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ADC Based Measurements: a Common Basis for the Uncertainty Estimation

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Abstract- In the last years, many Authors have dealt with the uncertainty evaluation of the measurement performed by using an analog-to-digital converter, proposing different approaches to analyze the uncertainty propagation. However, in these studies, in order to identify the uncertainty sources, different sets of parameters are used, and, often, it is not considered that the various uncertainty sources have different modalities of propagation. Obviously, this implies that the various proposed approaches are not directly comparable. One of the main reasons which has caused this situation is the coexistent of various Standards concerning the characterization of the analog-to-digital converters. Therefore, the manufacturers of converters have got a large arbitrariness in choosing and measuring the parameters which specify the performances of their products. With the aim to overtake these limitations and to suggest a common basis, in this paper, we identify, among the large number of parameters proposed by the various Standards, a minimum set of figures of merit which allows a correct uncertainty evaluation of a generic measurement performed by using an analog-to-digital converter. In order to verify the effectiveness of the proposed approach we applied the method to real measurements and compared the results with the ones obtained by means of experimental tests.

I. Introduction

Among the main applications of analog-to-digital converters (ADCs), there is doubtless their employment in the measurement world. However, the choice of the suitable ADC, among the unlimited assortment of typologies and models present on the market, is not a straightforward operation: the ADCs manufacturers, in fact, declare different sets of parameters to characterize their products and, moreover, these parameters are often defined and measured in different ways.

The task becomes more complicated considering that the instrument developers have to deal with the measurement uncertainty assessment. The problem is well known by the many Authors which have dealt with the uncertainty evaluation in the measurement performed by using an ADC [1-5] and have proposed different approach to analyze the uncertainty propagation (Monte Carlo approach; propagation law of the GUM; random-fuzzy variables). In fact, they use different parameters as starting point. The evaluation is performed by using: offset, gain and Effective Number Of Bits (ENOB) in [1]; offset, gain, non linearity, quantization and noise in [2]; offset, gain, quantization and noise in [3]; offset, gain and quantization in [4]. We also handled the topic and proposed an approach [5] which starts from the specifications of offset (included its temperature drift and its long term stability), gain (included its temperature drift, its long term stability and uncertainty of onboard calibration reference), integral non-linearity (INL), spurious tones, thermal noise, settling time, timing jitter, quantization, differential non-linearity (DNL) and crosstalk.

In any case, after the identification of the uncertainty sources, to assess the combined standard uncertainty of the measurement results, other two steps have to be carried out:

1. the composition of the uncertainties associated with each source to obtain the combined uncertainty of each acquired sample;
2. the study of how the uncertainties of each acquired sample propagate during the digital signal processing (considering that the result of a ADC-based measurement is a function of N acquired samples).

To correctly perform these tasks, it is absolutely necessary to consider that the various uncertainty sources have different modalities of compostion and propagation throughout the software block of the instrumentation. In particular, it is necessary to evaluate if the uncertainy sources are input signal dependent or not and it is necessary to estimate possible correlations among each acquired sample.

With this aim, we proposed a numerical approach based on the Monte Carlo method, developing a software tool which simulates a “true” A/D conversion and takes into account all the aforesaid uncertainty sources and their specific way to compose and propagate.

II. Identification of the parameters

The approach suggested in [5] leads to an accurate estimation of the uncertainties, but it is necessary to truthfully simulate a real A/D conversion process. This entails a large usage of resources and time both for developing the software and for performing the simulations. Moreover, the method requires a high number of parameters, which not always can be found in the manufacturer specifications.
With the aim to overtake these limitations, we studied, by using the software tool described in [5] and with a frequency domain analysis, the effect of each error source on the data obtained by processing a simulated single tone signal:

- the offset error reveals itself as a change of the DC component;
- the gain error produces a variation of the input signal spectral line amplitude;
- the INL causes the appearance of harmonics of the input signal;
- the spurious signals, which for various reasons can interfere with the A/D conversion process, appear as the corresponding frequency components;
- thermal noise, settling time, timing jitter, quantization and DNL generate a broadband noise, which, with good approximation, can be considered uniformly distributed all over the acquired spectrum.

Summarizing, offset errors, gain errors, INL and spurious tones always operate on well defined spectral components, while, on the contrary, the other uncertainty sources affect the whole frequency spectrum.
Another useful classification is the following:

- offset errors and spurious tones are input signal independent;
- gain errors and INL are input signal dependent;
- the broadband noise is actually input signal dependent, since some of the error sources, which generate it, depend on the shape, amplitude and frequency of the input signal (e.g. the timing jitter has no impact on a DC signal, but produces a evident effect on high frequency signals).

