Uncertainty Analysis in High-Speed Multifunction Data Acquisition Device

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Abstract- In instrumentation based on an analog-to-digital converter (ADC), the performance of data acquisition (DAQ) device has a direct impact on the performance index of the whole measurement system, so it has an important significance that research the uncertainty analysis of data acquisition board. This paper proposes an automatic measurement system based on DAQ board with automatic uncertainty evaluation of the measurement results according to the "guide to the expression of uncertainty in measurement" and its supplement. Theoretical aspects of the uncertainty analysis in high-speed multifunction data acquisition device and the LabVIEW interface carried out are analyzed and discussed.

I. Introduction

Instruments based on an analog-to-digital converter (ADC) and subsequent data processing are very powerful and flexible, supported by the availability of increasing computational resources in the personal computers; nowadays, such systems represent a valid solution for many typical measurement applications. Thus, working out this kind of measurement systems is often simple and straightforward, but not is evaluating the uncertainty of the obtained measurements. In ADC evaluation, modeling is mainly used to analyze the impact of error sources on the metrological characteristics of the component. Considering this aspect, even if the IEEE 1241standard [1] defines some figures of merit for characterizing ADC accuracy, no information is provided to determine their uncertainty in compliance with the GUM [2].
In order to characterize an automatic measurement system, based on a data acquisition board with transducers, signal conditioning accessories and the necessary software, from a metrological point of view, the uncertainty sources which can be introduced in the various components of the measurement chain have to be considered [3-5]. In this paper we take into account the typical architecture of an automatic measurement instrument and the main sources of uncertainty, in particular those generated in the data acquisition device, are considered. Furthermore, the propagation of their effects trough the measurement chain is analyzed. An automatic measurement system is carried out with an interface able to evaluate automatically the measurement uncertainty by means of a LabVIEW program controlled by PC. The uncertainty evaluation, for direct and indirect measurements, has been carried out according to GUM [2] and its supplement [6], using Monte Carlo Method (MCM), and the results obtained by the two methods are compared.

II. Data acquisition device and uncertainty evaluation

A typical automatic measurement system (Figure 1) is constituted by the following blocks:
- transducers and signal conditioning devices;
- data acquisition board (DAQ) with sampler, A/D converters and clock generator (in this work it has been used a National Instruments NI-USB-6251 High-Speed M Series Multifunction DAQ for USB - 16-Bit, 1.25 MS/s);
- Personal Computer & LabVIEW;

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. For example, National Instruments recommends to perform an external complete calibration of the DAQ device under examination once every 2 years to maintain the accuracy performances.

Figure 1 – Automatic Measurement System block scheme

A program was developed in the form of a LabVIEW Virtual Instrument (VI), designed to determine the uncertainty of measurement results. The VI spreading is due to the advantages characterizing such instruments, if compared with the standard solutions. The most important can be reach in flexibility and reusability; the possibility to carry out, simultaneously, a lot of measurements, also of different kind of quantities; easy to use and friendly interface; less expensive than stand-alone instruments.
Initially a self-calibration must be performed after the device has warmed up for the recommended time period, approximately 30 minutes for this DAQ family devices. The VI that has been developed allows to determine the expanded uncertainty for direct or indirect measurement as well as to visualize, in text and graphical form, the recorded measurement results. In particular, the uncertainty evaluation is carried out by means of statistical methods for a type A, according to the GUM; using the specifications provided by the manufacturer [7] of the acquisition board will be used to extract information about the statistical parameters (type B uncertainties) to be used for the estimation of the combined uncertainty.
The data acquisition device temperature is also taken into account to provide a more accurate uncertainty value and it is corrected automatically by the developed program. The monitoring of the DAQ temperature is fundamental because the measurements should be executed with a temperature excursion within ±1°C respect to which the self-calibration (±10 °C from the last external calibration) has been carried out to guarantee the accuracy declared in the datasheet [7].
To better understand the data acquisition device behavior, in terms of uncertainty performances, the Monte Carlo method [6] has been also implemented. This methodology is particularly useful in situations where the applicability of the law of propagation of uncertainty is difficult or impossible. Finally, a comparison between the two methods – GUM and MCM – has been carried out.

