Uncertainty Evaluation: Practical Aspects

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Abstract:
Evaluation of measurements uncertainty is an important activity, leading in most cases to refinement of the test methods, better knowledge of the test equipment limits, and understanding limitations in measurement accuracy. The first part of this paper will show an application of the concept of uncertainty evaluations using it to adjust a comparison test method in order to obtain higher accuracy. The analysis of the uncertainty components and their correlations will also emphasize some sources of common mistakes and the restrictions that apply. It will be shown that more accurate methods may require additional tests, and may be longer and more expensive than initially expected. In the second part of the paper, aspects will be presented on how the influence of the environmental parameters is accounted for in the uncertainty budgets, pointing to causes for underestimated uncertainties.

1 Introduction

While choosing a test method, achieving a high measurement accuracy is a goal and a criterion used in selecting the test instruments, establishing the measurement steps, and determining the precautions to minimize the various influences. But only the final uncertainty analysis will emphasize the ways to reduce the uncertainties, sometimes on the expense of introducing supplementary steps in the measurement. In the following section an example will be given of the use of the uncertainty analysis to refine the test method the measurement for the sensitivity of the sensors. Ways to minimize the uncertainties through preliminary tests, meant to better characterize the instrumentation, will be shown in conjunction with their influence on the uncertainty budget.

2 Sensor sensitivity test

The sensitivity S, defined as:

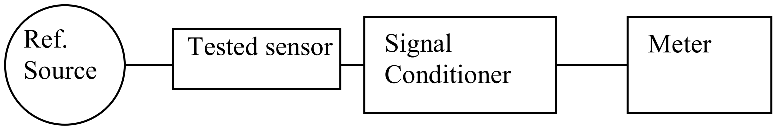
$$S = \frac{\Delta s_{out}}{\Delta s_{in}} \qquad (1)$$

represents the variation of the output signal Δs_{out} for a small variation of the input signal Δs_{in}. The nature of the input and output signals is different and depends on the type of sensor. This paper deals only with sensors that have electrical signals as output.

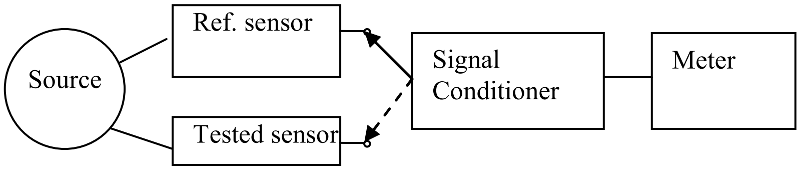
There are two general methods to measure the sensitivity of sensors, shown in Figure 1 below:

- the direct method which uses a reference input source,
- the comparison with a reference sensor, using a stable input source.

The direct method requires controlled physical processes to generate the known input magnitude for the sensor, therefore, most of the time it is more difficult and expensive to put in place. Secondary laboratories prefer the comparison method, known as accurate, which only needs a reference sensor and a signal that is stable for the duration of the measurement.



a. Direct method



b. Comparison method

Figure 1. Test methods for the sensors sensitivity.

The measurement relation for the tested sensor sensitivity using the comparison method is:

$$S_{DUT} = S_{ref}\frac{U_{DUT}}{U_{ref}}\frac{K_{ref}}{K_{DUT}} \qquad (2)$$

in which S_{DUT} and S_{ref} are the sensitivities of the device under test (DUT) and of the reference sensor respectively, U_{DUT} and U_{ref} are the voltages measured by the meter with the DUT and with the reference sensor, respectively in the measurement chain, K_{ref}, and K_{DUT} are the transfer functions of the signal conditioner when used with the two sensors and S_{in} is the input signal for the two sensors. In function of the nature of the two sensors, and /or the type of conditioners, the input, output or both signals involved may be continuous or alternative.

The uncertainty budget will comprise all components that affect the magnitudes in Equation (2) that come from instruments and influences of environment, instrument interaction, test duration, noise. By analyzing these components and their correlation, one can attempt changes in the test method or instrumentation in order to diminish global uncertainty.

2.1 Correlation issue

The reason for which the comparison method is known as accurate is that the uncertainties from the two voltage measurements U_{DUT}, U_{ref} are considered strongly correlated. Indeed, the voltages are measured with a same voltmeter, therefore the uncertainties will compensate as the magnitudes appear in a ratio. For these magnitudes, only the uncertainty components due to resolution, noise, and short-term drift influences are to be considered. The same reasoning applies to the uncertainties related to the ratio of the two values of the transfer function of the signal conditioner K_{DUT}, and K_{ref}.

