

DYNAMIC TESTS OF ANALOG-TO-DIGITAL CONVERTERS

Dimitar Petrov Dimitrov

Melexis - Bulgaria Ltd., 84 Ami Boue Str, 1618 Sofia, Bulgaria, e-mail: ddi@melexis-bg.com

With the increase of the speed and the accuracy of Analog-to-Digital converters (ADC), the evaluation of their performance has become a significant problem. The traditional "static" method employs a precision digital voltmeter to evaluate each code transition with high accuracy. However, this method fails to describe the converter's dynamic performance. The frequency-dependent behavior of data converters can only be evaluated by applying an AC input signal in the frequency range over which the converter is expected to operate and with an amplitude close to the converter's full range. The Fast Fourier Transform (FFT) as well as the histogram analysis is a powerful tool for evaluating the dynamic performance of data converters. However, processing the output code of the ADC under test into its FFT components requires expensive and elaborate software. This article proposes a simple procedure for evaluating the ADC dynamic performance which doesn't need complex data acquisition systems and expensive software. Various dynamic tests are considered and compared along with some practical aspects of their applications. A special low-cost data acquisition system was developed for practical test realization. The merits of the proposed methods and data acquisition system have been proved by experiments conducted on real ADCs. The results derived are compared to the results achieved by Matlab and static tests.

Keywords: ADC, mixed-signal, FFT, signal processing

1. INTRODUCTION

Static tests, no matter how comprehensive, are not sufficient for full A/D converter characterization. Dynamic tests reveal the behavior of the converter when an AC signal is applied, i.e. dynamic parameters describe the converter's ability to process the signals in the real world. The statistical analysis of ADC is based on applying an input signal with well known statistical properties and making a histogram that gives the number of occurrences for each code at the output of the converter. Next, the histogram is compared to the probability density function of the input signal. The accuracy of this method can be enhanced by simply collecting more samples. If a sine wave (or a combination of sine waves) is applied to the converter, the output data may be processed by means of Fast Fourier Transform (FFT) algorithm. The spectrum of the output contains the input sine wave, quantization error and harmonic distortions caused by the converter's nonlinearities. In this way the converter's nonlinearities can be evaluated. Processing the samples in order to obtain the output spectrum is tedious work. Some software is then needed to deal with the numbers. Software packages such as Matlab, Labview, and Mathcad can easily do the job. However, they need rather expensive licenses (Mathcad charges some \$1,195 for a single-user license). A cheaper and simpler substitute will definitely find wide application in engineering practice.

2. HISTOGRAM ANALYSIS

The ramp (or triangle) wave is the natural first choice for histogram analysis as it has the simplest code density function – for an ideal ADC, an equal number of counts is expected for each code:

$$P(i) = \frac{K}{2^N} = \text{const} \quad (1)$$

where K is the total number of samples and N is the number of bits (resolution) of the ADC under test. Sine input waves can be generated with high spectral purity. The probability density for the i_{th} code to occur is [3]:

$$P(i) = \frac{1}{\pi} \left[\arcsin\left(\frac{V(i - 2^{N-1})}{A2^N}\right) - \arcsin\left(\frac{V(i - 1 - 2^{N-1})}{A2^N}\right) \right] \quad (2)$$

where V is the input amplitude and A is the converter's full scale. An important advantage of the code density test is that it accurately describes differential nonlinearities and gives a more accurate estimate of the converter's noise since each output code is obtained many times.

2.1. Interpreting the histogram results

Let H be the number of counts observed for the i_{th} code. Ideally, the expected and the measured counts should be equal and their ratio should be one. If a particular step in the ADC transfer function is wider / narrower than the ideal value of $V_{\text{REF}}/2^N$, it will accumulate more / less counts, hence a Differential Nonlinearity (DNL) is observed at that code:

$$DNL = \frac{\text{Counts}_{\text{MEASURED}}}{\text{Counts}_{\text{EXPECTED}}} - 1 = \frac{H(i)}{K/2^N} - 1 \quad (3)$$

