

EVALUATION OF THE MEASUREMENT UNCERTAINTY OF PC-BASED INSTRUMENTS BY USING THE EFFECTIVE NUMBER OF BITS

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Abstract - *The paper deals with the measurement uncertainty evaluation of the PC-based measurement instruments, by using the effective number of bits, that is a well known parameter, usually employed to characterise the overall behaviour of an A/D converter. In order to verify if this parameter can be also used to assess the measurement uncertainty, we use an ad-hoc developed software tool. The results show that using the effective number of bits can lead to an underestimate of the uncertainties.*

Keywords: Measurement Uncertainty, PC-Based Measurement Instrument, A/D Conversion.

1. INTRODUCTION

The measurement instruments based on analog to digital conversion of acquired signals and their successive processing are becoming more and more common in each sector of the measurement field. Besides the traditional stand-alone instruments, these days the so called "PC-based measurement instruments" (PCBMI), are more and more frequently utilized. However, given that these instruments are usually designed, assembled and programmed by the users themselves, the difficulties in a correct evaluation of the uncertainties have limited their spread on the industrial environment and on the test laboratories.

A straightforward method to assess the uncertainties could be the use of a "black-box" approach, that is to subject the tested instruments to reference signals, and to check how the measurement results vary. But this approach shows some restrictions: it is expensive, since it requires high-priced instrumentation to generate the reference signals; its validity cannot be extended to other signals different from the reference ones; it is not applicable during the design stage, given that the instrument has to be already realized; it does not allow a complete uncertainties analysis, since the error sources which have a systematic behaviour cannot be pointed out in a single instrument test. Therefore it is necessary to look for an alternative way to carry out the task, trying to find out if it is possible to assess the measurement uncertainties directly starting from the characteristics of each component of a PCBMI, as prescribed by the ISO - Guide to the Expression of Uncertainty in Measurement (GUM) [1].

The typical PCBMI can be shortly defined as an assembled measurement instrument constituted of transducers and signal conditioning accessories, a data acquisition board and a personal computer, which processes the sampled data.

For the characterization of the whole measurement chain is essential to identify all the error sources that are present in the various blocks of the chain and evaluate the probability density function (PDF) associated with each source. This evaluation can be carried out by means of statistical methods performing a Type A evaluation according to the GUM, or it is also possible turning to manufacturers' specifications (Type B evaluation). Of course the second way is less expansive and less time consuming, since it does not require any kind of test from the user. Of course in this case the homogeneity of the specifications becomes very important. As for transducers and signal conditioning accessories, the specifications are enough standardized. On the contrary as regards the data acquisition boards, each manufacturer furnishes the specifications in an arbitrary way, sometimes inventing some new parameter. Moreover to characterize the data acquisition boards are often used some parameters that consider their overall behaviour. Among them there is the very famous "Effective Number of Bits" (ENOB) [2-3]. Actually these parameters arose to characterize the A/D converters; anyway their extension to the entire data acquisition board is spontaneous and could be useful. At this point the doubt arises if these parameters can be utilized to assess the measurement uncertainties, in case these boards are used to assemble a PCBMI, or if it is absolutely necessary to start from the standard uncertainties associated with each error source, as prescribed by the GUM.

We already dealt with the uncertainty estimation of the PCBMI, proposing a software tool [4] that simulates the measurement process and the introduction of the error sources. By means of this tool, it is possible to evaluate the combined standard uncertainties associated with the measurement results, using the Monte Carlo approach. The starting point is the evaluation of the PDF associated with each error source. On the contrary other Authors use the ENOB to estimate the uncertainties [5].

In this paper we do some considerations to find out

if the ENOB can be actually used for the uncertainties estimation of the measurement results. For this purpose, we make use of the already developed software tool, which simulates the behaviour of a generic data acquisition board and the introduction of the errors generated during the A/D conversion.

Without any lose of generality we do not consider the errors generated by transducers and conditioning accessories, even if these are often predominant if compared with the other errors. In this framework, we do not consider either the uncertainties generated during the digital data processing.

2. THE UNCERTAINTY EVALUATION

There are two typical configurations for a generic multi-channel data acquisition board: with n channels and with n A/D converters; with n channels, a multiplexer and a single A/D converter. We consider the second configuration that presents greater problems from the uncertainties viewpoint, since the acquisition channels are more strictly coupled one another.

The main components of this kind of boards are: multiplexer, amplifier (usually with programmable gain), the sample and hold circuits, the clock generator, the A/D converter and the memory buffer. Each one of these components can generate uncertainties.

The main errors sources are: offset and its temperature drift, gain and its temperature drift, long term stability and temperature drift of the possible onboard calibration reference, integral non-linearity (INL), noise, cross-talk, settling time, timing jitter, quantization and differential non-linearity (DNL) [2,3]. Some of these errors are generated in a particular component of the board, for instance the quantization is generated by the A/D converter and the time jitter is generated by the clock generator; other source of errors are distributed among various components, for instance the non-linearity arises both in the amplifier than in the A/D converter. Usually the specifications are given for the entire data acquisition and not for each single component.

