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REALISATION OF ADC ERROR CORRECTION BASED ON VOLTERRA FILTERING

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Abstract − Dynamic non-linearity of Analog-to-digital converters (ADC) contributes significantly to the distortion of digitalised signals. This paper deals with implementing Volterra filtration technique for compensation of dynamic non-linearities in ADCs. The method is demonstrated on measurements on real Integrating ADC, and method effectiveness is analysed.

Keywords: ADC, INL, Volterra.

1. INTRODUCION

The limits of the enormous potential hidden in digital signal processing are still beyond the horizon of our imagination. A crucial part of digitisation chain is its front end – the interface between the analog and the digital "world" – i.e. the analog-to-digital converter (ADC). Dynamic non-linear effects in ADCs cause a distortion of the digitised signal, resulting in a final inaccuracy exceeding the quantisation noise level. ADC error correction is constantly in the centre of many scientific studies.

There are several ADC error correction techniques (e.g. error-table method [3, 4]), all having advantages and disadvantages. As it is shown later, in some cases the ADC error is predominated by long-term memory effects, where the "current sample – previous sample", or "amplitude – slope" error tables do not describe properly the ADC error behaviour. Conceptually different methods of ADC error correction utilize mathematical models of dynamic non-linear systems, such as Volterra or Wiener models [5-7], [11]. The approach discussed in this paper is based on utilizing the Volterra model. By using a digital Volterra filter that provides the inverse Volterra model $\boldsymbol{G_M}$ (Fig. 1) with respect to the dynamic non-linear system $\mathbf{H_N}$ represented by the ADC, the ADC error is significantly reduced. This paper focuses on experimental verification of the method, and study of influence of filter order and memory of filter.

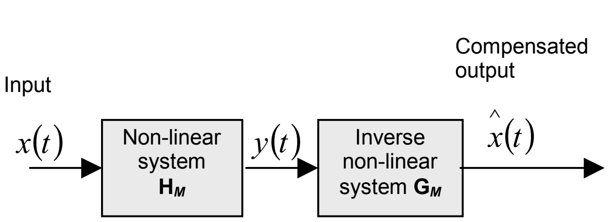

Fig 1. Principle of error correction by means of an inverse model

2. VOLTERRA MODELS

The well-known Volterra model is an exact mathematical approach for description of causal time-invariant systems, where dynamic and non-linear phenomena are present simultaneously [7]. According to this model, the output signal of the non-linear system can be expressed as series of Volterra functionals [5-12]:

$$\hat{y}(t) = h_0 + \sum_{i=1}^{\infty}\left\{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\dots\int_{-\infty}^{\infty} h_i(\mu_1,\mu_2,\dots,\mu_i)\prod_{j=1}^{i}x(t-\mu_j)\prod_{j=1}^{i}d\mu_j\right\} \quad (1)$$

where $x(t)$ is the input signal,, $\hat{y}(t)$ is the output signal, and $h_i(\mu_1,\mu_2,\dots,\mu_i)$ is the Volterra kernel of the i-th order.

3. APPLICATION OF VOLTERRA FILTERS

Volterra filters can be mathematically described as the discrete equivalent of the Volterra functional series (1). In particular, for the truncated model with a finite order M, and a finite memory of samples N we get [8-10]:

$$\hat{y}(n) = h_0 + \sum_{i=1}^{M}\sum_{m1=0}^{N}\sum_{m2=0}^{N}\dots\sum_{mi=0}^{N} h_{i_{m1,m2,\dots,mi}}\prod_{j=1}^{i}x(n-mj) \quad (2)$$

By organising the Volterra kernel elements h_0 and $h_{i_{m1,m2,\dots,mi}}$, and the input sample products $\prod_{j=1}^{i}x(n-mj)$ into convenient block vectors $\mathbf{H}(n)$ and $\mathbf{X}(n)$ respectively, (2) can be rewritten as [8-10]:

$$\hat{y}(n) = \mathbf{H}^T(n)\mathbf{X}(n) \quad (3)$$

The set of optimal Volterra kernels $\mathbf{H}^*$ will fulfil a given optimisation criterion for the $e(n) = y(n) - \hat{y}(n)$ error function. The least-mean-squares error optimisation criterion can be considered:

$$E\left[e^2(n)\right] = E\left[\left(y(n) - \hat{y}(n)\right)^2\right] \rightarrow \min \tag{4}$$

The solution leads to equation

$$\mathbf{H}^* = \mathbf{R}_{XX}^{-1}\mathbf{R}_{YX} \tag{5}$$

Where:

$$\mathbf{R}_{YX} = E\left[y(n)\mathbf{X}(n)\right] \tag{6}$$

is the higher-order mutual correlation vector of the input and the desired signals, and

$$\mathbf{R}_{XX} = E\left[\mathbf{X}(n)\mathbf{X}^T(n)\right] \tag{7}$$

is the higher-order autocorrelation matrix of the input signal. Equation (3) describes the dynamic non-linear system represented by the ADC.

