Features of Modeling of Analog-to-Digital Converter Transfer Function by Simulink

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***Abstract*—Analog-to-digital converters (ADC) are the most commonly used converters at measuring and control devices. The transfer function of a real ADC is different from the ideal one. There are additive, multiplicative and nonlinear components of the error. The number of bits of any ADC is finite, which results to the appearance of quantization error. Due to the presence of aperture delay and aperture jitter, there is a variable in time delay of sampling of the input signal. In case of measuring the integral parameters of the signal (root mean square value, active power, reactive power, apparent power, etc.), the evaluation of the impact of the ADC nonidealities at an analytical form is a difficult task. This is especially true in the case of nonlinearity and quantization error. For this reason, it is of interest to estimate the measurement error by performing simulation mathematical modeling. The problem under consideration is also relevant in the educational process for all areas related to measurement technology, where the simulation is actually the only opportunity in a limited academic semester time to assess the impact of these nonidealities of ADC measurement error of the considered parameter. Build of the ADC effective model can be done using Simulink. The article describes the sources of the ADC nonideality and approaches for their modeling by Simulink. The features of the modeling of ADC nonlinearity of successive approximation and Sigma-Delta ADC architectures. The model of the ADC, taking into account all these parameters.**

Keywords—analog-to-digital converter; linearity error; simulation modeling; quantization error; aperture delay

I. INTRODUCTION

Currently, analog-to-digital converters (ADC) are the part of the channels of the vast majority of measuring instruments and automatic control instruments [1-5]. ADC are designed to convert analog signal into the digital code. The conversion function of ideal ADC without discretization and quantization effects can be represented as linear and written at the following form [6-9]:

$$y_n(t) = \frac{x(t)}{q}, \tag{1}$$

where *x(t)* – immediate value of the input signal at the moment *t*; *q* – value of the least significant bit (quantum, *LSB*) of the considered ADC; $y_n(t)$ – value of the ADC output signal (code) at the moment *t*.

The value of the ADC *LSB* is determined by the following expression [6]:

$$q = \frac{U_{\max-\min}}{2^N}, \tag{2}$$

where *N* – ADC resolution; $U_{max-min}$ – value of the ADC input range.

To bring the ADC output code to the input scale it is needed to perform a multiplication by the ADC *LSB* value:

$$y(t) = y_n(t)\, q = x(t)\,, \tag{3}$$

where *y(t)* – normalized value of ADC output code at the moment *t*.

The expressions (1) – (3) are valid for cases of unipolar and bipolar ADC. For a unipolar ADC instead $U_{max-min}$ needs to application U_{ref}. For the case of a bipolar ADC instead $U_{max-min}$ needs to application $2U_{ref}$.

Any deviation of the ADC conversion function from the form specified by the expression (3) results to an error.

II. DISCRETIZATION AND QUANTIZATION ERROR

The output signal (code) of the real ADC is discrete by time domain and quantized by level. For this reason, the value of the output signal in a scaled form (reduced to the ADC input):

$$y[n] = round\left(\frac{x(t)}{q}\right) \cdot q\,, \tag{4}$$

where *round()* – rounding operation to the nearest integer; *n* – sample number of the ADC output signal.

The sample number of the ADC output signal is determined by the expression:

$$n = round(t\ f_S)\,, \tag{5}$$

where f_S – sampling frequency.

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The difference between the expression (4) and the expression (3) determines the ADC quantization error. The dependence of quantization error at time is called the quantization noise. The review of articles [6 – 16] shows that there are no effective analytical methods for estimating the influence of quantization noise to the measurement error of integral parameters of the signal. For this reason, the use of simulation modelling seems to be an effective approach.

The quantization error can be modeled [17] by the 'Quantizer' block of the Simulink software package. As a block for sampling the input signal can be used the sample-and-hold device – Simulink block 'Zero-order hold'. The sampling period of a given block ('Sampling time') must correspond to the value of the inverse sampling rate f_S.

III. Additive and Multiplicative Error Components

The additive error [6] is a component of the total error, which does not depend on the value of the measured value. As applied to the ADC conversion function, the additive component of the error can be represented as:

$$y(t) = x(t) + \Delta_{ADD}\,, \tag{6}$$

where Δ_{ADD} – additive component of the ADC error.

The additive component of the error is caused by the constant displacement of the ADC input amplifier and the displacement of its sample-and-hold device (SH). In the software package Simulink the additive error component can be modeled using the accumulator 'Sum' specified in the channel perform the conversion to blocks SH and quantizer.

