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FAST TESTING OF ADC USING UNIFIED ERROR MODEL

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Abstract − The progress in the technology of the analogue to digital converters (ADCs) suppresses the error effects linked with its inherent architecture. Multiperiodicity of differential nonlinearity and the impact of analog components at the ADC input on the integral nonlinearity prefers unified behavioural error model expressed as one dimensional image in the code k domain. The paper presents two new methods for low code frequency testing. The first one is based on synchronous detection of higher harmonics in ADC output record. Second apply repetitive best fitting method to estimate the harmonics. detection by multiplone utilise combination of the fast. testing methods, which allow to identify the model parameters. The high code frequency model component could be determined by fast histogram method using reduced FS triangular voltage.

Keywords ADC Modelling, ADC Testing.

1. INTRODUCTION

Differential or integral nonlinerities (*DNL*(*k*), *INL*(*k*)) as the function of the ADC code bin k depends mainly on the architecture of utilized ADC, the chip layout and on the technological procedure. The impact of the architecture on the error model is well known [2]. The effects of chip layout and technological processes in the production are unknown for the ADC end users. The improvement in the technology of the ADC production suppresses the regularity of the error occurrence [3]. Those facts prefer implementation of the error model, which is expressed as one dimensional image in the code *k* domain [1].

This image consists of two components:

a) Low code frequency component (LCF) represented by modelled polynomial approximation $^{LCF}INL_m(k)$ of error caused by analog error components. Function $^{LCF}INL_m(k)$ could be expressed by a polynomial [5].

b) High code frequency component (HCF) $^{HCF}INL_m(k)$ caused by a regular occurrence of the modelled values of $DNL_m(k)$. The periodical occurrence of various types of *DNL* allows to describe HCF component by the Walsh spectrum in the most consistent way [2], [3].

The modelled shape of the integral nonlinearity using both components is as follows

$$INL_m(k) = {}^{LCF}INL_m(k) + \sum_{l=0}^{k} DNL_m(l) \qquad (1)$$

The LCF integral nonlinearity component $^{LCF}INL_m(k)$ covers the discrepancy in the periodical properties of the $DNL_m(k)$ caused by effects omitted in the deduction of ADC model.

Polynomial function modelling the low code frequency component is expressed as follow:

$$^{LCF}INL_m(k) = A_0 + A_1 k + A_2 k^2 + \ldots + A_L k^L , \qquad (2)$$

where *L* is order of LCF modelling polynomial. Practical experiments indicate that the polynomial of fifth order apxorimates the LFC component with satisfying accuracy for common ADC.

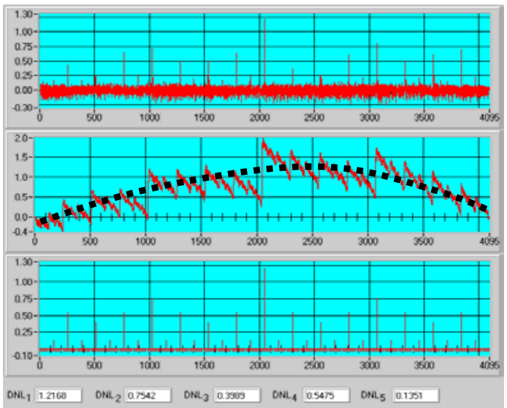

Fig.1.a.)Measured *DNL(k)* b.)Low and high code frequency component of $INL_m(k)$, c.) Modelled periodical occurrence of modelled $DNL_m(k)$.

2. TESTING OF LCF COMPONENT

The knowledge of the LCF and HCF model parameters allow to estimate the ADC error function with appropriate uncertainty. There is a close relation between the coefficients of polynomial (2) and the components of the frequency spectrum for harmonic exciting signal. Because of typically low values of integral nonlinearities for ADCs with mean resolution (less than 1LSB for 10-12 bit ADC), the harmonic components in the output spectra are hidden in the background quantisation noise background. Similarly to other dynamic ADC testing methods, the distortion of testing generator should be below level of expected $^{LCF}INL_m(k)$.

Let consider approximation of LCF component by a polynomial of fifth order. In [1], the dual slope ADCs were modelled just by a polynomial of third order with acceptable uncertainty. The spectral components are calculated for the case of the ADC excitation by the cosinusoidal signal $x = X_0 \cos \omega t$. DC component of input signal is H_0.

