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Realiable ADC testing using LabVIEW

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***Abstract* – The sinewave histogram test is a commonly used method to characterize nonlinear behavior of A/D converters. Accurate test results require wise choice of the test settings and signal parameters. However, standard methods do not support the recognition of bad parameter settings. In addition, those may provide inaccurate results even when the signal settings are optimal for the histogram test. This paper presents a software which helps handling above problems and deficiencies to guarantee the quality of the test results.**

I. INTRODUCTION

Characterization of analog-to-digital converters is an important field of measurement technology. A commonly used method for ADC testing is the so-called sinewave histogram test. In this procedure the ADC is excited with a sine input, then a histogram is created which is used to determine the transition levels of the converter. This estimation method requires accurate knowledge about the sine parameters. The histogram test and the sine parameter estimation method (four-parameters least squares fit) are described in details in the [1] IEEE standard. Furthermore, the standard defines strict conditions for the signal parameters which have to be fulfilled to ensure accurate results. However, there are a few deficiencies and disadvantages in the standard methods:

- No method is proposed to check the fulfillment of the conditions for the signal parameters.
- The proposed methods are sensitive to the signal parameters and are unable to recognize bad parameter settings which leads to incorrect characterization of the converter.
- Correct signal parameters by themselves still do not ensure precise estimation of the sine parameters since the least squares method is sensitive to the nonlinearities of the ADC.

This paper presents some advanced algorithms which are able to handle the above problems and support the accurate characterization of the A/D converters. Experimental results are included since the algorithms were realized in LabVIEW environment. The results are reproducible since the software will be available from the ADC Test project site.[1]

[1] http://www.mit.bme.hu/projects/adctest/

The LabVIEW tool is based on the work of Tamás Virosztek [14], [13].

II. BACKGROUND AND NOTATION

A. *The sinewave histogram test*

The histogram test is an effective way to estimate the transition levels of an A/D converter. The ADC is tested with a pure sine wave which slightly overdrives the input range (see [4]). A histogram is created which shows the number of hits in each code bin. Let $H(i)$ be the number of hits in code bin i (for an ADC of b bits $i = 0 \dots 2^b - 1$). Then the $H_c(j)$ cumulative histogram can be defined as

$$H_c(j) = \sum_{i=0}^{j} H(i). \tag{1}$$

Let the model of the excitation signal be

$$x(t) = C + R\cos(2\pi f_x t + \phi), \tag{2}$$

where C, R, f_x and ϕ are the offset, amplitude, frequency and initial phase, respectively. Using the parameters C, R, the number of samples N and the cumulative histogram H_c the kth transition level can be estimated:

$$T(k) = C - R\cos\left(\frac{\pi H_c(k)}{N}\right). \tag{3}$$

Above estimation procedure is very sensitive to the appropriate ratio of the f_x signal frequency to the f_s sampling frequency. This ratio defines the relation between the number of samples N and the number of periods J in the record:

$$\frac{f_x}{f_s} = \frac{J}{N}. \tag{4}$$

Standard [1] defines that the sampling has to be coherent (J has to be an integer value) and J has to be relative prime to N. These conditions are very important because they guarantee the unbiased, minimal variance estimation of the transition levels (see [1] and [11]). However, there is no proposal in the standard about checking the fulfillment of above requirements.

B. *The least squares method*

Precise knowledge about the signal parameters is quite important in ADC testing. For example, the fitting residuals strongly depend on the estimated parameters. Equation (3) also shows that the amplitude and offset parameters have to be known as exactly as possible to precisely determine the A/D characteristics. The proposed method is the so-called four-parameters least squares sine fit algorithm. The method uses the following model of the sine wave:

$$x(t) = A\cos(2\pi f_x t) + B\sin(2\pi f_x t) + C \qquad (5)$$

where $A = R\cos(\phi)$ and $B = -R\sin(\phi)$. The advantage of this model is that it is nonlinear only in the f_x signal frequency. Using the measured signal, the A, B, C and f_x parameters can be estimated iteratively (for more details, see [1]). Despite this is an effective way to estimate the parameters, it has several disadvantages:

- The precision of the estimator depends strongly on saturation, e.g. a 10% overdrive increases the variance significantly.
- The presence of harmonic components also affect negatively the precision of the estimation.
- The algorithm implicitly assumes that measurement data is quantized by an ideal quantizer, thus $ENOB$ calculation based on parameters estimated in least squares sense will be distorted.
- The computational costs increase quickly with the record length, however testing high-resolution A/D converters require long records.