The extreme case of DNL is the missing codes. Missing codes are easy to spot – there are no counts for them. Histogram tests also allow the converter's own noise to be measured. For a given DC input within the converter's input range, a noiseless converter will produce identical output codes, and any spread of the output codes would be a direct measure of the converter's internal noise. Although histogram analysis provides an accurate estimate of the converter's DNL, it is not suitable for integral nonlinearity (INL) evaluation. The integral nonlinearity at any code is by definition the sum of the differential nonlinearities at the codes up to it:

$$INL(i) = \sum_{n=0}^i DNL_n \quad (4)$$

Any nonlinearity in the input wave and any error in measuring the input signal amplitude would quickly accumulate in this summation and conceal the actual INL of the converter.

3. FFT ANALYSIS OF ANALOG-TO-DIGITAL CONVERTERS

The continuous Fourier Transform in its complex form is expressed as [4]:

$$F(t) = \sum_{n=-\infty}^{\infty} c_n \times \exp(jn\omega t) \quad (5)$$

where the complex coefficients are given by:

$$c_n = \frac{1}{T_0} \int_0^{T_0} h(t) \times \exp(-jn\omega t) dt \quad (6)$$

The continuous Fourier transform cannot be used to evaluate a data converter since the input signal is only digitized on a finite number of points. So the Discrete Fourier Transform (DFT) is used instead:

$$H_n = \sum_{k=0}^{N-1} h_k \times \exp(jk \frac{2\pi n}{N}) \quad (7)$$

where the discrete coefficients are given by:

$$h_k = \frac{1}{N} \sum_{n=0}^{N-1} H_n \times \exp(-jn\omega_0 t_k) \quad (8)$$

The FFT algorithm implies some $N \log_2 N$ complex multiplications; however, this is much better than the Discrete Fourier Transform (DFT), which requires N^2 complex multiplications. The FFT algorithm only requires that the input signal be smooth and periodic and the number of samples K be a power of two (i.e. $K=2^n$).

3.1. Frequency considerations

In order for the input wave spectrum to be accurately rendered, there must be a single spectrum line to represent the input fundamental frequency. Since the output spectrum is a discrete one and exhibits only frequencies with a step of $\Delta f = f_s/K$, it is necessary that f_{IN} as well its harmonics be integer multiples of the frequency step:

$$f_{IN} = M \times \Delta f = M \times \frac{f_s}{K} \quad (9)$$

where M is an integer number and K is a power of two ($K=2^n$).

To guarantee that f_{IN} and f_s are not harmonically related, it is necessary that M and K be mutually prime. Since K is a power of two this condition is easily met when M is an odd number. Eq. 9 expresses the coherent sampling criterion. If this requirement is not satisfied, spectral leakage is observed – the power of the fundamental frequency “leaks” to the adjacent frequency bins. Leakage can be reduced by means of special window functions which shape the raw data record so that it begins and ends at the same level – the shaped data record appears to be coherent.

3.2. The proposed test procedure

The main part of the task is to calculate the complex Fourier coefficients given in Eq. 8. The chief advantage of the procedure proposed is that it does not need elaborate mathematical software. The popular Excel package has a built-in routine that calculates the complex coefficients h_k out of the input series of samples H_n . The

FFT algorithm requires that the number of samples M be a power of two and Excel can handle up to 4096 samples.

First, all the samples are entered in the Excel worksheet. The Fourier routine is evoked in the “Tools” menu by selecting “Data Analysis” and then selecting “Fourier analysis”. After entering the input range and the place in the worksheet for the output data, Excel gives a column with the complex Fourier coefficients. K samples taken at sampling frequency f_s allow the spectrum to be evaluated with a resolution of $\Delta f = f_s/K$. The complex coefficients are symmetrical with respect to the folding frequency $f_N = f_s/2$, hence only the first $K/2+1$ complex coefficients are used, which represent the frequencies from DC to $f_s/2$. Since Excel has no way of knowing what the sampling frequency is, the frequency bins have to be evaluated. In the next column, the frequency bins from 0 to $K/2$ are listed with a step $\Delta f = f_s/K$. Next, the absolute values of the Fourier coefficients are calculated by means of the IMABS function. Finally, logarithms are taken out of the absolute values. As a result, the plot of the logarithms of the coefficients versus the frequency bins represents the output spectrum of the digitized input waveform.

