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PC-BASED MEASUREMENT INSTRUMENTS: CHARACTERISATION

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Abstract: In this paper the problem of characterisation, in terms of uncertainty, of the measurement digital instruments performances, based on the typical architecture of PC bus plugged data acquisition boards is considered. According to the GUM the measuring model and the various sources of uncertainty have been taken into account and the law of uncertainty propagation has been applied. Then theoretical and numerical analyses of combined uncertainties are carried out obtaining formulas for the estimation of the standard uncertainty of the measurement result of various hardware and software blocks of the measurement chain. The results of numerical simulations and experimental tests are presented to validate the proposed method. In particular a virtual instrument, with a complex measurement chain, for flicker evaluation has been considered. The so obtained results are in a very good agreement with the theoretical and numerical ones.
Keywords: PC-based instrument, Virtual Instruments, Uncertainty estimation.

1 INTRODUCTION

The measurement instruments based on a data acquisition board, inside a PC, with transducers, signal conditioning accessories and the necessary software, (PC-based instruments), are becoming more and more widespread.

In order to characterise these measurement instruments based on the AD conversion and digital signal processing from a metrological point of view, many papers have dealt with the various sources of uncertainties which can be introduced in the various hardware and software components of the measurement chain, but paying attention only in a particular uncertainty source and without dealing with how these uncertainties propagate trough the measurement system.

But after the publication of the ISO guide (GUM) [1], which establishes general rules for the evaluation and the expression of measurement uncertainty of the whole measurement process, some applications of the GUM method have been proposed in literature. In [2] and [3] the problem of evaluating the uncertainty that characterises some algorithms (mean value, rms value and DFT) is discussed by considering different sources of uncertainty (quantization, time jitter, finite wordlength). In [4] a classification of measurement models, that is more general than that considered by ISO GUM, is presented and the use of sampling techniques for the evaluation of uncertainty is compared with the application of the GUM.

In this paper we consider the typical architecture of a PC-based measurement instrument taking into account the main uncertainty sources, in particular the ones generated in the acquisition board (section 2). In section 3, by applying the GUM method, we study how uncertainties propagate through some digital signal processing blocks, obtaining formulas for the evaluation of combined standard uncertainties. In section 4, by means of numerical simulations, different types of uncertainty are introduced on the input data in order to test the behaviour of various processing blocks and verify the results of the theoretical considerations. In section 5 we apply the proposed uncertainty evaluation procedure to a virtual instrument flicker measurement realised by authors [5] and we verify experimentally the proposed method.

2 PC-BASED INSTRUMENTS AND SOURCES OF UNCERTAINTY

A typical PC based instrument is constituted of the following blocks:

- transducers and signal conditioning accessories (current and voltage transformers, attenuators and amplifiers, antitialising filter, multiplexer, track and hold circuits);
- data acquisition board with sampler, A/D converters and clock generator;
- general-purpose computer (e.g. PC);

– software (control, data processing, analysis, presentation, interfacing).

Each block of the measurement chain can generate uncertainties, which propagate through the successive blocks, giving a contribution to the combined standard uncertainty of the measurement result.

In this context we focus only on uncertainties due to A/D conversion board and processing algorithms. Errors due to transducers and conditioning accessories are already well modelled and known; errors due to software can be not taken into account if tested and validated control and processing software packages are used.

In the A/D conversion process we have to take into account, as quantities that can significantly contribute towards uncertainty to the measurement result: offset, gain, quantization, noise, linearity, time jitter, settling time, cross-talk, temperature drift and stability.

The characterisation of these uncertainty sources can be carried out by means of statistical methods (Type A evaluation according to the GUM) based on traditional approaches (beat frequency testing, histogram analysis, sine wave curve fitting, discrete finite Fourier transform) or novel approaches (joint time frequency analysis, wavelet analysis). It is also possible to turn to manufacturers' specifications (Type B evaluation according to the GUM).

Usually, from technical specifications it is possible to directly get standard uncertainty related to offset, gain, quantization, noise, linearity, settling time, cross talk, temperature drift, stability. According to the GUM, provided that there is no contradictory information, each input quantity deviation is to be considered equally probable to lie anywhere within the interval given by specification, that is modelled by a rectangular probability distribution. The best estimate of the uncertainty is then:

$$u = \frac{a}{\sqrt{3}} \tag{1}$$

where a is the half-amplitude of the distribution interval.

