A SOTWARE TOOL TO ESTIMATE THE MEASUREMENT UNCERTAINTIES IN THE A/D CONVERSION BASED INSTRUMENTS

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***Abstract** – In the paper we present a numerical method, which permits to evaluate the measurement uncertainties of the A/D conversion based instruments overcoming the possible inapplicability of the pure theoretical approach prescribed in the ISO – "Guide to the Expression of Uncertainty in Measurement".*

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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 measurement instruments with a dedicated software which performs a single kind or a very limited set of measurements, these days the so called "Virtual Instruments", usually assembled and programmed by the users, are more and more frequently utilized mainly in the industrial environment.

In both case these A/D conversion based instruments are constituted of a block for the transduction of the quantities and/or for the conditioning of the signals, a data acquisition block, a digital signal processor and the suitable software for the digital signal processing and the user interface.

For their correct employment, both stand-alone and virtual instruments have to be characterized and it is necessary to evaluate the uncertainties associated with the measurement results. And for a correct measurement uncertainty evaluation, according to the ISO – "Guide to the Expression of Uncertainty in Measurement" (GUM) [1], four fundamental steps have to be performed:

1. Identification of the uncertainty sources which give a contribution to the uncertainty of the measurement result during the transduction of the quantities, the conditioning of the signals and the A/D conversion.
2. Evaluation of the standard uncertainties associated with each source.
3. Composition of these standard uncertainties to obtain the combined standard uncertainty of each acquired sample.
4. Study of how the uncertainties of each acquired sample combine and propagate through the processing algorithms, which, in their turn, are uncertainty sources.

To strictly follow the procedures described in the GUM, we should perform the step four by means of the "uncertainty propagation law", but often the function describing the measurement algorithm is not an analytical and derivable function, so this procedure is not applicable. To avoid this obstacle, we carry out steps three and four using a software tool that simulates the A/D conversion process and the introduction of the sources of error. By means of this tool, it is possible to evaluate the combined standard uncertainties associated with the measurement results using a Monte Carlo approach.

In this context, we do not consider the errors due to transducers and conditioning accessories. Even if these errors are often predominant compared to the errors generated in the A/D conversion, the transducers and conditioning accessories variety is so wide, that it is necessary to analyse separately each particular situation. On the contrary, it is possible to carry out a general treatment in the case of the A/D conversion process and of the digital signal processing.

So in the following we deal with the identification of the uncertainty sources and with the evaluation of the standard uncertainties associated with each source (session 2). In session 3 we describe the uncertainties simulation block and how using it to estimate the combined standard uncertainty. In session 4 we apply the proposed uncertainty evaluation procedures to various basic digital signal processing block, typical of a measurement chain, comparing the so obtained results with experimental tests. The conclusions are exposed in session 5.

2 THE SOURCES OF ERRORS AND THE RELATED STANDARD UNCERTAINTIES

As regards the A/D conversion process, the main uncertainty 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].

The following step to do is evaluating the standard uncertainties associated with these uncertainty sources.

It can be carried out by means of statistical methods with a Type A evaluation according to the GUM, (but in order to estimate the uncertainties associated with all the sources we should test a statistically sufficient number of instruments of the same kind), or it is also possible to turn 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. However evaluating the standard uncertainties starting from the manufacturers' specifications is not a very effortless task, since each manufacturer furnishes the specifications in an arbitrary way, sometimes inventing some new parameter. In any case it is necessary to formulate some arbitrary hypothesis on the kind of the distributions.

For the offset, gain, temperature drift and long term stability errors, the manufacturers declare an interval $\pm a$ where the error surely lies. According to the GUM, provided that there is no contradictory information, each input quantity deviation has to be considered equally probable to lie anywhere within the interval given by specification, that is modeled by a rectangular probability distribution. The best estimate of the uncertainty is then $u=a/\sqrt{3}$. If there is reason to suppose that the values nearest to the mean are more probable, it is possible to hypothesize a normal distribution with a 99,73% confidence interval equal to $2a$. In this case the best estimate of uncertainties is $u=a/3$. It is possible to do a compromise, adopting a triangular distribution, for which the best estimate of the uncertainty is $u=a/\sqrt{6}$.

From our point of view in some cases, it could be adopted a U-shaped distribution (with the values nearest to the mean less probable); actually, if the error is on average much smaller of the upper limits, the instrument could be classified in a higher class by the manufacturer and easily sold at a higher price. In these cases the best estimate of the uncertainty is $u=a/\sqrt{2}$.

As for the non-linearity errors, the worst case values of INL and DNL are usually reported in the specifications.

The quantization error is generally considered uniformly lying within an interval of 1 LSB, so the best estimate of the standard uncertainty is $1/\sqrt{12}$ LSB.

The standard uncertainty related to noise can be directly obtained from the technical specifications, since it is usually expressed as rms value.

The cross-talk errors are produced by the interference in the multi-channel acquisition. Its related uncertainty is expressed as minimum ratio between the signal rms value and the interference signal rms value.

The settling time is the amount of time required for a signal that is amplified to reach a certain accuracy and stay within the specified range of accuracy. The manufacturer declares this range for the maximum sampling rate and for the full scale step, but the errors on the measured signal depend on the actual sampling rate and on the actual step.

Impact of timing jitter uncertainties of measuring chain is being transformed on the signal uncertainty as a function of signal derivatives. The manufacturer declares the aperture jitter value, typically expressed as rms value.