For the purpose of ADC error correction the inverse Volterra model has to be identified, what can be realised according to Fig. 2.

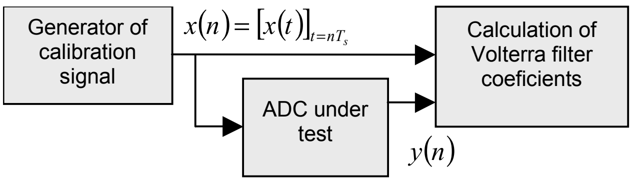

Fig. 2. Direct Volterra kernel calculation.

The vector of optimal Volterra kernels (filter coefficients) is obtained analogously as in (3):

$$G^* = \mathbf{R}_{YY}^{-1}\mathbf{R}_{XY} \tag{8}$$

Where:

$$\mathbf{R}_{XY} = E\left[x(n)Y(n)\right] \tag{9}$$

is the higher-order mutual correlation vector of the corrected and the desired signals, and

$$\mathbf{R}_{YY} = E\left[Y(n)Y^T(n)\right] \tag{10}$$

is the higher-order autocorrelation matrix of the corrected signal.

$Y(n)$ is the vector of ADC output sample products $\prod_{j=1}^{i} y(n - m_j)$ obtained analogously as in (3). Although $\mathbf{R}_{YY}$, and $\mathbf{R}_{YX}$ are statistical characteristics, primarily defined on the base of the statistical properties of the input and the desired signals, their value can be estimated from the finite sequence of deterministic input values and corresponding output codes:

$$\mathbf{R}_{XY} \approx \frac{1}{L}\sum_{n=1}^{L}\left(x(n)Y(n)\right) \tag{11}$$

$$\mathbf{R}_{YY} \approx \frac{1}{L}\sum_{n=1}^{L}\left(Y(n)Y^T(n)\right) \tag{12}$$

where L is the length of the data sequence.

The final filter expression for corrected output calculation is the following:

$$\hat{x}(n) = \mathbf{G}^T Y(n) \tag{13}$$

Method efficiency is evaluated in terms of filtering gain R by applying a test signal according to Fig. 3.

$$R = 20\log\left(\sqrt{\frac{1}{N}\sum_{i=1}^{N}(y_i - x_i)^2} \Big/ \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\hat{x}_i - x_i\right)^2}\right) \tag{14}$$

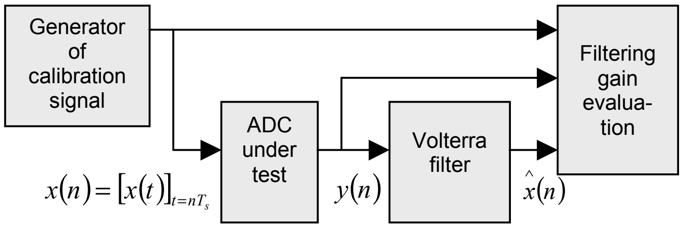

Fig. 3. Method efficiency evaluation.

4. EXPERIMENTAL IDENTIFICATION OF VOLTERRA FILTER COEFFICIENTS

For experimental verification of the method Volterra kernel identification was carried out on a real 12 bit ICL7109 (MAXIM) dual slope integrating ADC. The measurement configuration was chosen according to Fig. 4:

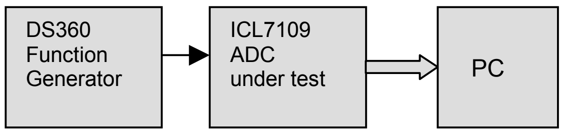

Fig. 4. Configuration of experimental set-up.

Both calibration and method efficiency evaluation signal were generated with DS360 ultra low distortion function generator (Stanford Research Systems), and could be considered ideal regarding to the ADC resolution.