To evaluate the time jitter uncertainty, which is a function of sampling rate, it is possible to use the following expression [6]:

$$u_{jitter} = 2^{-\left(\log_2\left(\frac{2}{\sqrt{3}p f_{samp} t_a}\right)-1\right)} \cdot V_{range} \tag{2}$$

where t_a is the aperture jitter and f_{samp} is the sampling rate.
Uncertainty related to the microprocessor finite wordlength can be modelled as follows [2], [7], [8]:

$$u_{fixed} = \sqrt{\frac{2^{-2 \cdot B_x}}{12}} \tag{3}$$

for each multiplication carried out by a fixed-point processor;

$$u_{floating,multipl} = \sqrt{0.18 \cdot 2^{-2 \cdot B_m}} \tag{4}$$

$$u_{floating,add} = \sqrt{p \cdot 0.18 \cdot 2^{-2 \cdot B_m}} \tag{5}$$

for each multiplication and addition, respectively, carried out by a floating-point processor;
where B_x is the fixed wordlength; B_m is the number of bit used to represent the mantissa; p is a factor depending on the probability of rounding occurrence in an addition.

Because the number of bits used by common processing software packages running on PCs to represent the mantissa is high (for instance LabView uses 52 bits in double precision), the uncertainties introduced by microprocessor finite wordlength are usually negligible compared with the other ones.

3 THEORETICAL ESTIMATION OF COMBINED UNCERTAINTIES

When a measurand estimate y is determined from N other quantities $x_1, x_2, \ldots, x_N$, through a functional relation y= $f(x_1, x_2, \ldots, x_N)$, the combined standard uncertainty estimate u_c(y) of the measurement result is the positive square root of the estimated variance $u^2_c(y)$, obtained from:

$$u_c^2(y) = \sum_{i=1}^{N}\left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i) + 2\sum_{i=1}^{N-1}\sum_{j=1, j\neq i}^{N}\frac{\partial f}{\partial x_i}\frac{\partial f}{\partial x_j} r(x_i, x_j) u(x_i) u(x_j) \tag{6}$$

where $u(x_i)$ is the estimated standard uncertainty associated with the input estimate x_i and $r(x_i,x_j)$ is the estimated correlation coefficient associated with x_i and x_j. This equation is based on a first-order Taylor series approximation of y.

Usually, in digital signal processing algorithms, each output sample *y* is a function of more than one input samples which can be correlated or not; as a consequence, it can be suitable to distinguish uncertainties of completely correlated input quantities (gain and offset) and uncertainties of absolutely not correlated input quantities (the other ones).

Moreover, in case of errors due to gain, the relative standard uncertainty $u_r(x)=u(x)/|x|$ is to be considered constant on each input sample. In all other cases it is the absolute standard uncertainty u, to be considered constant on each input sample.

According to these consideration we can divide the aforementioned sources of uncertainty in three classes:

I. offset and its temperature drift: completely correlated input quantities and $u_I=const$;
II. gain, its temperature drift and stability: completely correlated input quantities and $u_{rII}=const$;
III. quantization, noise, linearity, time jitter, settling time, cross talk: not correlated input quantities and $u_{III}=const$.

For I class sources $u(x_i) = const = u_I$ and $r(x_i,x_j) = 1$, so the (6) becomes:

$$u_{cI}(y) = u_I \sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i} \right) \tag{7}$$

For II class sources $u_r(x_i) = const = u_{rII}$ and $r(x_i,x_j) = 1$, so the (6) becomes:

$$u_{cII}(y) = u_{rII} \sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i} x_i \right) \tag{8}$$

For III class sources $u(x_i,x_j) = 0 \ \forall \ i \neq j$ and $u(x_i) = const = u_{III}$, so the (6) becomes:

$$u_{cIII}(y) = u_{III} \sqrt{\sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i} \right)^2} \tag{9}$$

In the followings, we take into account the applications to some processing algorithms, which are typical of a measurement chain.