From these considerations, therefore, we can state that the parameters, sufficient to perform an accurate measurement uncertainty evaluation, are: offset, gain; a parameter which quantifies the harmonic distortion (THD); a parameter which quantifies the spurious tones (TSD); a parameter which measures what is commonly called noise floor (SNR).
Therefore, starting from the values of these parameters, it is possible to assess the uncertainty of whatever measurement performed by using an ADC.
In order to prove this statement, we developed a simple simulator of the A/D conversion. The simulation of the errors represented by the selected parameters is performed in the following way:

- to simulate the offset errors, a constant value is added to each sample of the input signal. This value is a random number within the range declared by the manufacturer. For each trial, the generated random number changes so that it lies in the specification range according to a rectangular distribution;
- to simulate the gain errors, each sample of the signal is multiplied by a constant value. This value is a random number within the range declared by the manufacturer. For each trial, the generated random number changes so that it lies in the specification range according to a rectangular distribution;
- to simulate the THD errors, the transfer function is distorted with components from the second to the tenth order. The amplitude of these components, for each trial, produces an actual THD randomly distributed from 0 to the THD declared in the specifications;
- two sinusoidal signals are added to simulate the presence of spurious tones. The amplitude of these components, for each trial, produces an actual TSD randomly distributed from 0 to the TSD declared in the specifications;
- to simulate the noise floor errors, a gaussian noise equivalent to the noise floor is added to the input signal.

If compared to the one proposed in [5], the advantage of this method is, besides the reduction of the parameters used for the uncertainty evaluation, a huge diminution of the software tool complexity and of its execution time; in fact by using this version, the simulation of settling time, timing jitter and quantization (plus DNL) is performed just adding an equivalent noise to the input signal.

III. Validation

With the aim to verify the effectiveness of the proposed approach and to provide an effective and experimental validation, we applied the method to real measurements and compared the results with the ones obtained by means of experimental tests.
The tests were carried out by using three models of data acquisition boards (DAQ). We performed the rms value measurement of a sinusoidal signal, since for this kind of measurement we can count on a Fluke 8508A multimeter which can be used as a reference.
The test signal is a 50 Hz 1 V rms sinewave generated by the Fluke 5720A calibrator. In order to improve the purity of the generated signal and to avoid the aliasing phenomenon, the signal is sent to a VI order bandpass passive filter.
The LabView 7.0 is the programming language used to drive the DAQs and to extract the rms values from the acquired samples. In all cases considered in the following, we carried out a coherent sampling, acquiring 50 samples at a 500 S/s rate. All the measurements were performed at 25 ° C.
To obtain the uncertainty values, the proposed approach was applied carrying out 100,000 trials.
In the following all the uncertainty values are reported as expanded uncertainties with a 99% confidence level (k = 2.58).
The first experiment was performed by using a National Instrument (NI) AT-MIO-16E-10 12 bit DAQ. For this board the five parameters for the uncertainty evaluation are (for the input range ± 10 V): offset = ± 500 μV; gain = ± 0.05%; THD = 77 dB; TSD = 74 dB; SNR = 71 dB. Starting from these values and applying the proposed approach we get an uncertainty value of 1.1 mV. For this measurement the expanded uncertainty of the Fluke 8508A, used in AC voltage mode and in the range 2 V is 120 μV, therefore the measured values obtained by the multimeter can be considered a reference. At this point, we carried out (in different days) 50 measurements of the rms value regulating the calibrator output in a way the multimeter is always reading the 1,000000 value. In fig. 1, the 50 measured values are reported; the dotted lines stand for the assessed uncertainty range and the continuous lines stand for the uncertainty range of the reference multimeter.