The generator and the ADC were interconnected via voltage divider ensuring 50 Ohms input impedance. Using an attenuator on the input of ADC is often inevitable in real applications, e.g. in industrial environment with heavy interferences, or when measuring higher voltage level signals. However, the attenuator may cause additional distortion of the signal. An example of effect of voltage attenuator used in the experimental set-up is shown on Fig. 5. On the input of ADC a sinusoidal signal of amplitude 0.1V, frequency 0.5 Hz, and DC level 2.8V was applied, the sampling frequency of ADC was 28 Hz. Fig. 5. shows the error of ADC after subtracting the ideal values of the sinusoid, obtained by 4-parametric estimation. This error is composed from random noise, and a systematic, slowly variable component caused by heating of the input attenuator resistors due to input current. If the final sampling frequency is not critical, the random error component can be suppressed using oversampling. The remaining, slowly variable component shows nonlinear and dynamic characteristics simultaneously.

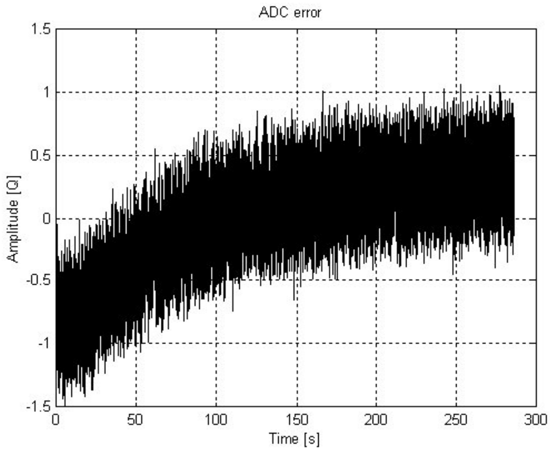

Fig. 5. An example of ADC error.

This type of distortion can be successfully suppressed using Volterra filtering. Optimal Volterra filter coefficients are calculated from the sequence of ADC output codes and the corresponding sequence of input signal sample values. Selection of calibration signal is crucial for effective error correction. It must sufficiently represent the statistical characteristics of the signal to be filtered. Finding optimal calibration signals for various types of input signals is still a matter for further study. This paper focuses on the case, where the input signal is slowly variable for a certain period, and then it changes to a different value that remains slowly variable for a certain time, etc. This is a situation e.g. on the output of an analogue multiplexer, which switches periodically different slowly variable input signals.
The applied calibration signal is shown on Fig. 6.

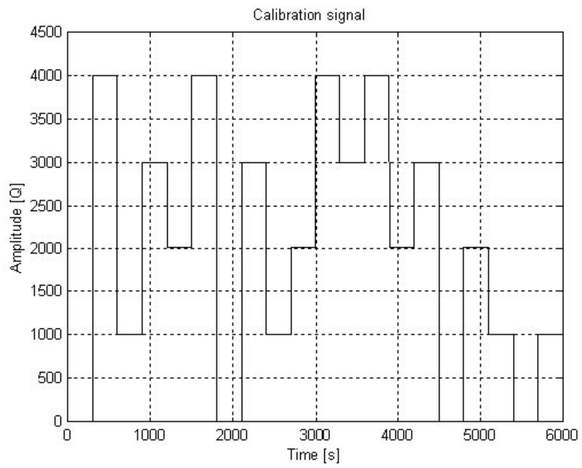

Fig. 6. Calibration signal for filter coefficient determination.

The calibration signal was designed as a sequence of constant DC segments (5 distinct levels were used, evenly covering the ADC input range). The whole calibration signal is composed from 20 subsequent DC segments, involving all possible transitions from each level to all others. The time between two subsequent transitions is 300 seconds. This value was chosen according to the time constant of the transient phenomena on the input attenuator.

For method efficiency verification a test signal was used according to Fig. 7. The ADC error before filtering is shown on Fig. 8, and after filtering with a Volterra filter of 2nd order, and memory of samples N=20 on Fig. 9. Figure 10 shows the error of the filtered signal using a filter of 1st order with memory of samples N=20. Table 1 shows the filtering gain according to (14) achieved for the same input test signal for different orders of filter and different memory of samples.

