development of a DAQ system in the frequency domain can present interesting challenges. A system consisting of a filter and a SAR ADC is usually evaluated with the performance specifications of the DC- and AC-amplifier and the converter. This article, however, evaluated the system's signal path from a frequency perspective.

The important frequency specifications are the signal bandwidth, filter corner frequency, amplifier bandwidth, and converter sampling speed. Even though the signal bandwidth is small, 1 kHz, the required AAF corner frequency should be 10 times higher than the signal bandwidth in an effort to reduce high-frequency gain errors. Additionally, the converter's sampling frequency is higher than expected in an effort to reduce complications caused by noise aliasing.

References

1. Bonnie Baker, "Analog filters and specifications swimming: Mapping to your ADC," On Board with Bonnie, TI Blog, Nov 5, 2014.
2. Bonnie Baker, "Analog Filters and Specification Swimming: Selecting the right bandwidth for your filter," On Board with Bonnie, TI blog, Nov 8, 2013.

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