The multiplicative component of the error [6] is a value that depends linearly by the value of the measured signal:

$$y(t) = x(t) + \Delta_{MUL}(t) = x(t) + \delta_{MUL}x(t)\,, \tag{7}$$

where $\Delta_{MUL}(t)$ – absolute value of the multiplicative component of the error of the ADC conversion function; δ_{MUL} – the relative value of the multiplicative component of the error of the ADC conversion function.

The multiplicative component of the error can be modeled using the summator block 'Sum' and the multiplier block 'Product', set in the ADC conversion channel before SH and quantizer. The multiplicative component is mainly caused by the deviation of the ADC conversion coefficient of the input amplifier from its nominal value and deviation of the ADC reference voltage from its nominal value.

IV. The Nonlinear Component of Error

In addition to additive and multiplicative components of error and the quantization error, the real ADC is characterized by the presence of a nonlinear error component (linearity error or ADC nonlinearity). Taking into account the nonlinearity of the ADC conversion function, the ADC output signal (code) (given to its input) can be recorded at the following form:

$$y(t) = x_{real}(t) = x(t) + \Delta_{NL}(t)\,, \tag{8}$$

where $\Delta_{NL}(t)$ – absolute value of the nonlinear component of the ADC error.

For the linearity error of an arbitrary ADC, the following ratio is typical [6, 18 –20]:

$$-INL \cdot q \le \Delta_{NL}(t) \le INL \cdot q\,, \tag{9}$$

where *INL* – limit value of the ADC integral nonlinearity [6] (specified at the ADC datasheet); q – value of the ADC least significant bit (quantum) [6].

In addition to the limit value of nonlinearity (parameter *INL*) at the ADC datasheet is often specify a typical dependence of nonlinearity for the ADC input range; the value of the differential nonlinearity (*DNL*) parameter, and a number of dynamic parameters, such as *SFDR*, *THD*, *SNR*, *THDN* [6]. The value of the parameter *DNL* [6] shows the maximum change in the integral nonlinearity at the transition of the input signal from the quantum to the quantum of the ADC transfer function:

$$DNL = \left. \frac{dINL(x)}{dx} \right|_{MAX}. \tag{10}$$

Currently, a large number of approaches are used to describe the ADC nonlinearity. The most popular approaches are: the use of polynomial functions [21-24]; the use of Chebyshev polynomials [21-24]; the use of harmonic functions [10-11]; the use of Walsh functions [25-36]; the use of Volterra integral equations [27-30]; the use of random functions [31-32]; other approaches based on the use of different functions [33-34]. Among the considered approaches, the most popular is the use of polynomial functions [21-22] due to the simplicity of application and error analysis. There is an analytical relationship between the coefficients of the approximating polynomial and the harmonic coefficients of the ADC output signal (ADC nonlinearity exists and the input signal is sinusoidal). In this case, the ADC output signal:

$$y(x) = \sum_{i=0}^{N_P} \left(A_i F_i(x)\right), \tag{11}$$

where A_i – value of the *i*-th coefficient of the approximating function; $F_i(x)$ – *i*-th member of applying approximating function; N_P – order of applying polynomial.

In addition to the approaches discussed above, an approach based on the representation of the ADC nonlinearity at the form of three components is used to approximate and correction of the ADC nonlinearity [34-37]:

$$\Delta_{NL}(x) = \Delta_{NL,P}(x) + \Delta_{NL,ST}(x) + \Delta_{NL,N}(x)\,, \tag{12}$$

where $\Delta_{NL,P}(x)$ – "smooth" nonlinearity component; $\Delta_{INL,ST}(x)$ – "sawtooth" nonlinearity component; $\Delta_{INL,N}(x)$ – "pseudorandom" nonlinearity component.

The considered principle (see expression (12)) of representation of ADC nonlinearity is used for the successive approximation ADC (SAR ADC) architecture and multistage ADC architecture (pipeline ADC) [6, 34–37]. For the case of a Sigma-Delta ADC, the conversion function can be represented by equation (11) (polynomial function) with a relatively low order. The conversion function of the real Sigma-Delta ADC have a smooth dependence of the nonlinearity. Fig. 1 shows the typical nonlinearity dependences for the ADC of the SAR ADC architecture – MAX1179 [38] (16 digits) and Sigma-Delta ADC architecture – MAX11200 [39] (24 digits), respectively. The manufacturer of both chips – Maxim Integrated company. It is seen that the nonlinearity of SAR ADC is more random than for Sigma-Delta ADC.