As for the software block we have to take into account the bias of the processing algorithms and the uncertainties related with the rounding phenomenon.

The algorithm bias is caused by the finite implementation of the measurement algorithms and represents the deviation of the actually measured result with respect to the theoretical response that the instrument should give.

The rounding phenomenon is caused by the microprocessor finite wordlength. It can occur in every multiplication carried out in a fixed-point representation and in every addition and multiplication carried out in a floating-point representation

3 THE NUMERICAL METHOD AND THE SOFTWARE TOOL

After the identification of the uncertainty sources and the evaluation of the associated standard uncertainties, to assess the combined standard uncertainty of the measurement results, we propose a numerical approach.

In a first stage, an input signal is digitally simulated and sent to the software block. By simulating a statistically sufficient number of measurements, and by evaluating mean and standard deviation of the results, we can estimate the standard uncertainty generated during the digital processing of the signals.

The algorithm bias (if the input signal is always the same) is an error with standard deviation equal to 0, therefore the difference between the obtained mean and the theoretical response which the instrument should give is exactly the bias. The estimate of the bias is often a very hard task, since it depends on the input signals as well as the algorithms. The search of the worst case could be useful to find an upper limit to the uncertainty. In many cases, the lack of knowledge of the bias becomes the main uncertainty source.

The measured standard deviation is the uncertainty due to the rounding occurrences. Since the number of bit used to represent the numbers is usually very high, this uncertainty is often negligible in comparison with the other ones.

Subsequently the A/D conversion simulation block is inserted between the input signals simulation block and the software block of the instrument, simulating a set of measurements carried out by different realizations of the same instrument.

The software tool takes into account all the uncertainty sources and simulates a set of M measurements performed on the same signal and using M different instruments of the same type. In the following its working principle is described.

The 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.

To simulate the offset, a constant value is added to each sample of the signal. This value is a random number within the range declared by the manufacturer. For each simulated measurement, the generated random number changes so that it lies in the specification range according to the chosen distribution. It is possible to choose among rectangular, normal and triangular distribution.

In the same way, gain errors are simulated. In this case each sample of the signal is multiplied by a constant value.

A white noise is added to simulate the thermal noise, and to simulate the crosstalk interference, another signal is added.

The INL errors are simulated distorting the transfer function with components of second, third, fourth and fifth order and with other two spurious components, so that the maximum deviation from a linear transfer function is always equal to the maximum INL value declared in the specifications.

As regarding the settling time errors, the software tool calculates the range of accuracy for the actual sampling rate, starting from the settling time accuracy at the maximum sampling rate; a random number within that range is generated and added to each sample.

The timing jitter errors are simulated by multiplying a random number, within the range of aperture jitter declared in the specifications, by the derivative of the signal; the so obtained values, which are the amplitude errors caused by the sampling time errors, are added to each sample.

At last, after the simulation of the quantization process, random number equally distributed in the range ± DNL are added to each quantization level, simulating the DNL errors.

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.

4 VALIDATION OF THE METHOD

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.

The measurands are respectively the mean value, the RMS value, the peak values of the filtered signal and the amplitude of the fundamental frequency.

In all cases the used sampling rate is 10 KS/s and the sampling is coherent with the generated signals, so in this way, the bias of the five algorithms is equal to 0.

Because the number of bits used to represent the mantissa is equal to 52, the uncertainties introduced by microprocessor finite wordlength are negligible.

Assuming 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

Uncertainty source	Manufacturer specification
offset	± 640 μV
gain	290 ppm
INL	± 1 LSB
DNL	± 0.5 LSB
quantization	± 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 behavior, cannot be pointed out as uncertainty in a single instrument test.

Table II

Combined standard uncertainties for the sinusoidal waveform

Algorithm	Expected value (V)	Numerical uncertainty (μV)	Experimental uncertainty (μV)
Mean	0,000	647	512
RMS	6,364	1859	1532
FIR filter	6,143	3001	2365
IIR filter	5,811	2096	1688
DFT	9,000	2620	2043

Table III

Combined standard uncertainties for the rectangular waveform

Algorithm	Expected value (V)	Numerical uncertainty (μV)	Experimental uncertainty (μV)
Mean	0,000	646	501
RMS	9,000	2644	2144
FIR filter	11,124	3407	3011
IIR filter	10,775	3199	2899
DFT	11,461	3339	2947

Table IV

Combined standard uncertainties for the triangular waveform

Algorithm	Expected value (V)	Numerical uncertainty (μV)	Experimental uncertainty (μV)
Mean	0,000	647	494
RMS	5,198	1522	1177
FIR filter	7,047	2444	1966
IIR filter	6,883	2079	1671
DFT	7,298	2121	1876

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 uncertainty sources of the utilized data acquisition board, declared in the manufacturer specifications.

The method can be used not only with simulated signals, but also with acquired signals. In this way it is possible to implement in the instruments algorithms that furnish besides the measurement results, the associated standard uncertainties.

5 CONCLUSION

In this work, a numerical method and a software tool to assess the measurement uncertainties of the A/D conversion based instruments, have been presented.

The approach is based on the Monte Carlo method and is applicable even if it not possible represents the DSP block implementing the measurement algorithm by a derivable function.

Some results obtained using this method have been compared with the ones obtained by means of experimental tests, and they are in good agreement.

Moreover by using this method it is possible to easily separate the uncertainties related with the software block from the ones generated in the A/D conversion process.

REFERENCES

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