# ИЗМЕРИТЕЛЬНАЯ ТЕХНИКА

УДК 621.317

*M. Kamenský*, PhD, Assistant Professor;
*K. Kováč*, PhD, Associate Professor;
*A. Krammer*, Assistant Professor;
Slovak University of Technology, Slovak Republic
*Y. R. Nikitin*, PhD in Engineering, Associate Professor
Kalashnikov Izhevsk State Technical University

## EXPERIMENTAL VERIFICATION OF ADDITIVE ITERATIVE METHOD FOR CORRECTION OF ADC ERRORS IN LSB REGION

*In application of additive iterative method (AIM) for an analog-to-digital converter (ADC) a combination of AIM with nonsubtractive dithering enables correction of errors in LSB region. In the paper real application of the method is discussed and tested with orientation to measurements based on a single-chip microcontroller. Circuits available on a chip can be employed for the correction and only few additional components are needed. Inverse element (IE), which is a fundamental part of AIM, is created using pulse width modulation output. To achieve precise processing of a signal generated on the IE output technique similar to deterministic dithering is employed. For processing of the measured signal in the initial step of a correction nonsubtractive dithering with a stochastic dither is used. Theoretical curve of root mean square error dependency on standard derivation of added noise is compared with experimental. According to the real dependency a quasi-optimal standard deviation is found and used for final correction. Automatic correction of both linear and nonlinear error of ADC is proven experimentally. Finally a special ending condition of iterative correction is found which is suitable especially for systems with quantizer.*

**Keywords:** ADC, errors, automatic correction

### I. Introduction

Self-correction functions are important for a measurement channel where high accuracy has to be guaranteed. E.g. by a measurement in the electromagnetic compatibility laboratories [1] a mistake committed by testing could propagate through the whole lifecycle of any tested unit. Analog-to-digital converter (ADC) integrated within a single-chip microcontroller is often used for signal level measurements. The method presented in the paper is focused on such types of ADC for automatic correction even of time changing and nonlinear errors less than 1 LSB.

Analyzes and ideas of automatic correction of ADC has been presented in [2]. Additive iterative method (AIM) uses a precise inverse element (IE) for correction of ADC errors except quantization error. A combination of AIM with dithering was proposed in [2] for design of a correction of systems with quantizers integrated in the measurement channel. Real experimental system has been designed following methodology from [2]. In the first step of the correction, when a measured signal is connected to the ADC input, nonsubtractive dithering with stochastic dither is implemented for increasing of ADC resolution. Then technique similar to deterministic dithering helps to obtain precise processing of the signal from IE. The paper presents qualities of the system and experimental properties of error before and after correction.

**II. Design of measurement system with correction**

In a single-chip microcontroller application many additional circuits are available on a chip besides ADC. Therefore AIM [3] is suitable method for improving of accuracy of microcontroller based measurements. In [2] the methodology of the automatic correction of ADC was presented with appropriate theoretical analyses. According to [2] only little additional hardware is needed to build main blocks of AIM:

- Corrected measurement transducer (MT) - ADC with averaging.
- Inverse element (IE) - pulse width modulation (PWM) and RC-filter.
- Switch - integrated multiplexer (MUX).
- Block of processing (BP) - microcontroller CPU with on-chip memory.

Digital-to-analog converter built from the pulse width modulation output of a microcontroller and a low-pass RC-filter represents IE in our system. As proposed in [2] the time constant $\tau_F$ of the filter has to be selected carefully and averaging of samples from ADC must be implemented to obtain positive effect of deterministic dithering. Number $N$ of averaged samples should represent the integer number of periods of a signal received from RC-filter as close as possible. Suitable number of $N$ ($N$ = 59, [4]) has been selected leading to quasi-synchronous sampling. The selection of filter time constant $\tau_F$ could be accomplished from curves of maximal IE error depicted in Fig. 1.