III. DAQ device accuracy

Data acquisition devices are subject to modification of their characterizing parameters according to the variation of temperature, ageing, electromagnetic coupling and other phenomena. Parameters which mainly contribute to varying the input effectively achieved are:

- Offset voltage and its temperature drift;
- Amplifier gain and its temperature drift;
- Long-term stability and internal/external calibration references temperature drift;
- Integral non-linearity (INL);
- Differential non-linearity (DNL);
- Noise;
- Cross-talk;
- Settling time;
- Aperture jitter;
- DAC quantization error.

Such parameters can be kept under consideration by developing a model which relates them to the output measurement , which in this case is the voltage measured by the module.
National Instruments (NI) supplies some relations [7], as shown below, which are necessary to estimate in a deterministic mode, the measurements accuracy of the module:

$$Accuracy = \pm\left(reading \cdot k_{e1} + range \cdot k_{e2} + u_r\right) \tag{1}$$

where:

$$\begin{aligned} k_{e1} &= k_{e1\,residual} + A + B && \text{with } A = K_{Dguad} \text{ and } B = K_{Drif} \\ k_{e2} &= k_{e2\,residual} + k_{eINL} + C && \text{with } C = K_{Doff} \\ u_r &= \frac{random\ noise(V_{rms})}{\sqrt{100}} \cdot 3 \end{aligned} \tag{2}$$

assuming K_{e1}, gain error constant; K_{e2}, offset error constant; K_{eINL}, INL error constant; K_{Dguad}, gain temperature drift coefficient; K_{Drif}, reference temperature drift coefficient; K_{off}, offset temperature drift

coefficient.
The noise uncertainty u_r given by (2), for averaging 100 points, is deduced by multiplying the standard deviation by the coverage factor equivalent to 3; random noise has been directly quantified by NI and indicated in (2) as *C* in function of each of the devices' range. The periodic procedure of calibration of the module can be carried out by using both an internal or an external source. By using an internal source, the device refers to one of its own voltage sources whereas external calibration proves necessary every two years due to the fact that the internal sources are subject to aging and therefore cannot be considered reliable on a long term basis. In order to carry out this calibration it is therefore necessary to dispose of a voltage reference to connect to the device input slots, which has to be continuous and stable.
Considering the modules' temperature small variability interval, for which Eq. (1) turns out to be minimum, it has also proven necessary to accurately monitor the DAQ board temperature, by interrogating on a cyclic basis the sensor which is integrated on the ADC and PGIA (Programmable Gain Instrumentation Amplifier) chip, by means of a particular LabVIEW widget. By introducing such functionality into the developed software, voltage measurements and their temperature have been carried out and saved.

IV. Indirect measurements according to GUM

In order to carry out a comparison between the uncertainty propagation probabilistic method [2] and the simulated one based on the Monte Carlo Method (MCM), suggested by [6], an indirect power measurement has been carried out, by acquiring the values of the continuous voltage applied to the resistor terminals and by measuring its value. By setting the sampling frequency to 50 kHz, range (-5÷5) V and the differential input to the program carried out in LabVIEW, it has been possible to achieve a high number of voltage samples with a temperature range between 41°C and 43°C. The scope of fixing a short duration sampling is that of reducing the entity of each and every possible cause result dispersion, with particular reference to the thermal drift of the device. Assuming *N* as the number of samples, the corresponding type A uncertainty in terms of expected value $\sigma(V_A)$ and the standard uncertainty $u(V_A)$ associated with it, can be evaluated as:

$$E(V_A) = \frac{1}{N}\sum_{i=1}^{N} V_i = 3.929130\, V \qquad (3)$$

$$\sigma(V_A) = \sqrt{\frac{\sum_{i=1}^{N}\left[V_i - E(V)\right]^2}{N-1}} = 540\mu V \qquad (4)$$

$$u(V_A) = \frac{\sigma(V_A)}{\sqrt{N}} = 0.340\ \mu V \qquad (5)$$

It is possible to deduce the type B uncertainty $u(V_B)$ in function of the range used and of Eq. (1) as follows:

$$k_{e1} = 70\,ppm + 13\frac{ppm}{°C}\cdot(1°C) + 1\frac{ppm}{°C}\cdot(1°C) = 84\,ppm \qquad (6)$$

$$k_{e2} = 20\,ppm + 60\,ppm + 21\frac{ppm}{°C}\cdot(1°C) = 101\,ppm \qquad (7)$$

$$Accuracy = \pm\left(3.929130\cdot 84\ ppm + 5\cdot 101\ ppm + \frac{140\cdot 10^{-6}}{\sqrt{100}}\cdot 3\right) = \pm 877\mu V \qquad (8)$$

By supposing an uniform probability distribution, the absolute value of uncertainty is:

$$u(V_B) = \frac{accuracy}{\sqrt{3}} = 506\ \mu V \qquad (9)$$

It is interesting to observe that the standard uncertainty of the sample mean is three magnitudes of size smaller that the corresponding value of supplied by datasheet. The relative combined standard uncertainty on the achieved voltage therefore turns out to be:

$$u(V) = \sqrt{u^2(V_A) + u^2(V_B)} \approx u^2(V_B) = 506\mu V \tag{10}$$

By using an HP 34401A multimeter, it is possible to evaluate the resistance value with mean equal to 119.006 kΩ. The formula supplied by the instrumentation constructor has been used in order to calculate the standard uncertainty:

$$Accuracy = \pm(0.010\% reading + 0.001\% range) = \pm 0.022\ k\Omega \tag{11}$$

By assuming, also in this case, an uniform distribution, it is possible to calculate *u(R)* as follows:

$$u(R) = \frac{Accuracy}{\sqrt{3}} = 0.013\ k\Omega \tag{12}$$

Now it is possible to calculate the power as:

$$\overline{P} = \frac{\overline{V}^2}{R} = 129.725\mu W \tag{13}$$

and the combined uncertainty in the case of uncorrelated input measures:

$$u(P) = \sqrt{\sum_{i=1}^{2}\left(\frac{\partial P}{\partial x_i}\right)^2 u^2(x_i)} = \sqrt{\left(\frac{\partial P}{\partial V}\right)^2\Bigg|_{E(V),R} \cdot u^2(V) + \left(\frac{\partial P}{\partial R}\right)^2\Bigg|_{E(V),R} \cdot u^2(R)} = $$
$$= \sqrt{K_{s1}^2\left(506 \cdot 10^{-6}\right)^2 + K_{s2}^2\left(0.013 \cdot 10^3\right)^2} = 0.036\mu W \tag{14}$$

where *Ks1* and *Ks2* identify the values assumed by the models' sensibility coefficient in the expected values for measures V and R, respectively.
If we hypothesize a gaussian probability density function (PDF) output (Figure 2), it is possible to calculate the uncertainty extended for a 95% confidence level, by using the quantiles of a normal distribution, and so obtaining:

$$P = \overline{P} \pm U(P) = \overline{P} \pm 1.96\, u(P) = (129.725 \pm 0.071)\mu W$$

