DATA ACQUISITION

Calculate an ADC's Effective Bits

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When selecting an analog-to-digital converter (ADC), you must examine several specifications. One spec to examine is effective number of bits (ENOB). ENOB takes many ADC errors (such as integral nonlinearity, differential nonlinearity, and total harmonic distortion) and conveniently reports them as one specification, providing an overall picture of an ADC's performance.

There are two methods for calculating ENOB. One lets you convert an ADC's signal-to-noise ratio (SNR) directly to effective bits. Another method relies on curve fitting, and that's the method I'll discuss. This method is also useful for evaluating data-acquistion boards and digital scopes.

ENOB represents an ADC's dynamic performance expressed in number of bits. ENOB is related to number of output bits, but the two specs differ. An ADC's output bits describe its theoretical performance, while the effective number of bits represents the device's actual performance.

Many parameters affect ENOB. Some change with frequency, while others don't. Integral nonlinearity (INL) and differential nonlinearity (DNL) directly change the ADC's quantization effects but don't change with frequency. That limits their usefulness as parameters for evaluating ADCs.

One parameter that does change with frequency is harmonic distortion. As input frequency increases, the ADC's internal amplifiers or comparators begin to slew-rate limit the ADC's performance. Harmonic distortion rises, and ENOB falls.

Another important factor in ENOB is signal amplitude. If an ADC has a bad DNL error near its full scale, then increasing the input signal's amplitude so the signal traverses this bad code will cause the ADC's RMS error to increase, thus decreasing ENOB.

A similar error can occur at low signal levels. If a converter has a bad code at midscale but has near-ideal performance elsewhere, reducing the amplitude will cause the midscale error to become a larger percentage of the overall error, causing a decrease in ENOB.

How to Calculate ENOB

To perform the ENOB calculation, you need to drive the ADC under test with a pure sine wave. **Figure 1** shows a typical setup you can use to

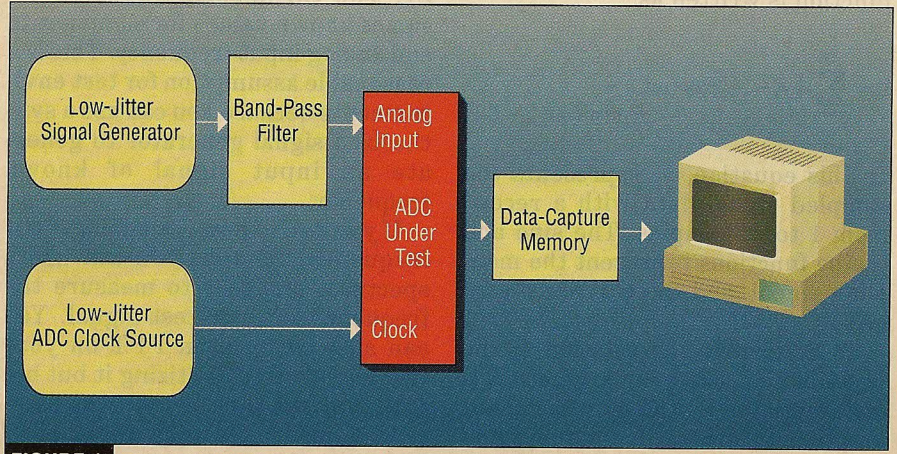

FIGURE 1. To calculate ENOB of an ADC, digitize a sine wave and apply a curve-fitting program in your PC.

measure the ENOB of an ADC. Because a signal generator's output may not be pure enough to test the ADC accurately, you should add a narrow band-pass filter to remove extraneous harmonics and noise.

The filter's pass band should be between 5% and 10% of the test signal's frequency. For example, if your test signal is 10 MHz, the filter's pass band should be between 500 kHz and 1 MHz, with center frequency of 10 MHz.

Collect the UUT's digital output in a high-speed data-capture memory. If you are evaluating a data-acquisition card, do not disable the card's front-end filters; consider the filters to be part of the overall system. After collecting the data, transfer them to a computer for storage and analysis.