III. THE ADC TEST SOFTWARE

A. *Main goals*

The main goal of this paper is to present a LabVIEW software [8] which helps the user in efficient ADC testing. In details, with respect to the disadvantages described above:

- Provides quality analysis of the measured data by checking saturation and the fulfillment of the conditions on the relation between sampling frequency and signal frequency.
- If the signal fails to fulfill the conditions, the software identifies a coherent part of the measurement for which J and N are relative primes. If this is not possible, a new signal frequency is proposed with which the measurement can be repeated. This way the quality of the results of the histogram test and the FFT test can be maximized since both of them require coherent sampling.
- Signal parameters are determined by the so-called Maximum likelihood (ML) algorithm. The ML estimator is not affected negatively by the nonlinear characteristics of the ADC under test, thus signal parameters, fitting residuals and ENOB can be determined with the best precision.

Next subsection presents the main steps of the measurement data processing in the software. It will be shown clearly that no a priori knowledge about the signal parameters or the ADC characteristics is used or required.

B. *The data processing chain*

Overdrive detection

Overdrive detection is important because distortions in the sinewave caused by saturation influence the results of the sine fit and the FFT test (see [15]). The purpose of this method is to identify the samples in the measured signal which supposed to be higher than the full scale (FS) of the ADC. For this purpose first the number of periods (J) in the signal is determined using IpFFT with Hann window [7], then a three-parameters sine fit [1] is done to determine the A, B and C parameters. Let $y(k)$ be the output of the ADC (codes), C_{min} the smallest and C_{max} the largest output code of the converter. Based on [6] only those samples are used during the three-parameters fit algorithm for which the following condition holds true:

$$C_{min} < y(k) < C_{max}. \qquad (6)$$

Then the $x_f(k)$ fit can be expressed as

$$x_f(k) = \hat{C} + \hat{A}\cos\left(\frac{2\pi \hat{J}k}{N}\right) + \hat{B}\sin\left(\frac{2\pi \hat{J}k}{N}\right). \qquad (7)$$

In the quantized signal the samples are represented with the codes of the ADC and the size of the quantization step (LSB) is 1. We will assume that the kth sample of $y(k)$ is overdriven if $x_f(k) \leq C_{min} - 1/2$ or $x_f(k) \geq C_{max} + 1/2$. These samples are replaced with the corresponding samples of $x_f(k)$:

$$y'(k) = \begin{cases} x_f(k) & \text{if } x_f(k) \leq C_{min} - 1/2 \\ x_f(k) & \text{if } x_f(k) \geq C_{max} + 1/2 \\ y(k) & \text{otherwise} \end{cases} \qquad (8)$$

Using $y'(k)$ instead of $y(k)$ during the FFT test and sine fitting will improve the results significantly.

Least squares fitting in the frequency domain

Disadvantages presented in section II.B. shows that the standard, time domain least squares method is not the best for ADC testing. Fortunately, most of these disadvantages can be handled by performing the fit in the frequency domain. For this purpose, first $y'(k)$ is windowed with the three-terms Blackman-Harris window [2], then the FFT of the windowed signal is computed. During the least squares fit only the points around the sinewave and DC frequency are used (for more details, see [9] and [10]). The method has the following advantages:

- Since it uses only a few points from the result of the FFT, the fit is done much faster.

- The statistical properties of the estimator are usually the same in comparison with the original method (on low frequencies the frequency domain estimator outperforms the original method)

- Due to the windowing the algorithm is much less sensitive to harmonic components.

However, the estimation of the parameters are still biased due to the nonlinearity of the ADC under test, but the influence of the characteristics is much more significant on parameters A, B and C in comparison with J. Thus, $\hat{J}_{LS}$ is approximately unbiased and it can be used to check the fulfillment of the conditions defined for accurate histogram testing (section II.A.).

Coherence analysis
The main purpose of this algorithm is to decide the suitability of the measured sinewave for histogram testing. This depends on the exact number of periods in the signal, J. This can be written as

$$J = \langle J \rangle + \Delta J, \tag{9}$$

where $\langle J \rangle$ is the rounded value of J and ΔJ is the residual, thus $-0.5 \leq \Delta J < 0.5$. The goal is to identify the longest record part in the measurement which is sampled coherently and meets the relative prime condition. The software uses the condition for coherence of Carbone and Chiorboli, who showed in [5] that if $\langle J \rangle$ and N are relative primes and

$$\Delta J \leq \frac{1}{2N} \tag{10}$$

holds true then the variance of the histogram test method does not increase significantly in comparison with the $\Delta J = 0$ case. This means that the sampling can be assumed coherent when the (10) condition is met. In [10] and [11] it was show that the standard deviation of $\hat{J}_{LS}$ is much smaller then $1/(2N)$, so the following questions can be answered:

- Does the N long record meet the coherence and relative prime conditions?