The following step to do is evaluating the PDFs associated with these error sources starting from the manufacturers' specifications. For this purpose the GUM prescribes some generic rules, however some assumption about the distributions of each error source has to be made, exploit all the knowledge on the matter. In [4], these rules and assumptions are discussed in detail.

After the identification of the error sources and the evaluation of the associated PDFs, to assess the combined standard uncertainty of the measurement results, we propose a numerical approach using a dedicated software tool. By means of this tool, it is

possible to evaluate the combined standard uncertainties associated with the measurement results, using the Monte Carlo approach. The software tool (totally described in [4]) takes into account all the error sources and simulates a set of M measurements performed on the same signal and using M different instruments of the same type.

An input signal simulator generates N samples as if they were obtained from an ideal sampling process of the signal. The core of the tool is a FOR loop executed M times. The N samples vector, inside the loop, is modified in order to simulate the errors generated during the A/D conversion process. The so modified N samples are sent to the software block of the instrument, which calculates the measurement result. The M measures are collected outside the loop and the standard deviation of the measurements results, that is the combined standard uncertainty, is calculated.

It is obvious that the effectiveness of the described approach is strictly depending on how the A/D conversion process and the introduction of the errors are simulated. So with the aim of verifying its usefulness, we applied the numerical method on various DSP basic blocks, which are typical of a measurement chain. The obtained results have been compared with the ones obtained by means of experimental tests.

For example, in the following we report the results of some tests carried out on a virtual instrument. It is constituted of a IV order lowpass filter, the National Instruments™ AT-MIO-16E10 data acquisition board (16 single-ended or 8 differential channels, successive approximation 12 bit ADC, 100 kS/s max sampling rate, ± 10 V maximum input signal range) and a PC with an INTEL™ 866 MHz processor; LabView™ 6.0 is the programming language used to drive the acquisition board, to process the acquired samples and to realize the user interface. The considered test signals (generated, for the experimental tests, by the National Instruments™ PCI-MIO-16XE10 board with a 16 bit D/A converter) are:

- 9 V peak value, 2 kHz sinusoidal waveform;
- 9 V peak value, 100 Hz rectangular waveform;
- 9 V peak value, 5 Hz triangular waveform.

The implemented algorithms are:

- mean value calculation;
- RMS value calculation;
- lowpass FIR filter;
- lowpass IIR filter;
- DFT;
- THD.

The measurands are respectively the mean value, the RMS value, the peak values of the filtered signal, the amplitude of the fundamental frequency and the THD value. In all cases the used sampling rate is 10 kS/s. Supposing to operate within ± 1 K of the data

acquisition board self-calibration temperature, within ± 10 K of factory calibration temperature, after one year of the factory calibration and with the gain set to 0.5, from the manufacturer specifications we get the values of table I.

Table I

National Instruments AT-MIO-16E10 Specifications

Error source	Manufacturer specification
offset	$\pm 1109 \mu\text{V}$
gain	502 ppm
INL	± 1 LSB
DNL	± 0.5 LSB
noise	0.07 LSB rms
settling time	± 0.1 LSB in 100 μs
timing jitter	± 5 ps
cross talk	- 80 dB

These values are inserted as inputs of the software tool, which calculates the uncertainty values (reported in tables II, III and IV) from a set of 10000 simulated measurements. In tables II, III and IV we report also the results of the experimental tests, obtained, also in this case, from a set of 10000 measurements. The experimental obtained uncertainties are (as prescribed in the GUM) the root sum square of the uncertainty actually measured and of the uncertainties due to offset, gain, temperature drift and integral non-linearity because the last ones, having a systematic behaviour, cannot be pointed out as uncertainty in a single instrument test.

Table II

Combined standard uncertainties for the sinusoidal waveform

Algorithm	Expected value	Numerical uncertainty	Experimental uncertainty
Mean	0.000 V	647 μV	512 μV
RMS	6.364 V	1859 μV	1532 μV
FIR filter	6.143 V	3001 μV	2365 μV
IIR filter	5.811 V	2096 μV	1688 μV
DFT	9.000 V	2620 μV	2043 μV
THD %	0.000	$1394 \cdot 10^{-6}$	$1012 \cdot 10^{-6}$

Table III

Combined standard uncertainties for the rectangular waveform

Algorithm	Expected value	Numerical uncertainty	Experimental uncertainty
Mean	0.000 V	646 μV	501 μV
RMS	9.000 V	2644 μV	2144 μV
FIR filter	11.124 V	3407 μV	3011 μV
IIR filter	10.775 V	3199 μV	2899 μV
DFT	11.461 V	3339 μV	2947 μV
THD %	45.689	$1884 \cdot 10^{-6}$	$1617 \cdot 10^{-6}$

Table IV

Combined standard uncertainties for the triangular waveform

Algorithm	Expected value	Numerical uncertainty	Experimental uncertainty
Mean	0.000 V	647 μV	494 μV
RMS	5.198 V	1522 μV	1177 μV
FIR filter	7.047 V	2444 μV	1966 μV
IIR filter	6.883 V	2079 μV	1671 μV
DFT	7.298 V	2121 μV	1876 μV
THD %	12.107	$2642 \cdot 10^{-6}$	$2128 \cdot 10^{-6}$

The experimental results are lower than the numerical obtained ones, also without considering the uncertainties introduced in the signal generation process and in anti-alias filtering. It means that the uncertainty values of some source are actually lower of the worst cases declared in the specifications. Therefore, these results validate the considered approach and the values of the various error sources of the utilized data acquisition board, declared in the manufacturer specifications.

