Methods to ensure the reliability of measurements in the age of Industry 4.0

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Abstract. The methods of increasing the reliability of measurement results based on the use of structural redundancy in the implementation of measuring instruments and multidimensional models, calibration of measuring instruments (including remote) and methods of processing large arrays of measurement results are considered. It is noted that these methods will be demanded by mass production in the age of Industry 4.0.

1. Introduction

In an era of Industry 4.0 a lot of attention should be given to the reliability of primary measurements. To ensure the accuracy the measurement results can be used in various ways, for example:

- the use of structural redundancy in the implementation of measuring instruments and multidimensional models;
- the use of calibration of measuring instruments, in the perspective of remote calibration of measuring instruments using the Internet of Things technology;
- the use of techniques for processing a large array of measurement results (big data), etc.

2. State in the redundancy application field

The addition of redundancy in the measuring instruments structure gives an opportunity:

- to increase reliability due to the addition of redundancy in expanse by using several measuring channels of the same type functioning in parallel [1];
- to carry out self-calibration in order to reduce the systematic components of error (additive, multiplicative, from nonlinearity) by adding amendments to the measurement results due to the addition redundancy in expanse and time by using built-in calibrators (more accurate than the calibrated measuring instrument) and additional measurement cycles [2, 3];
- to reduce the systematic components of the error from external influencing quantities (temperature, humidity, etc.) by adding redundancy in expanse and time – through the use of additional measurement channels of external influencing quantities and the addition of appropriate amendments to the measurement results, etc. [3, 4];
- to carry out self-check and self-diagnostics of measuring instruments, including the evaluation of the critical component of the error [5] and evaluation of residual metrological resource [4, 5] due to the addition of redundancy in expanse and time.
3. The use of structural redundancy in the implementation of measuring instruments and multidimensional models

One of the ways to ensure the reliability of measurement results is the introduction of additional devices into the structure of measuring instruments (that is, the introduction of some redundancy). Additional devices may include tools for measuring operating conditions, such as ambient temperature, supply voltage, etc. This will allow for the time point \( t_i \) to get not only the value \( x_i \) of the measurement result of the measured quantity \( X \), but also the value of \( \xi_{1i}; \ldots; \xi_{mi} \), measurement results of influencing quantities (operating conditions) \( \Xi_1; \ldots; \Xi_m \). The measurement results of measurable and influencing quantities obtained at different points in time can be the basis for constructing multidimensional mathematical models. These mathematical models will introduce amendments in the measurements due to the change of impact values (operating conditions) of measuring instruments. For example, with minor deviations of the measurement results of the influencing quantities \( \xi_{1i}; \ldots; \xi_{mi} \) according to the values in which the measuring instrument was calibrated, i.e. \( \xi_{10}; \ldots; \xi_{m0} \), it is advisable to use a multidimensional model type

\[
y_i = x_i + \alpha_1(\xi_{1i} - \xi_{10}) + \ldots + \alpha_m(\xi_{mi} - \xi_{m0})
\]

\( y_i \) – the value of the measured quantity \( X \) obtained in accordance with the model; \( x_i \) – the value of the measurement result of the measured value (reading of the measuring instrument) \( X \); \( \alpha_1; \ldots; \alpha_m \) – coefficients of the influence of the influencing quantities on the reading of the measuring instrument of the measured quantity \( X \).

In the case of a substantial systematic time drift of the characteristics of the measuring instrument, model (1) should be supplemented with one more component that takes into account the instability correction [4]:

\[
y_i = x_i + \alpha_1(\xi_{1i} - \xi_{10}) + \ldots + \alpha_m(\xi_{mi} - \xi_{m0}) + \beta(t_i - t_c)
\]

\( \beta \) – the drift rate; \( (t_i - t_c) \) – time interval since the last calibration of measuring tools \( t_c \).

As additional devices, built-in calibrators can also be introduced into the structure of measuring instruments [3]. As part of a measuring instrument, they can be used as multi-valued measures in the implementation of additional measurement cycles. The introduction of the results of additional measurement cycles into multidimensional models will make it possible to introduce corrections in measurement results due to instrumental uncertainty of measuring instruments.