Most of the time the sensors to be compared have very different sensitivities (different models or large tolerance domain and production spread for a same type) therefore the output signals will have different values. Consequently the working points of the conditioner will not be close and also the meter will measure signals that differ by large amounts.

With the solid-state devices, well known for nonlinear characteristics, and digitization, it is more reasonable to consider these uncertainty components not correlated [1]. Indeed, as shown in the Figure 2, within the tolerance domain, due to nonlinearities and digitization, unexpected jumps in the output levels may occur even for small steps of the input signal. Therefore the assumption that, for two measured levels, the errors act in the same way and will compensate, cannot stand anymore.

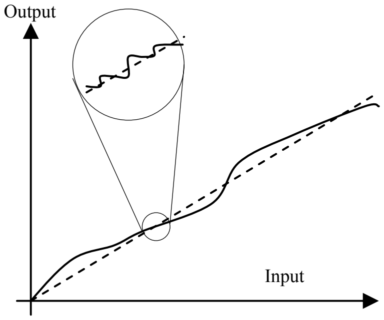


Figure 2. Nonlinearity and digitization effects on the transfer characteristics.

The specifications for some digital voltmeters include the restrictions to be considered when using such methods. The uncertainty of comparing two signals is separately listed in specifications, along with the domain of validity; these uncertainties are mainly due to noise and short-term drift and are very small. The restrictions concern the magnitude of the deviations in the signal level and signal frequency, use of same range, test duration, and resolution used.

In order to figure out the degree of correlation between the uncertainty components outside the narrow domain defined by the above restrictions, we would need a detailed knowledge of the uncertainty components that are characteristic to the measurement device, information that is not currently available. In these conditions, we only have the choice to overestimate the budget by considering the uncertainty components not correlated. Note that in other measurement configurations, when the magnitudes are not divided but multiplied, neglecting the correlation between the uncertainty components may lead to underestimating the budget.

In the above conditions, from the point of view of uncertainties, the test setup for the comparison method is in most of the cases equivalent to the one shown in Figure 3.

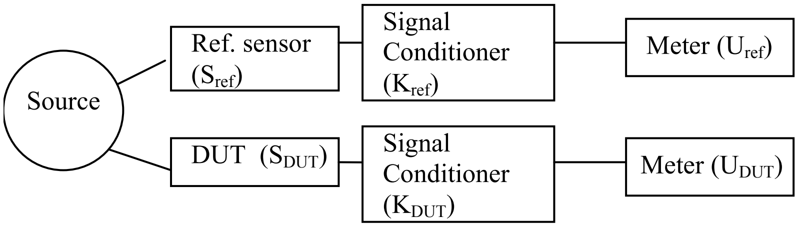


Figure 3. Comparison method with uncorrelated uncertainties.

2.2 Simultaneous or successive comparison

The test setup presented in Figure 3 applies also for simultaneous comparison between the responses of the reference and tested device. Simultaneous comparison reduces the requirements on the stability of the excitation source, while practically eliminating the corresponding uncertainty component from the budget. This is done on the expense of a more complex setup, a new uncertainty component due to the inter-influence of the two sensors, but with a big advantage of shortening the test. This method is most useful when the instability of the excitation is a major uncertainty factor and the raise in costs due to addition of extra instruments is acceptable.

2.3 Signal conditioner characterization

The uncertainty components due to the transfer-function values of the signal conditioner are usually known from the specifications. These are often overestimated as they need to cover not only the entire population of similar instruments but also the eventual drift. In order to estimate the actual uncertainties one can perform extra tests, through one of the following methods:

1. periodically measure the transfer function of the actual signal conditioner(s) at various signal levels and with lower uncertainties, then use these uncertainties in the budget, or
2. measure the actual transfer functions at the moment of the sensors test, using the exact signal levels involved in the sensors test.