Harmonic components are H_1, H_2, H_3, H_4, H_5 as the first, second, third, forth and fifth harmonic component respectively. The relations among polynomial coefficients and spectral components could be obtained by substituting the harmonic signal $X_0.\cos(\omega iT_S)$ into the polynomial (2). The contributions of single polynomial component are calculated by well known formulas for various powers of harmonic function. The final relation among amplitudes K_i of the i^{th} harmonic component and polynomial coefficients A_i could be expressed by matrix relation

.

$$\mathbf{H} = \mathbf{P.A} \qquad (3)$$

where,

$$\mathbf{P} = \begin{bmatrix} 1 & 0 & X_0^2/2 & 0 & 3X_0^4/8 & 0 \\ 0 & X_0 & 0 & 3X_0^3/4 & 0 & 5X_0^5/8 \\ 0 & 0 & X_0^2/2 & 0 & X_0^4/2 & 0 \\ 0 & 0 & 0 & X_0^3/4 & 0 & 5X_0^5/16 \\ 0 & 0 & 0 & 0 & X_0^4/8 & 0 \\ 0 & 0 & 0 & 0 & 0 & X_0^5/16 \end{bmatrix}$$

$$\mathbf{H} = \begin{bmatrix} H_0 \\ H_1 \\ H_2 \\ H_3 \\ H_4 \\ H_5 \end{bmatrix}; \quad and \quad \mathbf{A} = \begin{bmatrix} A_0 \\ A_1 \\ A_2 \\ A_3 \\ A_4 \\ A_5 \end{bmatrix}$$

Vector **A** represents polynomial coefficients multiplied by powered amplitude of testing signal. Vector **H** represents the amplitudes of the harmonic components in the measured spectrum. Matrix **P** represents relations among them.

The polynomial coefficient vector **A** could by calculated by inverse matrix relation.

$$\mathbf{A} = \mathbf{P}^{-1}\mathbf{H} \qquad (4)$$

The measurement uncertainty of the vector **H** components reduces the precision of calculation of the vector **A** by the inverse matrix. The solution of eq. (4) is very sensitive on correct estimation of H_0, H_1 from measurement because their values are about 70 dB – 80 dB above values of other higher harmonic components. Problems with calculation of polynomial components rise exponentially with ADC resolution and they are inversely proportional to the maximal value of the integral nonlinearity.

The FFT based method of harmonics determination was described in papers [4] and [5]. The main drawbacks of this FFT method are:

- The realisation of the coherent sampling is practically extremely difficult. Any forced synchronisation increases testing uncertainty caused by jitter errors.
- The recovering of the harmonic component hidden in noise by FFT method for ADCs with small integral nonlinearities (INL_{max}<0,2 LSB) is doubtful.
- Resampling of interpolated shape of test signal is excluded because of additional distortion of signal which hides effects caused by $INL(k)$ shape.
- FFT complex spectrum of data record contains vectors of harmonics, which, in relation to the phase shift of the basic harmonic, determine the positive and negative real value of each harmonics. The performed simulations showed that uncorrelated noise and incoherent sampling leads to the high uncertainty in phase spectrum calculation. The incorrect estimation of harmonic phases can spoil totally the approximation of ADC INL from the FFT spectrum.

Two new methods for practical measurement and consecutive calculation of polynomial coefficients were mutually compared, especially their robustness on measurement uncertainty. Both methods were compared with the basic one, based on the FFT calculus, which was described in the papers [4], [5].

The first method for spectra estimation proposed by authors is based on the reduction of DC component and first harmonic. Here the well known best fitting method of the harmonic input signal from ADC output data flux serves for recovering DC component and amplitude of the first harmonic. Output digital flux k_{real}(i) is approximated by harmonic function

$$h_1(i) = H_1 \cos(\Omega i T_S + \varphi_1) + H_0 \qquad (5)$$

Unknown parameters H_0, H_1, Ω, and ϕ are estimated by the four parametric fitting algorithm. First two parameters determine the DC and the first harmonic. Phase shift allows to determine sign of the first component. Approximated shape of the ADC input $h_1(i)$ serves for the recovering of residual function $res_1(i)=k_{real}(i)-h_1(i)$ with scalable frequency components.

The higher harmonic components are estimated by digital synchronous detection. The method itself is based on multiplication of the residual data record $res_1(i)$ by digitally generated reference harmonic signal with unique amplitude and frequency equal to the frequency of investigated spectral component. The product obtained by this way is subsequently passed through the digital low-pass filter. The frequencies of digitaly generated cosinusoidals are integer multiplies of basic harmonic frequency acquired from the four parameter best fit. The digital low pass filter is Chebychev' s filter of fifth order. The output signal caries also the harmonic relative sign because the digitally generated cosinwaves have the same phase shift as it was determine for basic harmonics.