Let us consider a finite impulse response filter. In this case

$$y = \sum_{i=1}^{N} a_i x_i \qquad \text{and} \qquad \frac{\partial f}{\partial x_i} = a_i \tag{10, 11}$$

so the (7),(8) and (9) become respectively:

$$u_{cI}(y) = u_I \sum_{i=1}^{N} a_i \tag{12}$$

$$u_{cII}(y) = u_{rII} \sum_{i=1}^{N} a_i x_i \Rightarrow u_{r\,cII}(y) = u_{rII}(x) \tag{13}$$

$$u_{cIII}(y) = u_{III} \sqrt{\sum_{i=1}^{N} a_i^{\,2}} \tag{14}$$

In the case of an infinite impulse response filter it is impossible to directly apply the (6), because each output sample is a function not only of the input samples, but also of some previous output samples. But we can calculate the impulse response *h* of the filter, and use this sequence to estimate the uncertainties. Therefore the (7), (8) and (9) become respectively:

$$u_{cI}(y) = u_I \sum_{i=0}^{\infty} h_i \tag{15}$$

$$u_{r\,cII}(y) = u_{rII} \tag{16}$$

$$u_{cIII}(y) = u_{III} \sqrt{\sum_{i=0}^{\infty} h_i^2} \tag{17}$$

In practical application you will consider a suitable finite number of terms such as the residuals of the two series are negligible with respect to other errors.

For a cascade of filters (FIR and/or IIR), obviously we must consider the whole system impulse response.

Let us consider an N points DFT and pay our attention on the modules. It is easy to recognise that:
for the I class sources uncertainties $u_{cI}(y) = 0$, except the DC component for which $u_{cI}(y)= u_I$;
for the II class sources uncertainties $u_{rcII}(y)= u_{rII}$;
for the III class sources uncertainties applying the (9), it is possible to obtain [2]:

$$u_{cIII}(y) = \frac{1}{\sqrt{2N}} u_{III} \quad (18)$$

except the DC component for which

$$u_{cIII}(y) = \frac{1}{\sqrt{N}} u_{III} \quad (19)$$

In order to perform a correct uncertainty estimation, the model of all the sources of uncertainty have to be known and characterised. Moreover the problem of correlation determination, between input quantities, is often difficult to manage, and in the evaluation of the uncertainty, the errors due to possible digital processing algorithms bias, if present, must be taken into account.

4 NUMERICAL SIMULATION

With the aim of testing the behaviour of each processing block and verifying the approximations of the GUM approach, we introduce the three classes of uncertainty source on the input data, using the LabView™ 5.1 environment.

The simulated input signal is a variously modulated and distorted 50 Hz sinusoidal voltage waveform, typical of electrical power systems, sampled at 2048 Hz. Running 20000 times the various algorithms we can calculate the standard deviation of each output sample for several values of uncertainty.

For instance, introducing a class III uncertainty source and considering the following DSP blocks, working at a 2048 S/s:

A) A 2048 samples DFT;
B) A first order IIR high pass filter with 0.05 Hz cut off frequency;
C) A sixth order IIR Butterworth low pass filter with 35 Hz cut off frequency;
D) A 512 coefficients FIR filter used as weighting filter in the flickermeter (see section 5);
E) A first order IIR low pass filter with 0.57 Hz cut off frequency;
F) The cascade of the B,C and D filter,

we obtain (for value of $u_r(x) \le 5\%$) [9]:

Table 1		
	Theoretical obtained uncertainty	Numerical obtained uncertainty
A	0.0156 u(x)	0.0158 u(x)
B	0.9999 u(x)	0.9972 u(x)
C	0.1859 u(x)	0.1887 u(x)
D	0.0976 u(x)	0.1013 u(x)
E	0.0285 u(x)	0.0294 u(x)
F	0.0963 u(x)	0.0968 u(x)

According to the central limit theorem, it is also verified that the observed distribution of the output samples is a normal one.

The obtained results are perfectly coincident with the theoretical ones.

The (6) can also be applied by means of numerical calculations. Therefore, when it is difficult to find analytical expressions of uncertainties propagation, a numerical simulation based method can be carried out to obtain the evaluation of combined uncertainty. In each case, it is very important to correctly model and quantify the uncertainties sources on the A/D board.

5 A VI FLICKERMETER: TESTS FOR UNCERTAINTY ESTIMATION

In this section we apply the proposed uncertainty estimation procedure to a virtual instrument for flicker evaluation on power systems [5].

The measurement chain can be separated into an hardware block and a software block. The first one is constituted by an analog filter to prevent the aliasing phenomenon and a digital acquisition board (DAQ) inserted on a PC which runs the data processing algorithms. The board is the National Instruments™ PCI-MIO-16XE10 whose features are listed below:

- 16 single-ended or 8 differential channels;
- successive approximation 16 bit ADC;
- 100 kS/s max sampling rate;
- ±10V maximum input signal range.