The "smooth" component (see expression (12)) is approximated by a polynomial of low order (typically, a polynomial not exceeding the 5-th order). The "sawtooth" component is approximated by a piecewise linear function (the number of piecewise linear sections is determined on the samples of output signal [37]). The "pseudorandom" component is approximated by applying a random function having a uniform distribution density. Currently, there is a technique [37] to determine the parameters of all components of the approximating conversion function of the ADC, which uses the ADC nonlinearity samples, which obtained experimentally. To apply proposed technique, a large number of experimental samples of ADC nonlinearity are required. In the case of commercially available measuring devices, this property is a significant drawback.

The datasheets of the produced ADCs shows that the nonlinearity dependencies of SAR ADCs are dominated by a random component of error (see expression (12)). In the case of representation of ADC nonlinearity as a random, the nonlinearity value consider a random variable with a given distribution density. To ensure the metrological reserve, the distribution density is chosen uniformly. In this case, the instantaneous nonlinearity value is limited to the maximal value of the ADC integral nonlinearity (*INL* parameter).

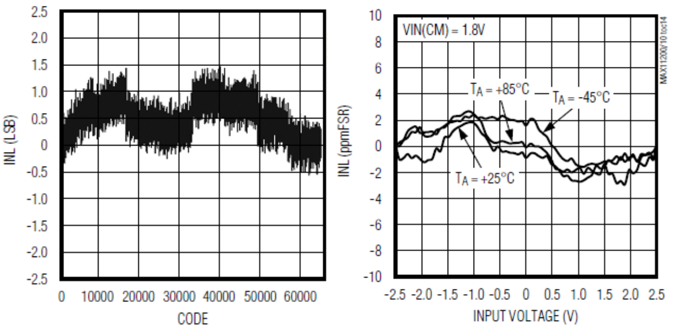

Fig. 1. Typical dependences of the ADC nonlinearity of the SAR ADC MAX1179 [38] (left) and Sigma-Delta ADC MAX11200 [39] (right)

Then the value of nonlinearity is determined by the equation:

$$\Delta_{NL,N}(x) = (rand(x) - 0.5)\, INL\,, \tag{14}$$

where *rand(x)* – random variable with uniform distribution density in the range of values (0-1); *INL* – value of integral nonlinearity of the applied ADC.

To implement the ADC nonlinearity by the Simulink, can be used the one-dimensional table ‘Look-Up Table’ block. The argument reference values (input signal values) and the function reference values (nonlinearity of the ADC conversion function values) are defined at the fields of ‘Breakpoints 1’ and ‘Table data’, respectively. The type of performed interpolation between the reference values can be set using the submenu ‘Interpolation method’. For modeling error components $\Delta_{NL,P}(x)$, $\Delta_{INL,ST}(x)$ can be used one collaborative block ‘Look-Up Table’. The values of ADC nonlinearity and the corresponding levels of the ADC input signal can be manually entered for the typical dependence of the nonlinearity, which is usually specified by the manufacturer’s datasheet. For the convenience of modeling the 'pseudorandom' component $\Delta_{INL,N}(x)$ a separate block ‘Look-Up Table’ can be applied. In this case, the input signal values should be placed evenly within the input range of the ADC. The values of 'pseudorandom' component of the ADC nonlinearity can be generated using the Matlab function *rand(*):*

$$\Delta_{NL,N} = (rand(1, N) - 0.5)\, DNL\,, \tag{15}$$

As the maximum value of the ‘pseudo-random’ component of the ADC nonlinearity, the value of differential nonlinearity can be used as specified at the expression (15).

ADC nonlinearity has a hysteresis effect. This effect is not taken into account in the developed ADC model, since the hysteresis effect is usually manifested at relatively high sampling rates. In the absence of information about the typical dependence of the nonlinearity of the ADC, this dependence can be represented by the ‘worst-case method’: for a positive input signal samples the nonlinearity takes the value *INL*, for a negative input signal samples – value *-INL*

V. THE RESTRICTION OF THE ADC INPUT RANGE

The input range of the real ADC is limited by the ADC reference voltage value. For bipolar ADC, the input voltage can vary in the range of:

$$-U_{REF} \le x(t) \le U_{REF}\,, \tag{16}$$

where U_{REF} – ADC reference voltage value.

For the case of a unipolar ADC, expression (16) takes the following form:

$$0 \le x(t) \le U_{REF}\,. \tag{17}$$

To create a limit of the ADC output range in the software package Simulink can be used block ‘Saturation’. To determine the values of the limits of the input range must be set the values of parameters ‘Upper limit’ и ‘Lower limit’.