- If not, how many samples (N') should be used from the record to fulfill the requirements?

- If N' is to small to characterize the ADC accurately, what adjustment is needed in the signal frequency to perform a new measurement with optimal settings?

If a measurement fails to fulfill the requirements, the algorithm starts to reduce the number of periods in the record until both conditions are met. If the new record length, N' is too short, a new signal frequency is proposed based on the nominal value of f_s and the estimated value of ΔJ. It is important to notice that the incorrect nominal value of f_s does not harm the proposed value of f_x, because only the ratio of these parameters is important, not the values themselves.

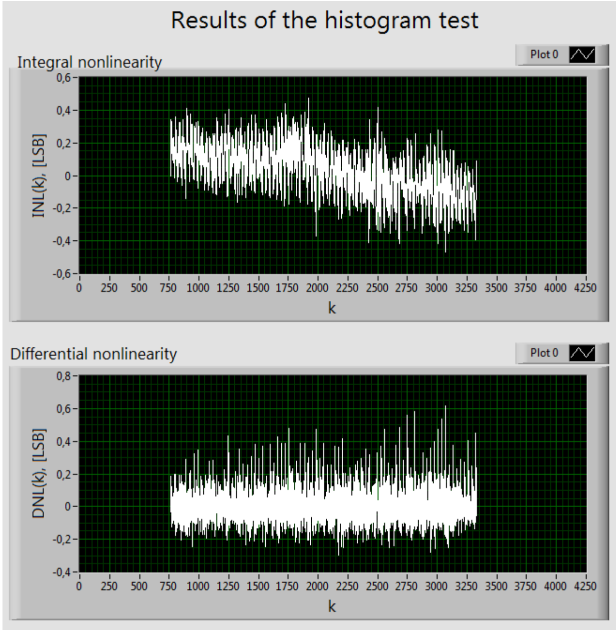

Fig. 1. Integral and differential nonlinearity of the tested ADC.

Histogram test
The histogram test is done exactly in the way recommended in [1]. At this point of the data processing coherence is assured thus the test will provide unbiased results. In addition, since the largest common divisor of J and N is 1 due to the relative prime condition. This means that every sample of the sinewave excited the ADC on a different voltage level, so every sample has a unique phase. These phases are uniformly distributed in the $(0, 2\pi)$ interval so the transition levels can be determined with minimal uncertainty (for more details, see [11]).

FFT test
The FFT test of the ADC provides information about the ADC in the frequency domain. The result of the test shows the spurious components in the measured signal. The spurious free dynamic range (SFDR) shows the relation between the carrier and the highest spurious component in the signal. Overdrive of the ADC or not coherent sampling significantly decrease the precision of results due to leakage and other harmonic components caused by clipping the peaks ([15]). Since both error sources are handled in the software, SFDR can be determined precisely.

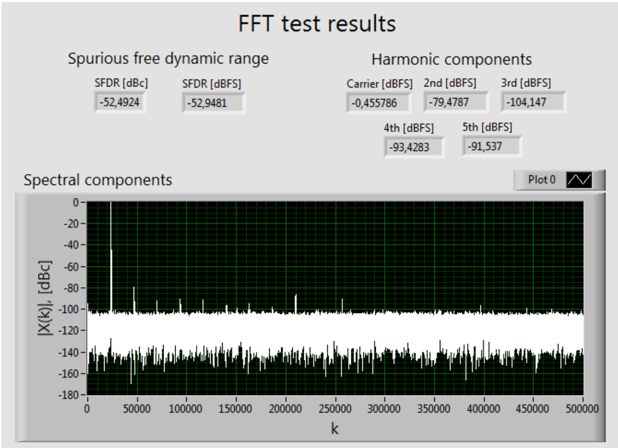

Fig. 2. FFT testing in the LabVIEW software.

Maximum likelihood estimation

Maximum likelihood estimation is the most precise algorithm to determine the signal parameters and noise variance when no a priori information is available. The most attractive (asymptotic) properties of the ML estimator are:

- unbiasedness,
- efficiency,
- normal distribution.