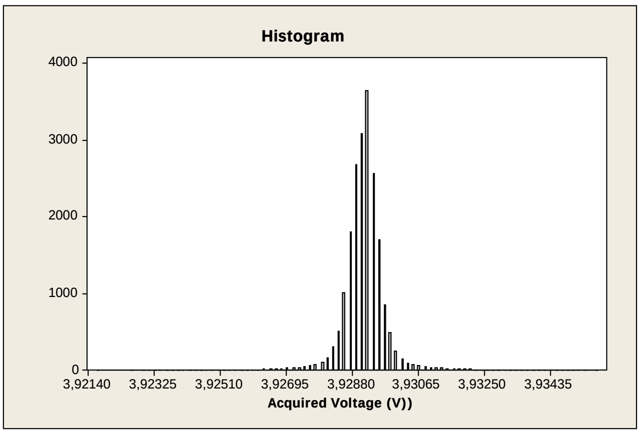

Figure 2 - Probability density function (PDF) of the output measurements

V. Indirect measurements: Monte Carlo Method

To carry out a simulation of PDF propagation through model (14), the Monte Carlo method is used by increasing as much as possible the number of samplings in order to obtain highly defined histogram. In order to simulate the other input measurements to the model, achieved voltage values and a series of pseudo-random data generated automatically by the PC have been used. Figure 3 shows a discrete representation of the input PDF, indicating on the x axis the voltage values subdivided into classes, and on the y axis the frequency density , that is the frequency of each class divided by its amplitude. The values achieved have been linked to a same number of other values obtained by means of a pseudo-random generation, in order to also consider the contribution of a type B uncertainty which has been supposed to be uniform. As to the probability density function associated to resistance values, on the basis of the considerations expressed in the previous paragraph, the value which has been measured turns out to be affected only by type B uncertainty . By assuming once more a rectangular PDF type, the histogram shown in Figure 3 is obtained.

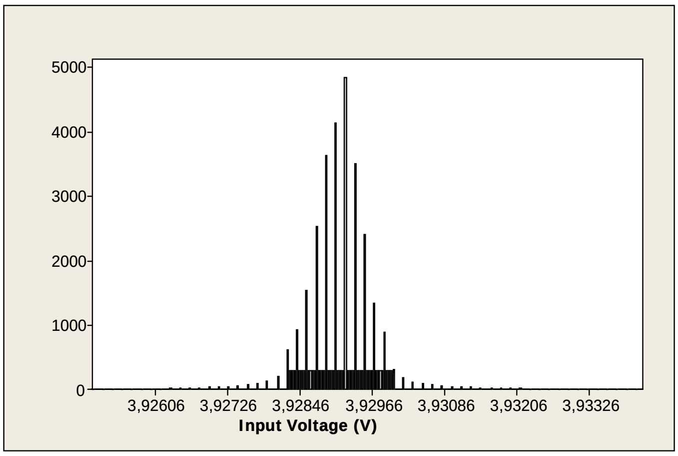

Figure 3 – Input voltage and resistance histogram

Enabling the two discreet PDF to spread through model (14), that is enabling the PC to automatically carry out the line by line multiplying and dividing operations of the two columns of numbers, a third column is determined and this third column refers to the power dissipated by the resistor; the outline of the histogram which refers to these values is shown in Figure 4. By analyzing the output discreet PDF, it can be seen that the histogram is slightly asymmetric, it has a slightly different aspect from that of a normal PDF and it has more than one peak. These three basic observations are sufficient to query the results obtained by the uncertainty propagation method used in the previous paragraph. Figure 4 shows an analysis of the output population through the confidence intervals, related to the set confidence interval (95%), in two cases: by using the traditional method based upon the assumption of a Gaussian PDF and by using the non parametric method, valid for whatever type of PDF.
As can be deducted from the “Normal Probability Plot”, the PDF which has been obtained is very different from a normal, therefore the most correct results are those obtained with the Monte Carlo approach.
The results are the following:

$P = (129.725 \pm 0.067)\mu W$ considering a relative confidence interval of 95% (non parametric method)

Figure 5 shows the part which refers to the analysis of the signal in the time domain, with each and every functionality of the oscilloscope, amongst which: trigger, direct or alternate coupling; time/division and volts/division handles; offset and cursors. On the top of the right hand side, the section referring to data statistic analysis has been introduced: average, effective value, standard deviation, uncertainty and accuracy of the device. Below the temperature of the DAQ module and the data saving function are shown. Finally, in the lower part of the picture, the section of data analysis in the signals’ frequency domain is shown with module and phase graphs, and you can also see the filtering window selection function.