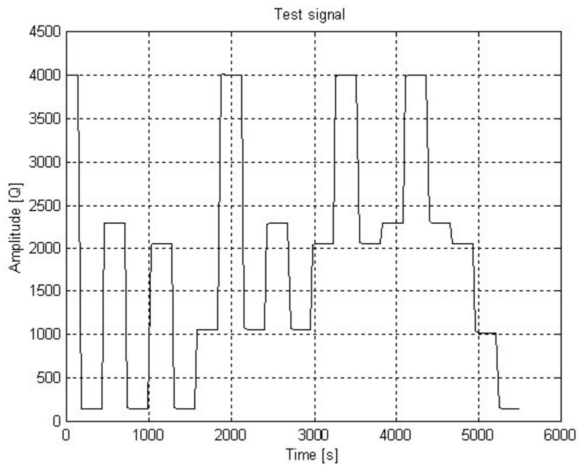

Fig. 7. Test signal for filtering gain evaluation.

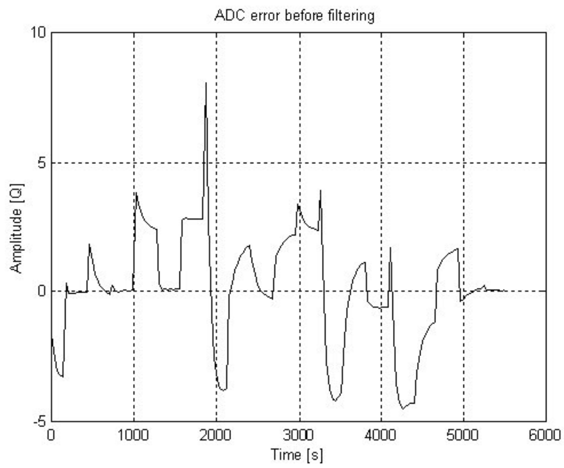

Fig. 8. ADC error before filtering.

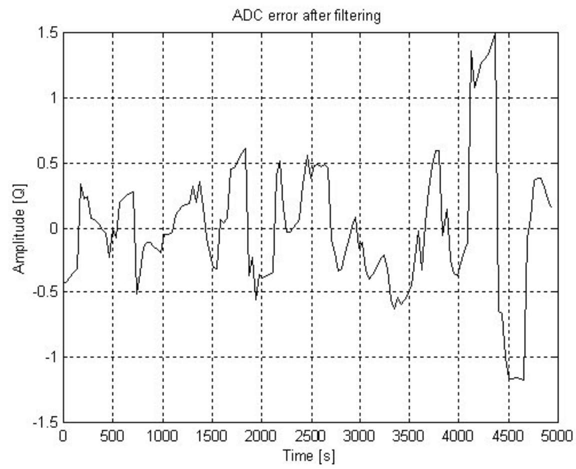

Fig. 9. ADC error after filtering with a filter of 2nd order with memory of samples N=20.

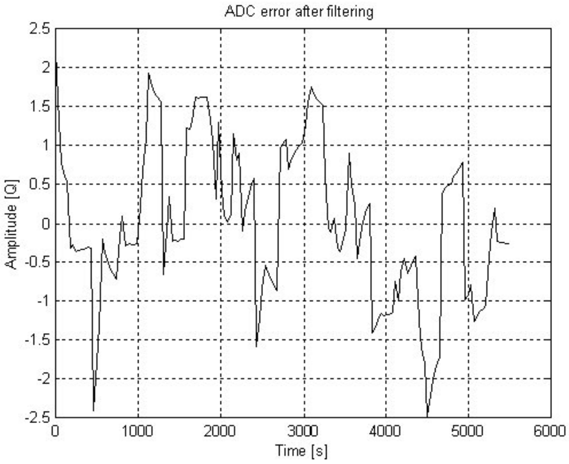

Fig. 10. ADC error after filtering with a filter of 1st order with memory of samples N=20.

TABLE I. Filtering gain for different orders of filter and memories of samples

Order of filter M	Memory of samples N	Filtering gain R [dB]
1	4	2.38
1	10	3.04
1	20	3.77
2	4	6.51
2	10	8.22
2	20	10.47

5. CONCLUSION

A method using Volterra filtering for inverse-model correction of the ADC error has been experimentally verified on real ADCs. The Volterra filter compensates memory and dynamic non-linear error effects simultaneously.

The effectiveness of this method for correction of long term error components, like the error caused by heating of the input attenuator resistors due to input current has been confirmed. For this type of error, conventional error-table method is not effective at all.

Results in Tab. 1. show, that filters of 2nd. order provide better results than filter of 1st. order, what means that the compensated error is characterized by not only dynamic, but also nonlinear nature. These results justify using of Volterra filters for this purpose.

Finding optimal calibration signals for various types of input signals is still a matter for further study.

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