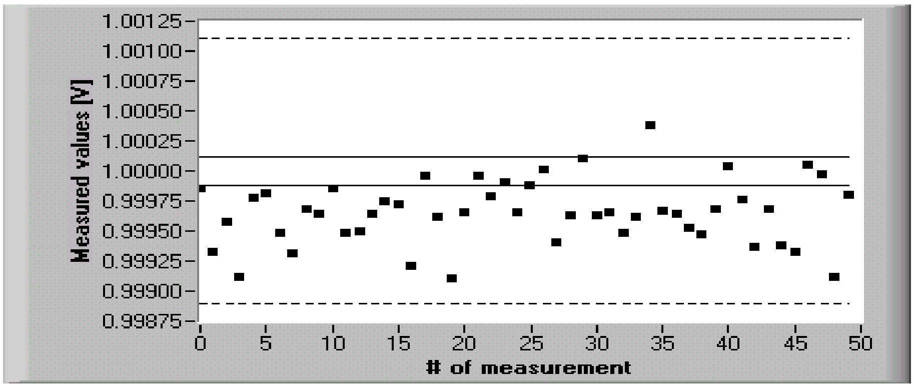

Fig. 1 Measurement performed by using the AT-MIO-16E-10 DAQ

All the measured values are within the calculated uncertainty range validating the obtained uncertainty estimate. It is possible to notice that the actual standard deviation of the 50 values are quite smaller than the estimated standard uncertainty; however, it is useful to underline that this apparent overestimate is due to the fact that some of the uncertainty sources (e.g. offset, gain, INL) cannot be pointed out in a single DAQ test.
The experiment was repeated performing a multi-channels acquisition and taking into account the crosstalk. According to the DAQ specifications, the crosstalk between two adjacent channels is 60 dB. This entails that the SNR value decreases at 59 dB. Performing the simulation with this new value, we obtain an uncertainty of 2.8 mV. In fig. 2, 50 measured values, obtained during a multi-channels acquisition, are reported.

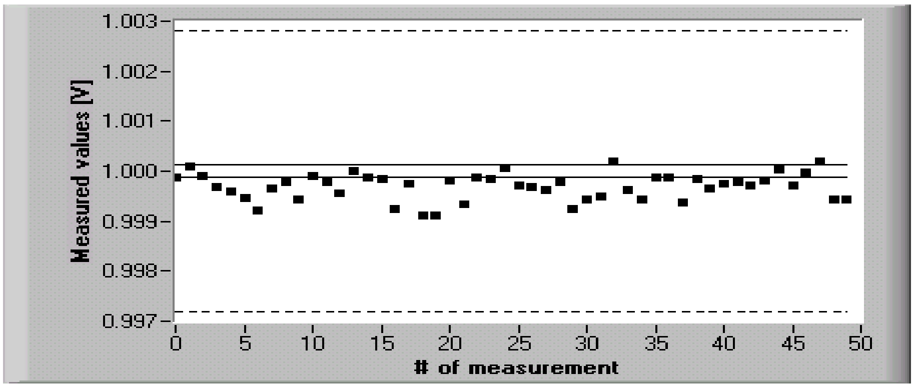

Fig. 2 Measurement performed by using the AT-MIO-16E-10 DAQ (multi-channels acquisition)

Also in this case all the measured values lie within the estimated uncertainty range.
Let's apply the proposed approach to a 16 bit DAQ, namely the NI PC-MIO-16XE-10. For this board the five parameters for the uncertainty evaluation are (for the input range ± 10 V): offset = ± 76 μV; gain = ± 30 ppm; THD = 90 dB; TSD = 92 dB; SNR = 90 dB. Starting from these values and applying the proposed approach we get an uncertainty value of 93 μV. In this case the Fluke 8508A cannot be considered as a reference, since the DAQ seems to have better performances. However, it is possible to compare the measures simultaneously carried out by the DAQ and by the multimeter and to verify if they are compatible. Therefore, we carried out (in different days) 50 measurements of the rms value regulating the calibrator output in a way the multimeter is always reading the 1.000000 V value. In fig. 3, the 50 measured values are reported; the continuous lines stand for the uncertainty range of the reference multimeter and the dotted lines stand for the measures obtained by the DAQ plus and minus the estimated uncertainty. All the 50 couples of measures are compatible.