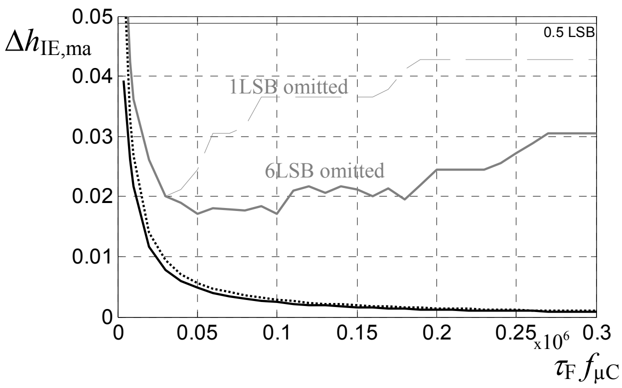


*Fig. 1*. Dependency of maximal IE error $\Delta h_{IE,max}$ on time constant of RC-filter $\tau_F$. Theoretical/simulation error without quantization - black solid line/dots; Simulation error including quantization if 6 or 1 LSB omitted at both ends of scale gray lines

Simulation results without quantization (dotted line) are very similar to theoretical (black solid line) obtained according to model of asynchronous sampling [2]. After addition of quantization into simulation the error is still similar to theoretical model around the middle of scale, however higher error occurs close to the both ends of scale. Here the peak-to-peak value of the RC-filter output oscillation is too small for suppression of quantization error. Therefore 6 LSB of ADC were omitted at both ends of the range when analyzing data for drawing gray solid line in Fig. 1. Finally good region for selection of $\tau_F$ seems to be interval from $50000/f_{\mu C}$ to $100000/f_{\mu C}$ ($f_{\mu C}$ is clock frequency of a microcomputer). We used $\tau_F = 100000/f_{\mu C}$ during testing and in experiments. Then, if $f_{\mu C}$ = 1 MHz, the time constant is $\tau_F$ = 0.1 s as presented in [2]. However to achieve faster measurements or higher precision at some end of scale lower $\tau_F$ could be selected (e.g. $50000/f_{\mu C}$ if only 1 LSB omitted, gray dashed line).

**III. Experimental identification of quasi-optimal standard deviation of dither**

In the initial step of AIM the measured value is at the input of ADC. Averaging might not lead to improving of ADC resolution if there is no sufficient fluctuation or noise in the input signal. Suitable noise (dither) intentionally added prior to quantization can help in this case. Such technique is called nonsubtractive dithering [5] as the noise is not subtracted from the signal after quantization.

Influence of dither on quantizer could be generally investigated using theory of quantization described in [5]. As in our case the number of averaged samples $N$ is quite small, appropriate error model should consider both mean error and dispersion of results of averaging. Based on [6] or [7] formula for theoretical root mean squared error (RMSE) has been written in [2] for uniform noise. The theory does not include other imperfections of ADC except quantization error. However due to correction of integral nonlinearity by AIM experimental dependency of RMSE on standard deviation of noise should be similar to theoretical obtained according to [2].

Experiments were performed with designed measurement system, where AIM and nonsubtractive dithering with averaging was implemented for error correction of 10-bit ADC. Precise data acquisition card was used in PC for testing. To be able to change dither dispersion a dither addition was not a part of the designed system. It was done by the data acquisition card on a PC side. Total RMSE ($RMSE_T$) curves are depicted in Fig. 2. Main contribution of the designed correction is a suppression of the nonlinear error component. Therefore the linear error part had been subtracted from the measurement results before evaluating the experimental RMSE. If only a natural noise is present the reduction of nonlinear error with AIM is little. According to Fig. 2 a dither with a standard deviation $\sigma_d = 0.2333q$ (0.02279 %) has really enhanced system accuracy. This quasi-optimal standard deviation is the final parameter of our design. As in our case a real system is tested the optimal dither dispersion is lower than a theoretical optimum due to the natural noise present in the input signal. In the case of no iterative correction the integral nonlinearity of ADC has caused notable shift of experimental curve against theory.

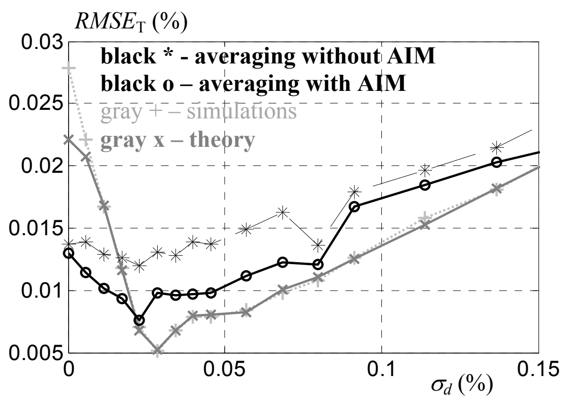


*Fig. 2*. Dependency of the total RMSE of ADC with averaging on standard deviation of dither before and after correction with AIM

**IV. Experimental results and discussion**

For the designed measurement system the mean error dependency on a measured value calculated from 20 measurements at each input level $s_m$ is depicted in Fig. 3. Results after averaging both without and with AIM are shown here. Correction of linear part of the error is notable. However, the linearity of error curve was also improved using AIM, which is better visible in Fig. 4 from curves of RMSE of the nonlinear error part. The points of minimum are influenced by dispersion of the results, which is higher after correction with AIM. More important is suppression of peaks caused by integral nonlinearity. Finally the error is suppressed considerably under the $1/\sqrt{12}$ LSB (0,02819 %) which would not be possible without dithering. Evaluated in ENOB (Effective Number of Bits) the error improvement is 2.26 bit with final value of 11.90 bit after correction.