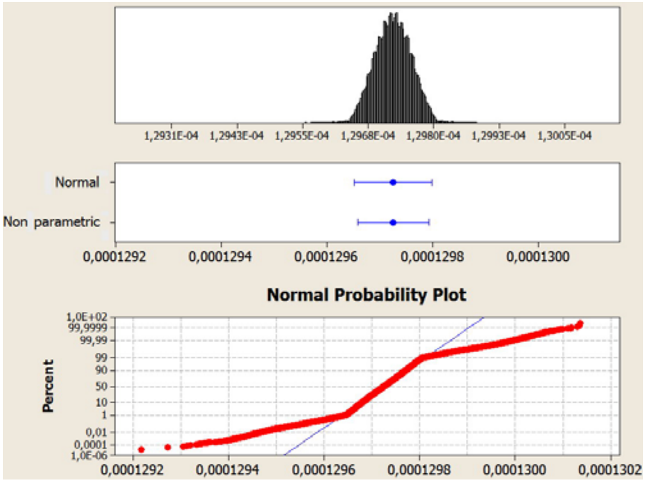

Figure 4 – Confidence interval (@ 95%) and distribution analysis for indirect measurement

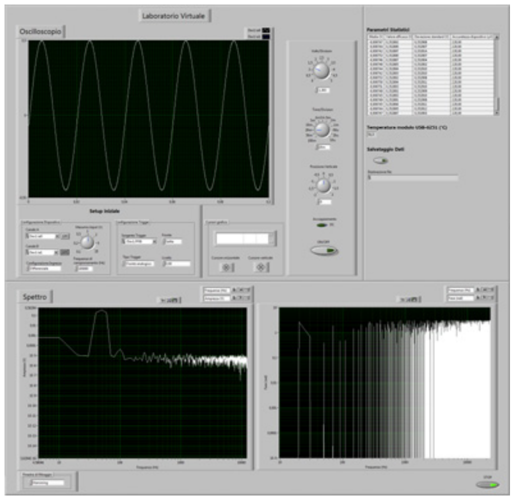

Figure 5 – Data Acquisition System Front Panel

VI. Conclusions

Data acquisition systems with modules for elaborators present many positive aspects. First of all, they enable great flexibility because measurements of various electrical quantities can be carried out with the same device. Then immediate use of the achieved data is possible and very accurate and quick elaboration of the data can be obtained for the PC capability.

The most interesting aspect is connected to the possibility of sampling a high number of values in short time intervals, with the great advantage of reducing uncertainty. In this paper, we have been able to observe how much smaller the measure of uncertainty determined statistically is compared to that declared by the constructor/supplier, specifically as it amounts to three orders of magnitude smaller. This is due to the fact that the uncertainty on a certain number of direct measures is correlated to the dispersion of the values compared to the average and also to the number of measurements; the smaller the dispersion, the bigger is the number of samples and the smaller the uncertainty will turn out to be. The declared accuracy is obtained, instead, by mathematical models in which the parameters contribute to supplying an estimation in the devices' worst operating condition .

In this paper we have been able to establish, with reference to the resistors' indirect power measure, that the GUM [1] based on the uncertainty propagation method, can lead to inexact results. In the case of automatic measurement systems based on a PC, considering the high number of samples that can be obtained, it is much more correct and convenient to refer to the Monte Carlo method. The comparison among the two methods shows that the range of values obtained by Monte Carlo method is smaller than the value obtained by the propagation of uncertainties. This difference is due, in part, to the approximation introduced in the first-order Taylor development, which the GUM assumes as hypothesis and, in part, to some input variables not normally distributed.

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