Curve Fitting

You can calculate ENOB with a sine-wave curve-fit program that I have written (you can obtain a copy of the QuickBasic source code from *Test & Measurement World*[1]). My program extracts a best-fit sinusoidal signal (it reconstructs the original signal based on the data samples from the ADC) using a least-mean-square fitting technique. The technique is similar to linear regression except that it is based on a sinusoid rather than a straight line. The RMS error function is written as:

$$\varepsilon = \sum_{n=1}^{M} [y_n - A_1\cos(\omega t_n) - B_1\sin(\omega t_n) - C]^2$$

In this equation, y_n represents the sampled signal data with a record from 1 to M samples. The sine and cosine functions represent the modeling signal, and the C is the signal offset.

To determine the solution to the best-fit sine wave, this function is differentiated by the four variables: amplitude, offset, frequency, and phase. These equations are then minimized and simultaneously solved. (The unit sample rate is assumed known for the tests.) The result is the RMS error between the input signal and the fitted sinusoidal signal.

After the program calculates RMS error, it can compare the result to the ideal quantization error of the ADC. The ideal quantization error is the error that would result from a perfect ADC with the same number of bits as the ADC under test. The RMS error of an ideal 12-bit ADC is $Q/\sqrt{12}$, where Q is the size of the ADC's least-significant bit (1/4096 for a 12-bit ADC).

The logarithmic ratio between the actual RMS error and the ideal error gives the error in terms of bits. This is subtracted from the actual number of bits to provide the ENOB:

The logarithmic ratio between the actual RMS error and the ideal error gives the error in terms of bits.

$$ENOB = Bits - \log_2\left(\frac{\text{error}_{RMS}}{Q/\sqrt{12}}\right)$$

While complex in nature, this method is easy to implement in software. The method, however, is recursive and requires initial values. You need to accurately "guess" all but one of the variables for the equations to work. Providing the initial values for four variables to within a few percent can be difficult.

To simplify the process, you can use a three-term sine-wave curve fit. The three-term equation assumes known values for sample rate and analog input frequency. This is a reasonable assumption for test environments because you can use a synthesized signal generator to generate an input signal of known frequency.

If you don't know the analog input frequency, though, you can use a spectrum analyzer to measure the frequency of your test signal. You can also perform an FFT on your test signal after digitizing it but before applying the curve-fitting algorithm—just be sure the number of samples you take is a power of two. The three-term curve fit makes no initial assumptions about the amplitude, offset, or phase of the input signal.

The three-term method provides a poor estimate of the actual effective bits, but it does provide an excellent estimate of the signal parameters, usually within 1% of their actual values. You can calculate the ENOB by first performing a three-term sine-wave curve fit and then using the updated estimates of frequency, phase, amplitude, and offset as initial values for the four-term solution.

ENOB Has Limits

Despite being a convenient spec for comparing ADCs, ENOB does have several drawbacks. It provides no measure of gain or offset error and does not provide information of gain flatness over frequency.

Although ENOB will show degraded performance over frequency, the measurements made at each frequency become normalized in amplitude and do not directly show information on width. Therefore, you should not rely on ENOB as the sole criterion for evaluating ADCs. *T&MW*

FOOTNOTE

1. To receive the QuickBasic source code for the curve-fit program, send an e-mail message to tmw@cahners.com with the words ENOB CODE in the subject field; or, circle 233 on the reader service card.

FOR FURTHER READING

"Dynamic Performance Testing of A to D Converters," *Hewlett-Packard Product Note 5180A-2*, Hewlett-Packard, Santa Clara, CA, January 1989.

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Kester, Walt, "High Speed Design Seminar," Analog Devices, Norwood, MA, 1990.

Peetz, Bruce E., Arthur Muto, and J. Martin Neil, "Measuring Waveform Recorder Performance," *Hewlett-Packard Journal*, Palo Alto, CA, Vol. 33, No. 11, November 1982.

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