3.3. Evaluating ADC performance by means of FFT

The total harmonic distortion (THD) is the ratio of the rms values of the first five harmonics to the rms value at the fundamental frequency [2]:

$$THD = 10 \log \left(\frac{V_2^2 + V_3^2 + V_4^2 + V_5^2 + V_6^2}{V_1^2} \right) \quad (10)$$

The Signal-to-Noise and Distortion Ratio [SNDR] is an important figure of merit and is defined as the ratio of the power at the input signal frequency to the sum of the powers at all the other spectral components:

$$SNDR = \frac{V_{\text{SIGNAL}}^2}{\sum_{j=0}^{K/2} V_j^2 - V_{\text{SIGNAL}}^2} \quad (11)$$

An ideal ADC has quantization noise only and the maximum theoretical S/N ratio is $6,02N+1,76$ dB, where N is the number of bits. Hence for a given SNDR obtained by test, the Effective Number of Bits (ENOB) can be expressed as:

$$ENOB = \frac{SNDR - 1,76}{6,02} \quad (12)$$

4. EXPERIMENTAL RESULTS

Essentially the same hardware is used for both histogram and FFT analysis. A specially designed test kit based on a single-chip microcontroller and a commercially available waveform generator were used to collect the samples. The device under test (DUT) was an 8-bit semi-flash ADC designed in Melexis – Bulgaria. Output codes from the ADC under test are first sampled at a sampling frequency of 222kHz and saved in a fast internal memory, and then the data are transferred to a personal

computer via optically isolated interface. To perform the histogram tests, batches of 32,768 samples were collected for ramp (triangle) and sine input waves at different frequencies. An input overdrive of 5% was applied to guarantee that the whole input range of the DUT is explored. For the needs of FFT analysis, batches of 8,192 samples were collected by means of coherent sampling. To guarantee the high spectral purity of the sine waves, and to make it possible to experiment with different input frequencies, low-pass filters were inserted between the waveform generator and the ADC input. Then the samples were processed by means of two different software packages. Batches of 8,192 and of 4,096 samples were processed by Matlab and batches of 4,096 samples were processed by Excel. The FFT spectra obtained of 4,096 samples in Matlab and Excel are identical. The only difference between 8,129 samples FFT (done by Matlab) and the 4,096 samples FFT (both for Excel and Matlab) is that 8,192 samples give higher spectral resolution.