For example, in the case of a linear transformation function of the measuring instrument \( X \) a multidimensional model can be constructed using two additional measurement cycles:

\[
\begin{align*}
y_{i1} &= \varepsilon + (1 + \eta)x_i \\
y_{i2} &= \varepsilon + (1 + \eta)x_{i1} \\
y_{i3} &= \varepsilon + (1 + \eta)x_{i2}
\end{align*}
\]

\( \varepsilon \) and \( \eta \) – the values of the additive and multiplicative components of the error of the measuring instrument; \( x_{i1}, x_{i2} \) – the values of \( X \), reproduced by the built-in calibrator.

The solution of the system (3) relatively \( x_i \) gives:

\[
x_i = \frac{y_{i3} - y_{i2}}{y_{i1} - y_{i3}} x_{i1} + \frac{y_{i1} - y_{i2}}{y_{i1} - y_{i3}} x_{i2}
\]

that allows to make changes amendments to the measurement results due to the instrumental uncertainty of the measuring instruments, i.e. take into account the values of the additive and multiplicative components of the error of the measuring instrument.

Thus, the introduction of structural redundancy in the implementation of measuring instruments together with the use of multidimensional models will improve the reliability of measurement results.
4. Using calibration of measuring instruments

Calibration of measuring instruments is a traditional way to increase the reliability of measurement results obtained with its help. However, in an era of Industry 4.0 should be further developed in the calibration of measuring instruments remotely. Preferably, when implementing the remote calibration of measuring instruments, the procedures namely without human intervention, provided for by the Internet of Things should be used:

- the analysis and identification of the need for calibration of measuring instruments (through the establishment of intervals between calibrations);
- to identify the moments in those the measuring instrument is not used for the purpose;
- work was carried out to search the network for necessary standards that meet the characteristics that would be available at the required time points (not occupied by other consumers) for calibrating the measuring instrument;
- work is carried out for the calibration of measuring tools, etc.

In contrast to the recommendations of ILAC-G24 / OIML D 10: 2007 [6] a new approach is offered below for determining the intervals between calibrations of measuring instruments, based on taking into account the component of measurement uncertainty caused by instability of the measuring instrument in the expanded measurement uncertainty, and comparing the later with some previously accepted maximum permissible measurement uncertainty is offered.

When calibrating the measuring instrument, the calibration certificate, together with the ratio between the values provided by the standards and the corresponding readings of the measuring instruments, also indicates the expanded uncertainty $U$, which is usually obtained by multiplying the summary standard measurement uncertainty $u$ by the coverage factor $k$ (corresponding to the accepted probability $P$):

$$U = ku$$  \hspace{1cm} (4)

It should be noted that the value of the summary standard measurement uncertainty $u$ is obtained in the calibration laboratory and belongs to the time of the calibration. At the same time, during the operation of the measuring instrument (after a certain time interval $t$ from the moment of calibration), in addition to this, it is necessary to take into account the component of measurement uncertainty due to the instability of the measuring instrument $u_{\text{drift}}(t)$ due to the instability of the measuring instrument.

Then the summary standard measurement uncertainty $u^*$, taking into account, in addition to a summary of the standard measurement uncertainty $u$, obtained in the calibration laboratory, also the component of the uncertainty $u_{\text{drift}}(t)$ from the instability of the measurement, will be equal to:

$$u^* = \left[ u^2 + u_{\text{drift}}^2(t) \right]^{1/2}$$  \hspace{1cm} (5)

Supposedly that after a certain time interval $t$ from the moment of calibration, the component of measurement uncertainty due to the instability of the measuring instrument $u_{\text{drift}}(t)$ will be $b(t)$ times greater than the summary standard measurement uncertainty $u$, i.e:

$$u_{\text{drift}}(t) = ub(t)$$  \hspace{1cm} (6)

where a certain function of time is $b(t)$ (in the simplest case, linear).

After the substitution (6) into (5) we get:

$$u^* = \left[ u^2 + ub^2(t) \right]^{1/2}$$  \hspace{1cm} (7)

In this case, the expanded uncertainty of measurements $U^*$, taking into account the component of uncertainty from the instability of the measuring instrument, will be equal to:

$$U^* = k^* u^*$$  \hspace{1cm} (8)

where the coefficient of coverage is $k^*$ (the value of which may be different from $k$).
After the substitution (7) into (8) we obtain:

\[ U^* = k^* u \left[ 1 + b^2(t) \right]^{1/2} \]  

(9)

or subject to (4):

\[ U^* = U(k^*/k) \left[ 1 + b^2(t) \right]^{1/2} \]  

(10)

Certainly, that the calibrated measuring instrument can continue to be used until, over time, the extended measurement uncertainty does not exceed some pre-accepted maximum allowable uncertainty \( MPU \).

In particular, for determining the \( MPU \) may be used recommendations OIML G19 [7]:

\[ MPU = \ell MPE \]  

(11)

where \( \ell \) is the coefficient equals to 0.2 or 0.33; \( MPE \) is the maximum admissible error.

Then the right side of (10) should not exceed \( MPU \), i.e.

\[ U(k^*/k) \left[ 1 + b^2(t) \right]^{1/2} \leq MPU \]  

(12)

Using a new approach will allow us to objectively determine the need for remote calibration of measuring instruments. Expressive examples of measuring instruments in respect of which there is a huge demand for remote calibration of measuring instruments are:

– most of the measuring instruments for medical purposes, used by patients of medical institutions at home (primarily patients with disabilities);

– multichannel geographically distributed measuring systems, etc.

To perform remote calibration of measuring instruments, many issues will have to be resolved, such as:

– financially justified complication of the structure of measuring instruments in terms of the implementation of the possibility of calibrating remotely (for example, the introduction of a switch for connecting a measured quantity or a value realized using a standard, as well as the introduction of elements implementing information exchange protocols between devices complying with the Internet of Things standard);

– implement for the use as standards only of those standards, with the help of which calibration can be carried out remotely, for example, frequency (time) standards, etc.

The later will lead to the need for a significant change in the structure of the currently used built-in calibrators (referred to in paragraph 3 of this article), which should be based on frequency converters (time) to other quantities necessary for the built-in metrological control of measuring instruments.

5. Using methods for processing a large array of measurement results

The presence of a large array of measurement results allows us to solve many problems of increasing the reliability of measurement results, mainly when using multi-channel measurement systems:

– the use of a multidimensional model of the object of measurements together with an array of measurement results obtained using a multi-channel measurement system will not only clarify the type and parameters of the multidimensional model of the object, but also can serve as the basis for the construction of various criteria for checking the reliability of measurement results [8];

– the results of calibration of a set of similar measuring channels of a measuring system can be the basis for developing a methodology for assessing the reliability of values assigned to a standard during its calibration, etc.

When constructing these techniques, it should be remembered that the measurement result is not just a number, but a number with the corresponding measurement uncertainty.
6. Conclusions
The age of Industry 4.0 opens up new opportunities for improving the reliability of measurement results, which can be solved by using the following promising methods:

– use of structural redundancy in the implementation of measuring instruments and multidimensional models;
– the use of calibration of measuring instruments, in the long-term perspective, using the Internet of Things technology;
– the use of techniques for processing a large array of measurement results (big data), etc.

References
[1] Czichos H, Saito T and Smith L 2011 Handbook of metrology and testing (Heidelberg Dordrecht London New York: Springer) p 963
[2] Danilov A A and Kucherenko Yu V 2013 Meas. Tech. 55 1447-50
[3] Danilov A A, Kucherenco Yu V, Berzhinskaya M V and Ordinartseva N P 2014 Meas. Tech. 57 228-30
[4] Berzhinskaya M V and Danilov A A 2009 Meas. Tech. 52 220-22
[5] Pronin A N, Saposhnikova K V and Taymanov R E 2015 T-Comm 9(3) 32-37 (In Russian)
[6] ILAC-G24/OIML D 10: 2007 Guidelines for the Determination of Recalibration Intervals of Measuring Equipment Used in Testing Laboratories
[7] OIML 2017 OIML G19:2017 The Role of Measurement Uncertainty in Conformity Assessment Decisions in Legal Metrology
[8] Sheinin E M 2013 Meas. Tech. 55 1442-46