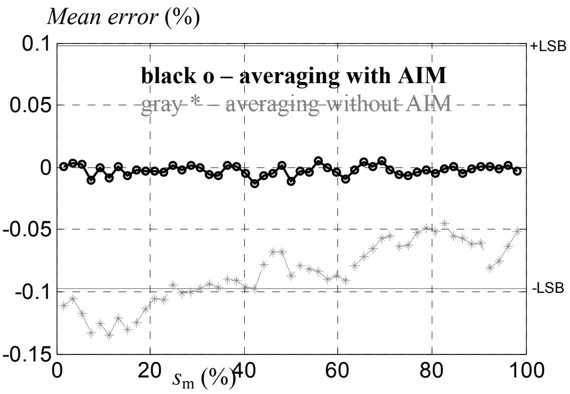


*Fig. 3*. Mean error of ADC with dithering before and after correction with AIM

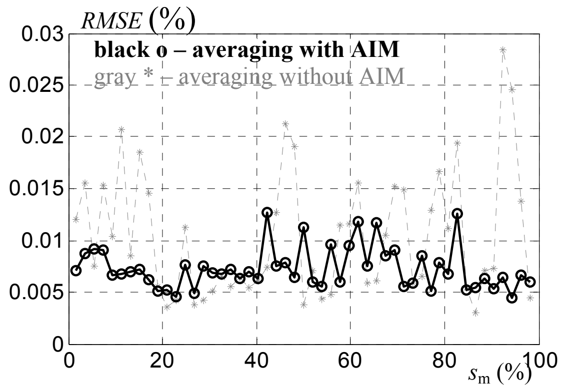


*Fig. 4*. RMSE of ADC with dithering before and after correction with AIM

In Fig. 5 for the given level of $s_m$ a number of 20 correction processes could be observed in the order as they were collected. Results obtained after correction with AIM ("o") are visibly closer to the ideal value (dashed line) compared to uncorrected results ("+"). Constant number of 8 (additional) steps of iteration was used in every correction process during experiments. One can notice from Fig. 5 that there are redundant steps in some cases. If every process is stopped after two identical subsequent values the maximum number of steps is less than 8 for many input levels and the average number of steps is 3.35. Furthermore, small oscillations occur in correction process. This is a consequence of quantization in ADC as the resolution of results is still finite (14 bit) after averaging. Oscillations extend duration of a correction process. Therefore we proposed special ending condition based on assumption of oscillation. According to this new condition the actual correction process stops if two identical values are obtained anywhere within iterations. Finally, the mean of points within the glimpse between identical values is evaluated as the corrected result. Using the last ending condition the average number of steps is only 2.71 and maximum of 5 steps is sufficient for almost all tested cases. Using any of last two alternatives of ending condition the ENOB value increased to 12.01 bit.

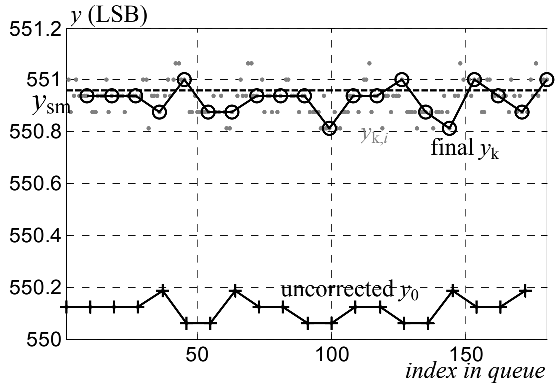


*Fig. 5.* Example of 20 correction processes with constant number of steps

## V. Conclusion

The ideas of automatic correction of an analog-to-digital converter (ADC) were presented in [2]. Real application of the correction for a system with a single-chip microcontroller has been discussed in this paper. Combination of two methods was used. Additive iterative method (AIM) is based on precisely designed inverse element and the method automatically corrects integral nonlinearity. Non-subtractive dithering with averaging enables correction below the level of 1 LSB of used 10-bit ADC. Both the linear error and the RMSE of the nonlinear error part were significantly reduced. Special ending condition of iterations was designed for systems comprising quantization. The ENOB (Effective Number of Bits) was improved in 2.37 bit with final value of 12.01 bit.