The second proposed methods starts from the same first phase as the first proposed method – recovering the first harmonic from data flux $k_{real}(i)$ by the four parameter best fit method. The second harmonic component $h_2(i)$ is obtained in the next phase from the residuals res_1(i) $=k_{real}(i)-h_1(i)$ by the three parametric fitting method. Three components H_2, ϕ_2 and component DC value H_{02} are calculated solving the linear system of three algebraic equations for known frequency $2.\Omega$ [7]. Phase ϕ_2 allows to determine sign of second harmonic component in relation to phase of basic harmonic ϕ_1. The last operation in this phase is calculation of the new residual record $res_2(i)= res_1(i) - h_2(i)$.

Estimation of other higher harmonic $h_{j+1}(i)$, j=2,3, …, can be done by the recurrence of estimation process from residual record $res_j(i)$. The new partial residuals is calculated for the previous harmonic h_j using

$$res_{j+1}(i)= res_j (i) – h_{j+1}(i). \quad (6)$$

and frequences $j\Omega$ by the tree parameter best fit method.

3. EXPERIMENTAL RESULTS

All testing signal acquired from the ADC under test were processed by complex software developed in Labwindows/CVI and LabVIEW using the special data processing and analysing library for ADC testing [8]. The software consists of stand-alone routines working with standard internal data exchange format. The set of the routines contained:

1. Routine for *INL*(*k*) testing by standard histogram method and harmonic calibrating signal.
2. SW for determination of best fitted harmonic signal by four parametric method.
3. SW for determination of harmonic components by digital synchronous detection using four parametrically best fitted first harmonic (the first proposed method)
4. SW for determination the best fitted higher harmonics from residual time records by the three parametric method. The frequency of basic harmonic component is being determined by four parametric method from time record $k_{real}(i)$. The residual shape for *j*-th harmonic estimation is being calculated recursively from the previous time record by removal of the previous (*j*-1)-th best fitted harmonic signals. (the second proposed method)
5. ADC simulator with eligible error model
6. Routines for acquiring and saving data from various ADCs under test.

The robustness of proposed methods was studied for real acquired data from the ADC converter with dominant low code frequency component. Such feature is typical for integrating and sigma delta ADCs. The converter with buffering amplifier meeting this requirement is for example the one chip sound CODEC with 16-bit sigma delta converters ALC100/ALC100P by Avance Logic, Inc. with programmable resolution. The CODEC is implemented on PC sound cards. Tested ADC allows studying of proposed method for different ADC resolutions. The reference *INL*(*k*) was measured by the standard histogram method [7]. The calibrating generator in the testing setup was the calibrator Stanford Research DS360. This generator produces harmonic signal with THD better than 106 dB. Peak-peak value of the calibrating signal covered FS in 95 to 99% range.

The Fig. 2 shows ability of proposed second methods to recognise the LCF component in the modelled INL for low and high value of integral nonlinearity. The upper figure in Fig.2 compares measured *INL*(*k*) with modelled one for mentioned ADC with 8 – bit resolution.

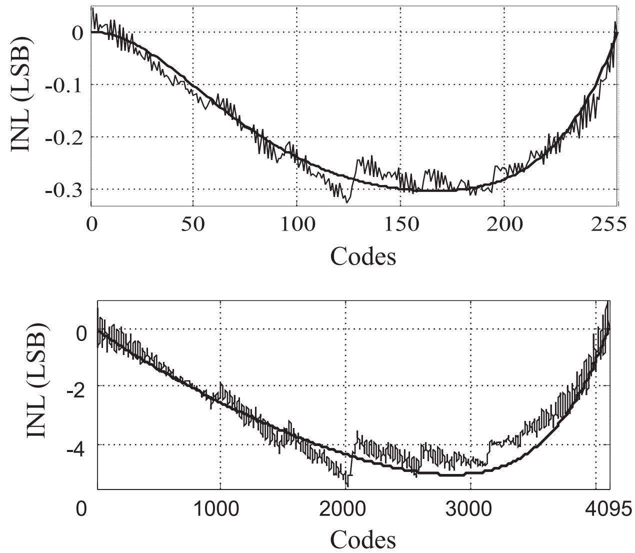

Fig.2. Measured and modelled *INL*(*k*) for ADC with resolution of 8 and 12 bit.

The proposed method is satisfactorily resistant on the superimposed high code frequency component. The best fitting method has inherent smoothing procedure. Fig.3. shows determination of LCF for DAQ board Lab 1200 by National Instruments.