VI. MODELING OF APERTURE DELAY AND APERTURE JITTER

The aperture delay is manifested as the occurrence of the input signal sampling delay relative to the clock signal. In this case, the delay value can be represented as two components: a constant component (which does not change from sample to sample) – aperture delay and a variable component that varies from sample to sample – aperture jitter. Samples of the ADC output signal at the presence of aperture jitter and aperture delay can be presented at the following form:

$$y[n] = x(nT_S + \tau[n]), \tag{17}$$

where $\tau[n]$ – aperture delay and aperture jitter for sample n.

The ‘Variable Time Delay’ block can be used at the Simulink software package to simulate aperture delay and aperture jitter of ADC. The external control parameter of this block is the delay value. The constant component of delay (aperture delay) can be determined using the ‘Const’ block – the value of which is set through the parameters of the ADC mask model. Aperture jitter can be modeled using a random noise generator (‘Band Limited White Noise’ block).

VII. ADC MODEL IMPLEMENTED BY THE SIMULINK SOFTWARE PACKAGE

Fig. 2 shows the visual design of the user dialog box to set the operating modes and parameter values of the ADC model.

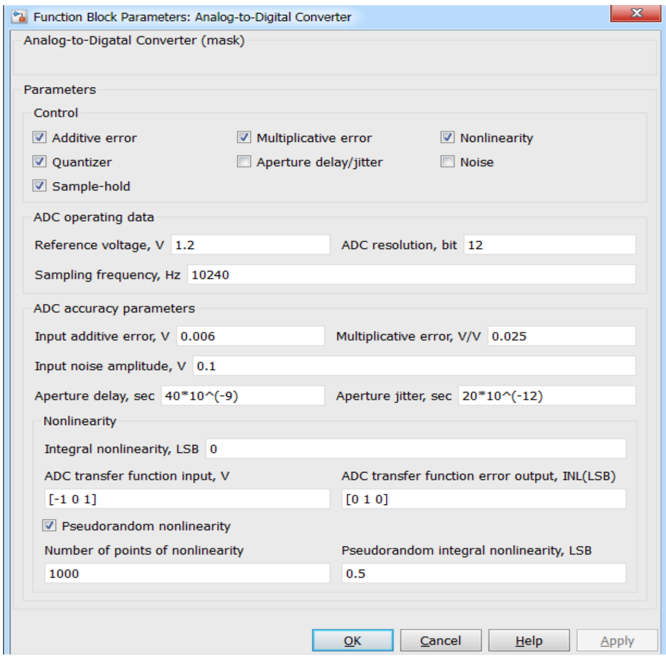

Fig. 2. Visual design of the user dialog box for setting operation modes and ADC model parameter values

A group of controls ‘Control’ are designed to control the simulation mode of the various internal ADC modules. This allows to simplify the model and perform its adjustment to a specific modeling task. Fig. 3 shows the combined ADC conversion channel simulation model implemented at the Simulink package. This figure also shows the visual appearance of the ADC mask block.

For convenience at the ADC model allocated the components (modules) that perform simulation of the corresponding parameter of the ADC. The diagram shows the modules of the additive, multiplicative and nonlinear components of the error, the module of input noise, the module of restriction of the input signal level and combined module of aperture delay and aperture jitter.

The ADC output code is limited to the range of values determined by its bit depth and input type. For a unipolar ADC, the output code is a straight line with a range of zero to 2^N*-1*. For ADC with bipolar input, the output code is optional with a range of values from $-(2^{N-1}-1)$ to $(2^{N-1}-1)$. To bring the ADC output range to the input range, an additional ‘Gain ' block with a gain equal to the ADC quantum is used.

On the basis of the proposed model of construction of the ADC, models of simulation modeling of errors of the most measuring converters used at measuring devices can be developed. Such converters include operational amplifiers, decisive amplifiers, instrumental amplifiers, difference amplifiers, active filters, integrators, differentiators, logarithmic amplifiers.

CONCLUSION

As a result of the work developed a universal model of Analog-to-Digital Converter (ADC) at the Simulink software package.

The developed model allows to take into account the finite resolution of the ADC (quantization noise caused by finite ADC resolution), additive, multiplicative components of the ADC conversion channel error, ADC nonlinearity. Implemented the ability to set the aperture delay and aperture jitter.

The input range of the developed ADC model is limited by the voltage of the reference source for the case of bipolar and unipolar inputs.