A Type B evaluation of standard uncertainties, based on manufacturer's specifications, is considered and rectangular distributions are assumed. By summing the contribution of each source of uncertainty the values of Tab. 2 are obtained [9]:

Table 2

Source class	Uncertainty source	Standard deviation
I	Off set	118 μV
II	Gain	0.0036%
III	Quantization, noise, INL	406 μV

The PC is based on a 233 MHz Pentium II Intel™ processor. The software block is the implementation, based on LabView™ 5.1 programming language, of suited digital signal processing algorithms.

The DAQ samples the input voltage at 2048 S/s and sends samples vectors to the flickermeter block, which furnishes the instantaneous flicker level S(t), constituted (according to [10]) by:

1. squaring multiplier;
2. first order high pass filter with 0.05 Hz cut off frequency;
3. sixth order Butterworth low pass filter with 35 Hz cut off frequency;
4. eye-brain system simulation filter (weighting filter) whose transfer function is established in [10];
5. squaring multiplier;
6. first order low pass filter with 0.57 Hz cut off frequency.

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

Also the uncertainties due to the time jitter and the settling time are negligible for a so low sampling rate and being the aperture jitter equal to 5 ps.

We don't consider the cross-talk uncertainty, assuming a single channel acquisition.

In our analysis we consider a coherent sampling, without generating the leakage phenomenon.

The offset errors, modulating with the carrier, generate, after the squaring, a carrier frequency component and a DC component, which are eliminated by the high pass filter, the Butterworth filter and the weighting filter. A notch filter, centred at the carrier frequency, could be introduced to reduce the flickermeter sensitivity to the offset uncertainty.

The gain uncertainty, for the presence of two squaring multipliers, is multiplied by four.

Regarding the III class uncertainty sources, the squaring multipliers cause that the output uncertainty depends on the input disturbance value and so, on the S(t) value.

By means of numerical calculation [9], we have obtained the following exp ression for the output uncertainty:

$$u_{cIII}(S) = k u_{III} \sqrt{S} \tag{20}$$

where k is a coefficient depending on the input disturbance frequency and form. Considering the worst case, it results k = 10/V when u_{III} is expressed in volts.

The output uncertainty due to all aforementioned uncertainty sources is then:

$$u_c(S) = 4u_{rII} S + k u_{III} \sqrt{S} \tag{21}$$

Experimental tests have been carried out, considering the testing procedure prescribed by [10].

In Tab. 3, for a 10 Hz sinusoidal disturbance, the standard uncertainties obtained using the (20) ($u_{\text{worst case}}$), by means of numerical simulation ($u_{\text{num.}}$) and experimentally ($u_{\text{exper.}}$) are reported.

Table 3

ΔV/V%	S(t)	$u_{\text{worst case}}$.	$u_{\text{num.}}$	$u_{\text{exper.}}$
2.600	100.00	0.0406	0.0338	0.0326
0.822	10.00	0.0128	0.0106	0.0088
0.260	1.00	0.0041	0.0034	0.0030
0.082	0.10	0.0013	0.0011	0.0010
0.026	0.01	0.0004	0.0003	0.0003

The experimental results are in good agreement with the worst case theoretical ones and with the numerical simulation obtained ones and validate the considered model and the values of the various uncertainty sources of the utilised data acquisition board.

For each measurement result, the instrument can furnish the associated standard uncertainty.

6 CONCLUSIONS

Analytical, numerical, by simulation and experimental approaches are presented and compared to evaluate the uncertainty that characterises the measurement results of PC-based digital instruments.

According to the GUM the measuring model and the various sources of uncertainty have been taken into account and the law of uncertainty propagation has been applied. Then a theoretical and/or numerical analysis of combined uncertainties is carried out obtaining formulas for the estimation of the standard uncertainty of the measurement result of various blocks (hardware and software) of the measurement chain.

The results of numerical simulations, with also experimental tests, have validated the proposed method, the considered model and the values of the various uncertainty sources of the utilised data acquisition board.

The proposed approach for evaluation of uncertainty applied to a PC-based instrument can be helpful both in the phase of instruments design (hardware and digital signal processing algorithms set up), in the phase of metrological characterisation and to implement, in the VI instruments, algorithms which furnish the standard uncertainty of the measurement result.

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