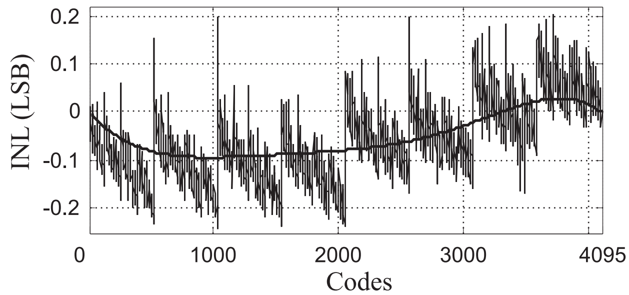

Fig.3. Measured and modelled ${}^{LCF}INL(k)$ 12 bit for Lab 1200 NI

The main advantage of the proposed methods consists in the short required record length giving satisfactory information about error model. Authors repeated estimation of ${}^{LCF}INL_m(k)$ by both methods for ADC with 12 bit resolution implemented in National Instruments multifunction data acquisition card Lab PC 1200.

Authors also studied experimentally the uncertainty of the error model identification by the proposed methods. The study was targeted on taking measures about necessary signal record length for acceptable testing uncertainty.

The estimated ${}^{LCF}INL_m(k)$ calculated by above mentioned new developed methods are identical for record length until 20000 samples. Decreasing record length shows increasing difference between ${}^{LCF}INL_m(k)$ calculated by first and second method. ${}^{LCF}INL_m(k)$ function calculated by second methods keeps its shape and vertical scale until 5000 samples. Fig.4a.), 4 b.) 4 c.) show ${}^{LCF}INL_m(k)$ of the tested

ADC for 12-bit resolution. Upper picture shows INL estimation by first method and lower one by second method.

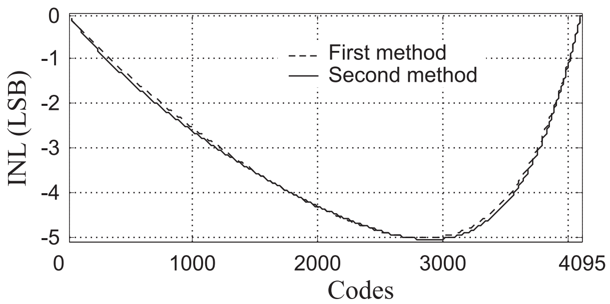

Fig.4.a. Estimation of ${}^{LCF}INL(k)$ with 12 bit resolution using time record with 100000 samples.

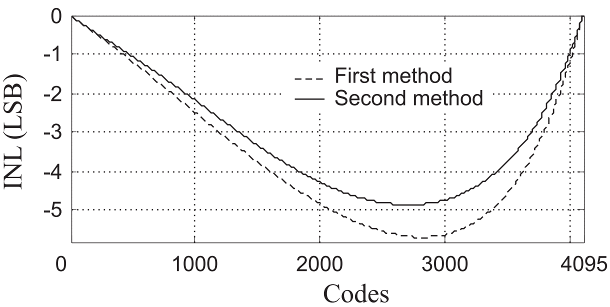

Fig.4.b Estimation of ${}^{LCF}INL(k)$ with 12 bit resolution using time record with 10000 samples.

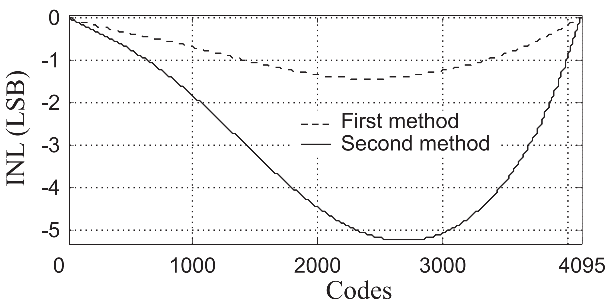

Fig.4.c Estimation of ${}^{LCF}INL(k)$ with 12 bit resolution using time record with 5000 samples.

HCF component of ADC error model could be determined with histogram test for narrow saw-tooth voltage [6]. The narrow voltage histogram testing procedure is repeated more time covering characteristic code bins $k = j.2^{N-i+1} - 2^{N-i}$ for each bin position *i*. As shown for tested ADC the most important *DNL* values are in the middle of FS k=2^N-1 $DNL_O(1)$ and in quarters k=2^N-2, k=3.2^N-2 where modelled $DNL_O(2)$ occurs.

4. CONCLUSIONS

The proposed new methods for identification of LCF component of the unified error model showed:

- Both methods of LCF estimation are appropriate for practical implementation because of their independency from coherency between sampling frequency and calibrating signal.
- Synchronous detection requires higher record length until the value at the digital filter output is settled.
- Practical experiments indicate that proposed methods are less sensitive on some disturbance like hysteresis errors which deteriorate histogram test.

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