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METROLOGICAL CHARACTERISTICS OF MEASURING INSTRUMENTS: PROBLEMS AND METHODS OF STANDARDIZATION

V. A. Granovskiy and T. N. Siraya

Concern CSRI Elektropribor, JSC St. Petersburg, Russia
30 Malaya Posadskaya, 197046, St. Petersburg, Russia

Abstract: The paper considers standardization problems and methods that are concerned with metrological characteristics of measuring instruments in the context of the system approach. The main aims and principles of standardizing and estimating metrological characteristics are presented. General objectives and possible methods of standardization are discussed. Related concepts of pattern and norm are analyzed. Proposals on improving standardization methods for various groups of measuring instruments are elaborated.

Keywords: measuring instrument, metrological characteristic, norm, standardization, control.

1 INTRODUCTION

Metrological characteristics (MCs) of measuring instruments (MI) present its properties which affect the estimate of a measurand and the error (uncertainty) of this estimate[1]. MCs are rather heterogeneous: among these are characteristics that directly present the MI properties (e.g., calibration characteristic and its uncertainty) and characteristics of error components (e.g., root-mean-square deviation of the random basic error or partial uncertainty).

Standardization of MCs of MIs, first of all, MIs errors, is traditionally important for metrology, both theoretical and practical. These problems are widely covered in scientific publications [1–3] as well as in normative documents [4–6], etc.

However, modern practice, in particular, such user needs as pattern testing of new MIs for type approval, performance testing of approved type MIs, estimation of errors of MIs and systems, using the known MCs of MIs, and development and certification of measurement procedures, show that many issues of standardization problems have not been adequately studied.

The most important of them are the following three. Firstly, the main efforts in the problem of standardization are directed at justifying the list of standardized MCs instead of essentially establishing norms. Secondly, little attention is given to search and formalization of the completeness criterion for the MC list. Thirdly, the standardization problem is only solved for establishing the MI type.

These gaps are explained by the fact that general methodology is rather fragmentary; it does not allow solving specific problems for the following reasons.

First of all, individual MCs of MIs of the same type naturally differ. These differences, which emerge in manufacturing of MIs, are conditioned by their designs. