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PRINCIPLES OF MEASUREMENT UNCERTAINTY

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I. The measurement concept

The concept of measurement has deep roots in the human culture since the origin of civilization. Measurements have always been the bridge between the empirical world of phenomena and the abstract world of concepts and knowledge. For this reason, the measurement activity is the basis of knowledge gleaned from experimental results. Apart from science, it even applies to the quantitative assessment of goods in commercial transactions, the assertion of a right, and so on. become more and more important. Galileo Galilei put experimentation at the base of science, showing that it is the only possible starting point for the validation of any scientific theory. More than one century ago, William Thomson, Lord Kelvin, reinforced this concept by stating (in a lecture to the Institution of Civil Engineers, United Kingdom, on 3 May 1883).

II. The GUM Approach to Uncertainty: Definitions and Methods for Its Determination

The great merit of the GUM is to provide an operative definition of uncertainty and operative prescriptions of how to estimate it. The mathematical background of all definitions and prescriptions is probability theory, which is the bestknown and most effective mathematical theory for handling incomplete information. The main assumption of probability theory is "the result of a measurement has been corrected for all recognized significant systematic effects." Under this assumption, the remaining effects that cause the "dispersion of the values that could reasonably be attributed to the measurand" are random effects.

Therefore, this dispersion can be represented by a probability density function (pdf), which can be characterized by its first two moments: the mean value and the standard deviation. The mean value is taken as the measurement result x, and the standard deviation, called "standard uncertainty" $u(x)$ is used as the "parameter that characterizes the dispersion of the values that could reasonably be attributed to the measurand" [1].

Type A Evaluation

As far as the evaluation of the uncertainty components is concerned, the GUM suggests that some components may be evaluated from the statistical distribution of the results of a series of measurements and can be characterized by experimental standard deviations. Of course, this method can be applied whenever a significant number of measurement results can be obtained, by repeating the measurement procedure under the same measurement conditions. The evaluation of the standard uncertainty by means of the statistical analysis of a series of observations is defined by the GUM as the "type A evaluation."

Type B Evaluation

Other components of uncertainty may be evaluated from assumed probability distributions, where the assumption may be based either on experience or on other information. These components are also characterized by the standard deviation of the assumed distribution. This method is applied when the measurement procedure cannot be repeated or when the confidence interval about the measurement result is known a priori , i.e., by means of calibration results. The evaluation of the standard uncertainty by means other than the statistical analysis of a series of observations is defined by the GUM as the "type B evaluation."

III. Around values attributed to the measurand confidence interval evaluation

The method for expressing and evaluating uncertainty should also provide a confidence interval, which is an "interval about the measurement result within which the values that could reasonably be attributed to the measurand may be expected to lie with a given level of confidence" [1].

The probability theory ensures that the probability density function associated with the dispersion of the measurement result is known (or assumed); the width of such a confidence interval can be obtained by multiplying the standard uncertainty by a suitable coverage factor, K. [2] This coverage factor depends, of course, on the probability density function of the result and the given level of confidence The expanded uncertainty $U = K \cdot u(x)$ is thus obtained, so that the confidence interval (with the given level of confidence) $x \pm U$ about the measurement result x is obtained. [1]

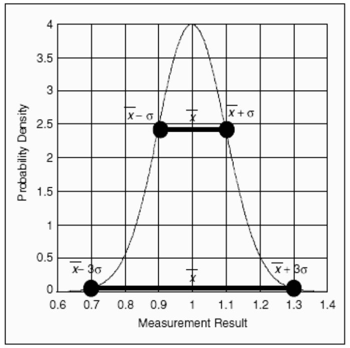

Fig. 1. Example of determination of the interval of confidence starting from a given pdf

The results of a measurement distribute according to a normal distribution about the mean value ¯x, as shown in Figure 1.

The standard uncertainty is given by the standard deviation σ of this distribution. If K=1 is taken, a confidence interval $\bar{x} \pm \sigma$ is obtained and the level of confidence is 68.3%. If K = 2, then the confidence interval is $\bar{x} \pm 2\sigma$ and the level of confidence climbs up to 95%. Similarly, if K=3, then the confidence interval becomes $\bar{x} \pm 3\sigma$ and the level of confidence increases to 99.7%

IV. Combined Standard Uncertainty

The uncertainty that has to be associated with the result of such a measurement should be obtained from the uncertainty values associated with the single measurement results employed in the evaluation of the measurand [1]. The GUM defines this uncertainty value as the "combined standard uncertainty," that is, the "standard uncertainty of the result of a measurement when that result is obtained from the values of a number of other quantities, equal to the positive square root of a sum of terms, being the variances or covariances of these other quantities weighted according to how the measurement result varies with changes in these quantities" [1].

Such a definition can be easily expressed with a mathematical equation when the result y of a measurement depends on N other measurement results x_i, $1 \le i \le N$ according to the following relationship:

$$y = f(x_1, x_2, ..., x_i, ..., x_N) \qquad (1)$$

If the hypotheses of the central limit theorem are met, that is, if the

1.) relationship f (•) is linear (at least in a suitable interval about the measurement result, which generally happens when the uncertainty values are reasonably small);[4]

2.) the number N of the measurement results x_i tends to infinity (or at least is high enough to approximate this condition);

3.) none of them is prevailing over the others (These hypotheses are generally satisfied, at least at first, in many practical applications. A short discussion on how to deal with the cases when they are not satisfied is reported in the next section.) [5];

4.) the final result y can be supposed to distribute according to a normal probability distribution, whose combined standard uncertainty is given by [1].

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

where $u(x_i)$ is the standard uncertainty associated with the measurement result x_i and $u(x_i, x_j)$ is the covariance of x_i against x_j. It is worth noting that, from a strict mathematical point of view, (2) provides correct results only when all mathematical constraints listed above are satisfied. In practice, this is not always verified, and (2) can only approximate the correct result; the effectiveness of such an approximation should be checked each time [6].

If the degree of correlation between x_i and x_j is expressed in terms of the correlation coefficient

$$r(x_i, x_j) = \frac{u(x_i, x_j)}{u(x_i)u(x_j)}, \qquad (3)$$

where $r(x_i, x_j) = r(x_j, x_i)$ and $-1 \le r(x_i, x_j) \le 1$, can be slightly altered

$$u_c(y) = \sqrt{\sum_{i=1}^{N}\left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i) + 2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\frac{\partial f}{\partial x_i}\frac{\partial f}{\partial x_j}r(x_i, x_j)u(x_i)u(x_j)}. \qquad (4)$$

If the measurement results x_i and x_j are totally uncorrelated, then $r(x_i, x_j)$=0, and therefore the combined standard uncertainty is given by

$$u_c(y) = \sqrt{\sum_{i=1}^{N}\left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i)}. \qquad (5)$$

Conclusions

The following fundamental concepts of measurement science have been briefly reported in this article:

1.) the result of a measurement provides only incomplete knowledge of the measurand, whose true value remains unknown and unknowable;

2.) a measurement result can be usefully employed only if the associated uncertainty is estimated and if it can be traced back to the appertaining standard; otherwise, it is a meaningless value;

Although this approach has proved to be effective and provided fairly correct results in many different situations.

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UNCERTAINTY ANALYSIS OF STRAIN GAGE CIRCUITS

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Abstract: A new topology of strain gage sensor signal conditioner based on the alternative current loop is proposed. The mathematical model of this sensor is discussed and its advantages are revealed. The results of computer simulation confirming the theoretical result are given.
Keywords: Gage sensors, current loop circuit, digital signal processing, Wheatstone bridge, interval analysis.

1. Introduction

Historically, the development of strain gages has followed many different approaches, and gages have been developed based on mechanical, optical, electrical, acoustical and even pneumatic principles [1]. Electrical resistance strain-gauge nearly satisfies all of the optimum requirements for a strain gage; therefore it is widely employed in stress analysis and as the sensing element in many other applications. The minute dimensional change of mechanical elements in response to a mechanical load, pressure, force, and stress causes a change in the resistance of the strain gage.

The bridge circuit has been a standard measurement circuit topology for over a century. Some derivative of it could reliably estimate almost any resistive and reactive electrical quantity when the product of the opposite bridge arm impedances was adjusted to be equal. As an electrical circuit for variable-impedance sensor element signal conditioning, the classic Wheatstone bridge provides a number of well-known

advantages [3]. However, there are important limitations inherent to this circuit [4], namely: 1) only half the signal from each element's impedance change is typically consumed in adjacent bridge arms; 2) the output signal is usually a nonlinear function of impedance change per individual bridge add measurement uncertainty, particularly when they occur in the inter-bridge wiring and especially when the various changes do not evolve identically; 4) the transfer function, including compensation, of a bridge transducer is typically not adjustable after manufacture and installation when the actual operating environment becomes known. Therefore, it is necessary to carry out the previous precise calibration of the gage sensor using the discrete trimming as well as accurate laser trimming techniques [2]. To eliminate the influence of connecting wires and nonlinearity of bridge circuit it was suggested [5] to use the current loop circuit put forward by K.F. Anderson [4]. It allows one to account for the parasitic influence of environmental variations in transducers' resistances as well as the induced noise and to introduce the required corrections into the output signal of this signal conditioner.

2. Analysis using interval arithmetic

In strain measurement, the uncertainty can arise from the process, strain gage, measuring circuits, lead wire and data representation element. In comparison to the classical methods, interval method considers all the sources of uncertainty and estimate in a single step of evaluation [6]. Hence it is proposed that interval method is a viable and alternative tool for uncertainty analysis of strain gage measuring circuits.

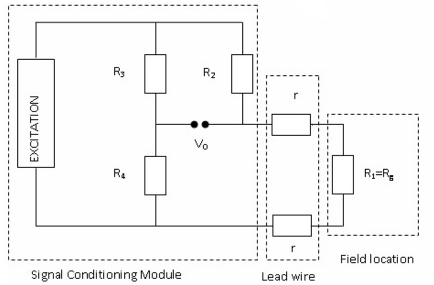

Fig. 1 Strain Measuring circuits (Quarter bridge)

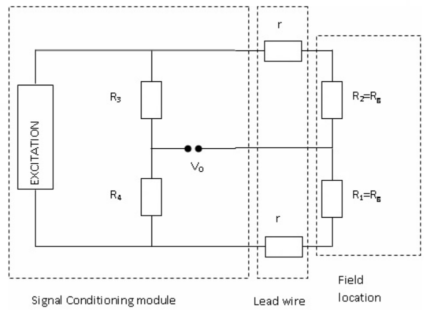

Fig. 2 Strain Measuring circuits (Half bridge)