Both methods will replace in Equation (2), each of the transfer function (K_{ref}, K_{DUT}) with a ratio of two voltages (U_{out}/U_{in}) multiplied by the impedance Z of a passive adaptor circuit, eventually needed to feed the signal into the conditioner:

$$S_{DUT} = S_{ref}\frac{U_{DUT}}{U_{ref}}\frac{U_{out-K_{ref}}}{U_{in-K_{ref}}}\cdot\frac{U_{in-K_{DUT}}}{U_{out-K_{DUT}}}\cdot\frac{Z_{ref}}{Z_{DUT}}\frac{S_{in-ref}}{S_{in-DUT}} \tag{3}$$

If method 1 is chosen, then the four extra voltages have different values, and, as discussed in §2.2, even if measured with the same voltmeter, the corresponding uncertainties are independent. Also, these uncertainties are not correlated with any of the other components present in the budget, i.e. those that are related to other magnitudes from Equation (2) as independently measured, at different moments and test conditions.

The new uncertainty components due to the passive linear impedance of the input adaptor will be correlated, therefore will be eliminated through the ratio. If the short term stability of this device can be neglected, then it does not introduce errors. Note that if the compared sensors are not similar in nature, then the adaptor circuits eventually needed to test the conditioners will be of different types, therefore their corresponding uncertainties will count entirely.

This first method will prove useful only if the new uncertainties are very small, which implies the use of expensive and very accurate instruments and adaptors.

In the second method, the transfer function values are measured in an extra step when the sensors are compared, using the same signal parameters as the ones provided by the two sensors.
In this way one has the following advantages:

- the transfer function of the conditioner is measured at almost the same working point as when working with the sensor,
- the uncertainties coming from the measurement of the output voltages involved in the characterization of the transfer functions are correlated with the corresponding ones measured when the sensors are connected (very close values measured in a short time interval with the same meter), therefore these will be eliminated; in this case only two voltage measurements will contribute to the global uncertainties: $U_{\text{in-Kref}}$ and $U_{\text{in-KDUT}}$
- uncertainty components accounting for long term stability of the conditioners characteristic do not appear in the budget;

The input adaptor circuits eventually needed to measure the transfer functions of the conditioners will affect the uncertainty budget in a similar way as for the previous case.

This method will prove useful only if the uncertainties related to the measurement of the two voltages $U_{\text{in-Kref}}$ and $U_{\text{in-KDUT}}$ are low enough – which may be a challenge when the input voltages are of low values.

2.4 Influence of signal frequency

When alternative signals are involved in measurements, the frequency of the signals is another influencing parameter, sometimes forgotten. The frequency will add uncertainties that are function of the slope m_i at the frequency f of the transfer characteristic k_i of the devices present in the measurement chain, according to the relation:

$$u_{i,f} = \left[\sum_i \left(\left.\frac{\partial k_i(f)}{\partial f}\right|_f \cdot u_f \right)^2 \right]^{1/2} = \left(\sum_i (m_i|_f \cdot u_f)^2 \right)^{1/2} \tag{4}$$

in which u_f is the uncertainty on the signal frequency. It is obvious that this is an important uncertainty component when the relative attenuation of filters or weighting networks is tested. For characteristics that are supposed flat, the frequency influence on uncertainties will still appear at the limits of the frequency domain and will vary from one unit to another. The difficulty to evaluate this component consists of determining the slope of the characteristic around the test frequency, as shown in Figure 4 below, and in expressing it in units that match the ones from other uncertainty terms.

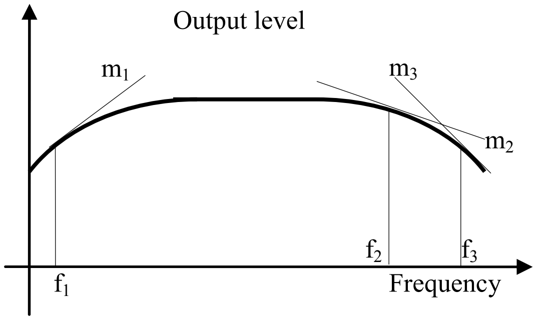


Figure 4. Variable slopes on various transfer functions

For instance for a high pass filter with a slope of the characteristic of m=18 dB/octave and a generator with 0.025% accuracy in frequency, the uncertainty component defined by relation (4) is about 0.01 dB (or 0.1%).