3. CAN THE ENOB BE USEFUL TO EVALUATE THE MEASUREMENT UNCERTAINTIES?

The ENOB is defined in [2] as “A measure of the signal-to-noise ratio used to compare actual ADC performance to an ideal ADC”. For an input sine wave of specified frequency and amplitude, after correction for gain and offset, the effective number of bits is:

$$ENOB = N - \log_2 \left(\frac{rms \ noise}{ideal \ rms \ quantization \ error} \right)$$

where N is the number of bits of the converter.

Let's now verify which ones of the considered error sources give a contribution to the value of the ENOB. Analyzing the definition, we can notice that offset and gain errors do not give contribution to the ENOB. All the other error sources, generating rms noise, lower the ENOB value. Moreover the ENOB is calculated for a particular signal (sinusoid) and for a particular frequency and amplitude.

Only making these considerations, we should deduce that the ENOB cannot be used to evaluate the measurement uncertainties, since it does not take into account two of the main error sources and it is defined only for sinusoidal signals. However it could be useful to verify if the three specifications of ENOB, offset and gain can be used to estimate the uncertainties. For this purpose we utilized the Monte Carlo approach, by using a simplified version of the software tool. Offset and gain errors are simulated in the same way; than a white noise equivalent to ENOB is simply added. By applying the modified simulation tool to various basic measurement

algorithms and by comparing the results with the ones obtained by means of the already validated version of the software tool, it will be possible to draw some conclusion. The compared results are reported in tables V, VI and VII.

Table V

Combined standard uncertainties for the sinusoidal waveform

Algorithm	Uncertainty calculated by using the ENOB	Experimental uncertainty
Mean	521 μV	512 μV
RMS	1733 μV	1532 μV
FIR filter	2144 μV	2365 μV
IIR filter	1344 μV	1688 μV
DFT	2412 μV	2043 μV
THD %	$648 \cdot 10^{-6}$	$1012 \cdot 10^{-6}$

Table VI

Combined standard uncertainties for the rectangular waveform

Algorithm	Uncertainty calculated by using the ENOB	Experimental uncertainty
Mean	544 μV	501 μV
RMS	2275 μV	2144 μV
FIR filter	2778 μV	3011 μV
IIR filter	2649 μV	2899 μV
DFT	3078 μV	2947 μV
THD %	$945 \cdot 10^{-6}$	$1617 \cdot 10^{-6}$

Table VII

Combined standard uncertainties for the triangular waveform

Algorithm	Uncertainty calculated by using the ENOB	Experimental uncertainty
Mean	521 μV	494 μV
RMS	1288 μV	1177 μV
FIR filter	1844 μV	1966 μV
IIR filter	1417 μV	1671 μV
DFT	2121 μV	1876 μV
THD %	$1285 \cdot 10^{-6}$	$2128 \cdot 10^{-6}$

The results show that using the ENOB can lead to underestimate the uncertainties, mainly in the THD measurement. The reason is that, using a white noise equivalent to the ENOB to evaluate the uncertainties, is the same as not considering the systematic behaviour of harmonic and spurious components, which are always present in a real data acquisition board. In this way the evaluated uncertainties could be smaller than the true values.

The frequency components, which give contribution to the ENOB and consequently to the signal to noise and distortion ratio (SINAD), can be divided in three classes, which respectively generate the harmonic components, the spurious components and the noise floor: the total harmonic distortion (THD), the total spurious distortion (TSD) and the signal to non-harmonic ratio (SNHR) [2]. The first and second class components have a systematic behaviour, whereas the third class components show a casual behaviour. By using the three specifications of THD, TSD and SNHR, it is possible to separate the systematic components from the casual components, obtaining an accurate evaluation of the measurement uncertainties.

5. CONCLUSIONS

In this paper the problem of the uncertainty estimation of the PC-based measurements has been considered. According to the GUM, the measuring model and the various error sources have been taken into account, and a numerical method is applied to obtain the values of the standard uncertainty of the PCBMI measurement results. By means of these simulations we found out that the ENOB cannot be generally useful to correctly evaluate the measurement uncertainties. The main reason is that this parameter does not take into account some of the error sources, as offset and gain. Furthermore the ENOB is defined just for sinusoidal signals at a particular frequency and amplitude, so it loses its validity if used with generic signals.

If well measured, the ENOB is useful to characterize the overall performance of a data acquisition board, whereas to evaluate the PCBMI measurement uncertainties, it is our opinion that the starting point should be the evaluation of the PDFs associated with each error source.

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