The designed technique is suitable for microcontroller based measuring for which the high speed is not the necessity. The speed limit for proposed correction method depends mainly on error properties of uncorrected ADC and on the system clock frequency. For usual types of integrated 10-bit ADC and 6 MHz clock up to 5 corrected measurement results per second could be obtained.

**Acknowledgements**

Work presented in this paper was supported by the Slovak Ministry of Education under grant No. 2003SP200280802 and by the Slovak Grant Agency VEGA under grant No. 1/0963/12.

**References**

1. *Галлон Й., Гартянски Р., Биттера М., Караваев Ю. Л.* Оценка взаимного влияния датчиков электромагнитного поля // Интеллектуал. системы в пр-ве. – 2010. – № 2. – С. 82–91.

2. *Каменский М., Ковач К., Крамер А., Никитин Ю. Р.* Использование аддитивного итерационного метода для коррекции ошибок в младшем разряде АЦП // Интеллектуал. системы в пр-ве. – 2011. – № 1. – С. 256–263.

3. *Muravyov, S. V.* Model of procedure for measurement result error correction // Proceedings of the XVI IMEKO World Congress, Hofburg, Vienna, Austria, 25-28 Sept. 2000. Published on CD ROM, sept. 2000.

4. *Kamenský, M., Kováč, K.* Iterative Correction of Measurement with Averaging of Dithered Samples // Advances in Electrical and Electronic Engineering. – 2008. – Vol. 7. – Nr 1-2. – Pp. 358-361.

5. *Widrow, B., Kollár, I.* Quantization Noise: Roundoff Error in Digital Computation, Signal Processing, Control, and Communications. Cambridge University Press, 2008.

6. *Skartlien, R., Oyehaug, L.* Quantization error and resolution in ensemble averaged data with noise // IEEE Trans. on Instrumentation and Measurement. –2005. – Vol. 54. – Nr 3. – Pp. 1303-1312.

7. *Carbone, P.* Quantitative Criteria for Design of Dither-Based Quantizing Systems // IEEE Transactions on Instrumentation and Measurement. –1997. – Vol. 46. – Nr 3. – Pp. 656-659.

***

*М. Каменски*, кандидат технических наук, старший преподаватель, Словацкий технологический университет

*К. Ковач*, кандидат технических наук, доцент, Словацкий технологический университет

*А. Краммер*, инженер, старший преподаватель, Словацкий технологический университет

*Ю. Р. Никитин*, кандидат технических наук, доцент, Ижевский государственный технический университет имени М. Т. Калашникова

**Экспериментальная верификация аддитивного итерационного метода для коррекции ошибок в младшем разряде АЦП**

*В применении аддитивного итерационного метода (АИМ) для аналого-цифрового преобразователя (АЦП), сочетание АИМ с методом подмешивания псевдослучайного сигнала без его вычитания позволяет исправлять ошибки в младшем разряде АЦП. Обсуждается реальное применение данного метода и его проверка при измерениях на базе однокристальных микроконтроллеров. Схемы, расположенные на кристалле, могут быть использованы для коррекции и требуется лишь несколько дополнительных компонентов. Инверсный элемент (ИЭ), который является основной частью AIM, создается с помощью широтно-импульсной модуляции выхода. Для достижения высокой точности обработки сигнала, генерируемого на выходе ИЭ, используется метод, похожий на детерминированное подмешивание псевдослучайного сигнала. Для обработки измеряемого сигнала на начальном этапе коррекции используется метод подмешивания псевдослучайного сигнала без его вычитания. Сравнивается теоретическая зависимость средней квадратической ошибки в зависимости от стандартного отклонения прибавленного шума с экспериментальными данными. В соответствии с реальной зависимостью находится квазиоптимальное стандартное отклонение и применяется для окончательной коррекции. Экспериментально доказана автоматическая коррекция как линейных, так и нелинейных ошибок АЦП. Наконец, найдены специальные условия окончания итерационной коррекции, которые особенно подходят для систем с квантователем.*

**Ключевые слова:** АЦП, ошибки, автоматическая коррекция

Получено: 16.04.12