Maximum likelihood estimation of the parameters can be determined by optimizing the ML cost function (the Likelihood function):

$$L(A, B, C, J, \sigma) = \prod_{k=1}^{N} P(Y(k) = y(k)), \tag{11}$$

where

$$\begin{aligned} P(Y(k) = l) = \tfrac{1}{2}\Big[&\mathrm{erf}\Big(\tfrac{T(l+1)-x_f(k)}{\sqrt{(2)}\sigma}\Big) - \ldots \\ &-\mathrm{erf}\Big(\tfrac{T(l)-x_f(k)}{\sqrt{(2)}\sigma}\Big)\Big]. \end{aligned} \tag{12}$$

Above $Y(k)$ is a discrete probability variable, its possible values are the output codes of the ADC. $P(Y(k) = l)$ describes the probability that the corresponding sample of $y(k)$ fall between the lth and $(l + 1)$th transition level. In other words, the ML estimation of the sine parameters are the most likely parameters for a given measurement. The parameters can be estimated without bias since the method uses the previously determined transition levels of the ADC. Maximum likelihood estimation of the parameters also guarantees accurate determination of ENOB and SINAD (instead of the LS method which commonly overestimates such values in the case of nonlinear ADC characteristics). For more details about ML estimation see [3], [14] and [12].

IV. EXPERIMENTAL RESULTS

Above algorithms were tested in real measurements using an NI myDAQ 16 bit ADC device which has a sampling frequency of $f_s = 200$ kHz. The excitation signal was generated by a Brüel & Kjaer Type 1051 sine generator. The amplitude and frequency of the signal was set to $A = 1.2FS$ (where FS is the full-scale voltage of the ADC) and $f_x = 97$ Hz, then $N = 2^{20}$ samples were measured. These nominal values seems to fulfill the coherence and relative prime conditions. First the results of the proposed and the original least squares fitting algorithm (see [1]) were compared. Table 1. shows the results. The difference in the values (except for parameter J) are caused by the overdrive of the ADC. Overdrive leads to the presence of harmonic components which affect negatively on the performance of the original method. Since the proposed method is able to detect overdrive and minimize the effect of the harmonic components, it provides more precise results.

Table 1. Comparison of the original and the proposed least squares fitting methods

Parameter	Original	Proposed
A [LSB]	-30834.5	-30886.4
B [LSB]	12140.2	12160.1
C [LSB]	32789.8	32793.3
J	211.005	211.005
SINAD [dB]	48.240	79.114
ENOB	7.721	12.849

Next the result of two histogram tests are compared, where the first was done using coherence analysis, while the second was performed using the whole record. Coherence analysis showed that the optimal record length for histogram testing is $N_{opt} = 288227$. Fig. 3 shows the results and the error of the INL estimation. In the first case the coherence condition is not fulfilled, so the histogram test provides distorted results. The error curve shows that 57 transition levels were estimated with an error higher than 3 LSB, 4113 transition levels were estimated with an error higher than 2 LSB, while the mean value of the estimation errors is 0.957 LSB.

In the last test the results of the least squares and maximum likelihood estimators are compared. Since the ML method uses the transition levels of the ADC during the optimization process, it is not harmed by the nonlinearities of the ADC so the results are more precise in comparison with the LS estimator. The results are shown in Table 2.

The SINAD and ENOB parameters are found to be smaller using ML fit, this is because the LS method minimizes the error, thus maximizes SINAD and ENOB, while the ML method maximizes the probability with respect to the parameters.

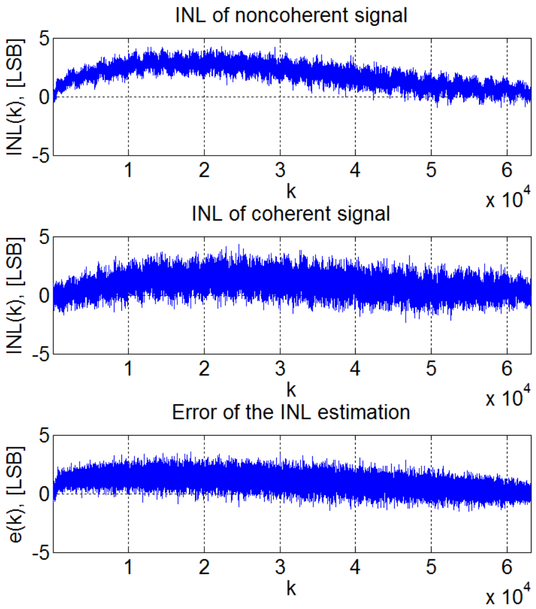

Fig. 3. Comparison of the results of histogram tests using coherent and noncoherent input signals.

Table 2. Comparison of the least squares and maximum likelihood fitting algorithms

Parameter	ML	LS
A [LSB]	-30886.4	-30886.4
B [LSB]	12160.1	12160.1
C [LSB]	32792.8	32793.3
J	211.005	211.005
SINAD [dB]	78.918	79.114
ENOB	12.817	12.849

V. CONCLUSION

A LabVIEW toolbox was presented which is able fully characterize an ADC. Experimental results show that the applied methods provide precise results even if the ADC is overdriven and the coherence and/or relative prime condition is not fulfilled.

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