Implemented the ability to define the shape of the nonlinearity of the ADC conversion function. For ADC built by the successive approximation architecture, the possibility of defining the form of nonlinearity in the form of a random function is realized.

The proposed ADC model can be widely used in the educational process. When you run the virtual laboratory workshop using the software package, Simulink can be used to study various features of the ADC conversion associated with nonideal conversion function. When performing the course and diploma design by simulation mathematical modeling can be calculated the influence of the imperfection of the ADC conversion function on the measurement error of the integral parameters of the input signal.

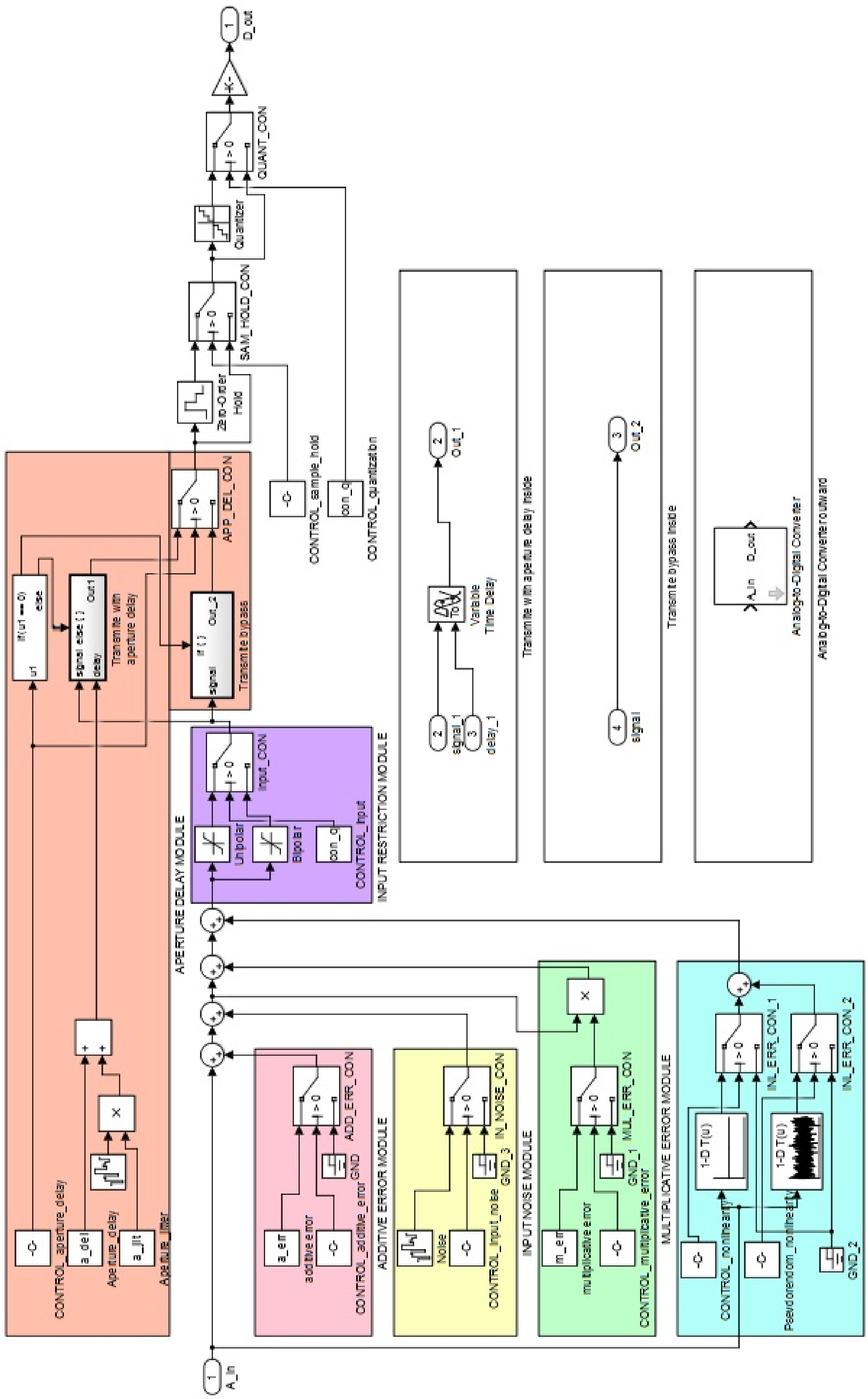

Fig. 3. The United simulation model of a channel ADC conversion performed in the software package Simulink

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