3 Accounting for environmental influences

In most of the cases, the equipment used for calibration, sensors included, is highly sensitive to the environment influences. The common way to correct for these influences is to use the previously determined sensitivity coefficients to various environmental parameters. For example, the sensor sensitivity at reference environmental parameters $S_{DUT}(P_0,T_0,RH_0)$ can be calculated from the measured value at actual conditions $S_{DUT}(P,T,RH)$ using correction terms as shown below:

$$S_{DUT}(P_0,T_0,RH_0) = S_{DUT}(P,T,RH) - k_{DUT-P}(P-P_0) - k_{DUT-T}(T-T_0) - k_{DUT-RH}(RH-RH_0) \quad (5)$$

where $k_{DUT\text{-}P,T,RH}$ are the sensitivity coefficients of the device under test to atmospheric pressure, P, to temperature, T, and to relative humidity, RH. The uncertainty budget will contain terms to account for the instrumental inaccuracy in determining the actual values of the parameters and the uncertainty on the value of the coefficients k_{DUT}.

Usually overlooked is that, during the test, the parameters may vary by large amounts that can overcome all uncertainty terms mentioned above. This may be due to:

- the insensitivity domain of the controlled systems,
- the low thermal inertia of small rooms,
- the temperature and humidity gradient in the room if the ventilation is not adequate,
- the manipulation by hand of the small sensors– which will rapidly change their temperature;
- transient temperatures due to measurement signals,
- other causes specific to each domain.

Therefore, in uncertainty budgets there are terms introduced due to the short term variations of the P, T, and RH based on the information collected continuously on the environment. Ideally the actual variations during the test should be measured, at the location of the compared devices, then determine if extra influences are also present, and then calculate the extra uncertainty terms. But, due to the lack of information, cost of such an analysis, and foreseeable error on this evaluation, for most of the cases, it is better to slightly overestimate the budget, by using one of the following ways:

a. Measure the environmental parameters at the working place for each repetition of the measurement, calculate the average and variation of each and use these values to evaluate the uncertainty components.

b. Using the environment monitoring data records, with values recorded every 30 min., as exemplified in Figure 5 below:

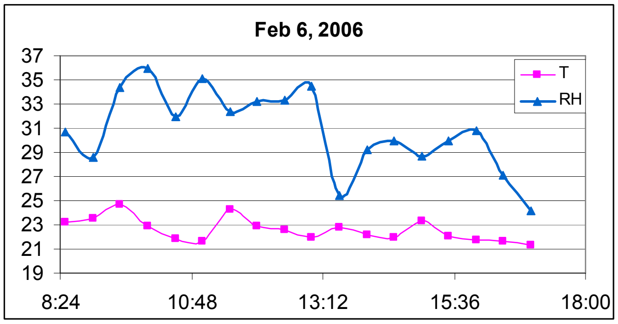


Figure 5. Laboratory temperature T (deg.C) and relative humidity RH (%) during working hours

In this case it is implicitly assumed that, around the tested devices, the parameters do not vary more than the global variation characteristic for the laboratory *for the duration of the test*. Therefore determine the standard deviation of the environmental parameters for periods of three hours (average test duration) and use these as additional standard uncertainty affecting the values of temperature T, relative humidity RH, or atmospheric pressure P.

c. In the case of the budgets that are pre-calculated and meant to cover any situation, the data from the environment monitoring system is used to determine the extent of the most probable domains for the parameters. This analysis showed that the temperature and the atmospheric pressure follow a normal distribution, while the relative humidity has a trapezoidal distribution confirming difficulties in controlling humidity during the wintertime.

The parameters values to be entered in the calculation of corrections are chosen at the limit of the confidence interval that has approximately 70% confidence level and the supplementary standard deviation due to the parameter variation affecting this value is the standard deviation of the distribution. The influence of this approach on the budget depends on the sensitivity of the tested devices to environment, going from hundreds to thousands of ppm.

4 Conclusions

This paper shows some aspects encountered in the daily practice, related to the calibration of sensors using the comparison methods. As the correlation between partial uncertainties must be reconsidered when using electronic equipment, the paper analyses the uncertainty budget of

several versions of the classic comparison method. These prove adequate for reducing the uncertainties when the excitation source is not stable enough or the instruments used need to be more accurately characterized.
Further, ways are suggested on how to account for the uncertainties due to the variation of the environmental parameters during the tests by valorizing the existing data from environment monitoring.

References

1. M. Buzduga, “Aspects of uncertainty evaluation”, Proceedings of the 2005 NCSLI Workshop & Symposium, Washington D.C., August 7-11, 2005.
2. ANSI/NCSL Z540-2-1977 (R2002), US Guide to the Expression of Uncertainty in Measurements.