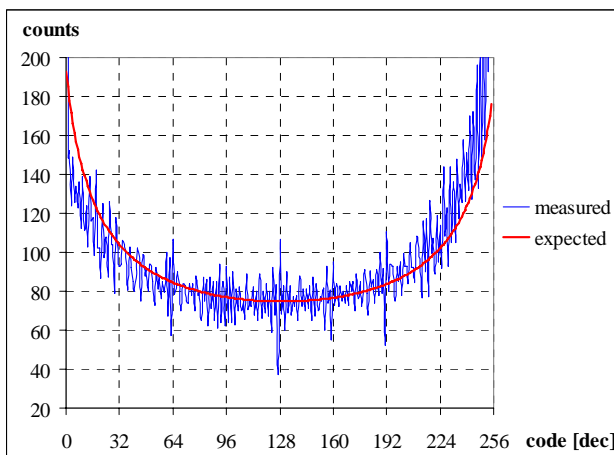


Fig. 1 Sine wave histogram,
 $f_{IN}=10\text{kHz}$, $K=32,768$ samples

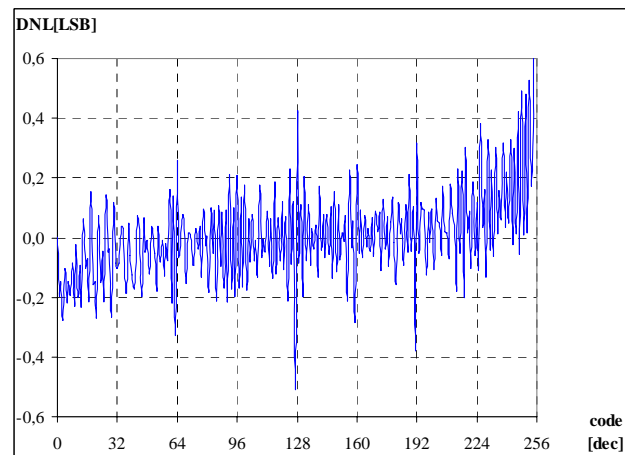


Fig. 2 DNL obtained by histogram
analysis, $f_{IN}=10\text{kHz}$, $K=32,768$ samples

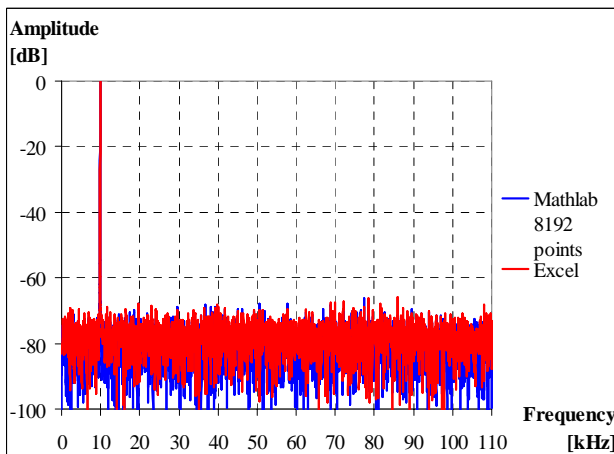


Fig. 3 Single tone FFT plot,
 $f_{IN}=10\text{kHz}$, $K=4,096$ samples

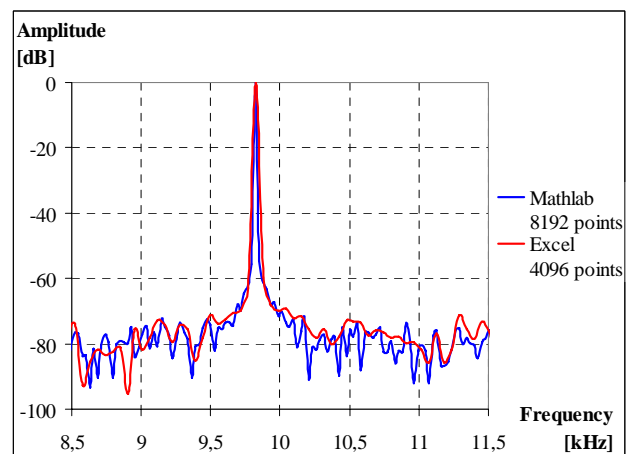


Fig. 4 Single tone FFT plot, detail

Table 1. Test methods comparison(All parameters measured at $V_{DD}=5V$; $T=25^{\circ}C$)

parameter method	Offset [LSB]	INL [LSB]	DNL [LSB]	THD [dB]	SNDR [dB]	ENOB
Static tests	0.5	0.3	0.3			
Histogram analysis	0.57		0.51			
FFT analysis				-62.8	43.5	6.9

5. CONCLUSION

Two major methods for evaluating the dynamic parameters of an analog-to-digital converter have been examined. Histogram analysis has proven to be the best way to evaluate a converter's DNL, as well as missing codes, gain error, offset and noise. The large number of samples that histogram analysis needs to attain the desired accuracy is generally not a problem with low- to medium-resolution converters. FFT is best in evaluating INL, SNR, THD, etc., even though it is very sensitive to signal noise. Applying either histogram analysis or FFT involves collecting a large number of samples and then processing the data with the help of a computer. A simple data acquisition kit was developed which makes it possible to conduct some basic ADC dynamic tests. Despite the complexity of some calculations, most of them don't need elaborate mathematical software. The widely available Excel package was used instead. The validity of the procedures and hardware proposed was proved through experiments on a real two-step flash converter developed in Melexis – Bulgaria. The results obtained in this way coincide with the results obtained by much more elaborate and expensive software packages.

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6. REFERENCES

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