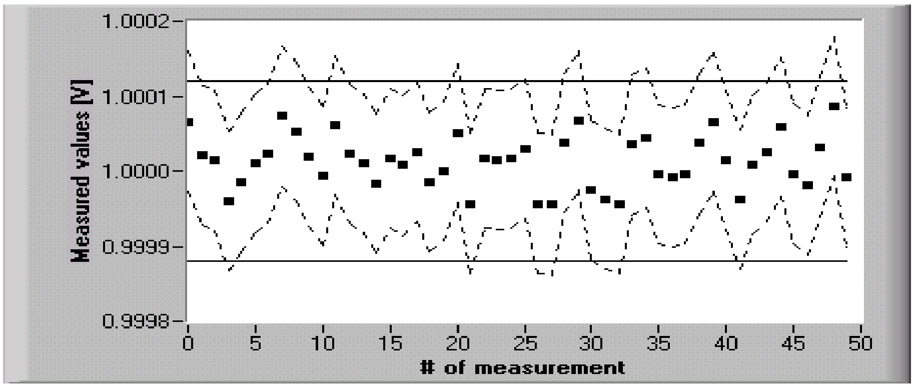

Fig. 3 - Measurement performed by using the PC-MIO-16XE-10 DAQ

It is to remark that the values of the five proposed parameters, besides from the manufacturer specifications, can be obtained by a Type A evaluation, if an adequate instrumentation is available. For instance, we performed the test by using a low cost 12 bit DAQ, i.e. the NI USB 6008. Since for this board the manufacturer does not provide the five parameters for the uncertainty estimate and given that we have got ten DAQs of this model, we decided to measure the five parameters of the ten boards. Offset and gain were obtained by drawing up the transfer characteristic, which, in its turn, is obtained from a five points least minimum squares method. As reference the Fluke 5720A calibrator was used. THD, TSD and SNR values were obtained by a FFT test acquiring a full-scale sinewave generated by the Fluke 5720A calibrator and handled by the aforesaid bandpass filter. From these tests we obtained the following values (for the input range ± 10 V): offset = ± 1.8 mV; gain = ± 0.12%; THD = 63 dB; TSD = 70 dB; SNR = 68 dB. Using these values and applying the proposed approach we get an uncertainty value of 2.1 mV.
At this point, we carried out (in different days) 150 measurements of the rms value by using three DAQs randomly chosen among the ten available boards. In fig. 4, the 150 measured values are reported (values 1-50 obtained by using the DAQ N.1; values 51-100 obtained by using the DAQ N.2; values 101-150 obtained by using the DAQ N.3).

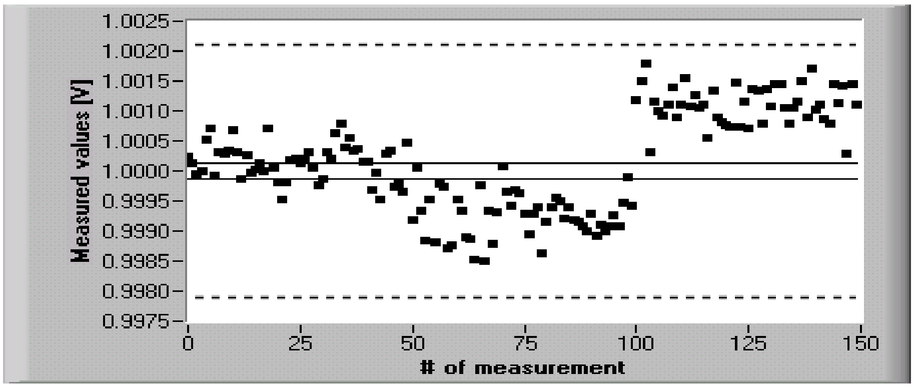

Fig. 4 - Measurement performed by using three USB6008 DAQs

Also in this case the results validate the proposed approach.

IV. Conclusion

In this paper the problem of the uncertainty estimation of the measurements performed by using an ADC has been considered. The various error sources introduced during the A/D conversion and their specific way to compose and propagate have been taken into account. Starting from this analysis we found out that the offset, gain, THD, TSD and SNR parameters take in consideration all the uncertainty sources, which arise during the A/D conversion, and their specific behavior. Therefore, starting from the values of these parameters, it is possible to assess the uncertainty of whatever measurement performed by using an ADC.
In order to prove this statement, we applied the method to real measurements and compared the results with the ones obtained by means of experimental tests. The comparison has shown that the choice of the five proposed parameters leads to an accurate estimation of the uncertainties.
Obviously, our proposal does not diminish the significance of other parameters which can give useful information about ADCs, such as Spurious-Free Dynamic Range (SFDR), SIgnal-to-Noise And Distortion ratio (SINAD), Effective Number Of Bits (ENOB).
Even if in this paper the five parameters have been used for a Monte Carlo approach, they could be safely employed as basis for other uncertainty propagation methodologies, such as the propagation law of the GUM or the random-fuzzy variables technique.

References

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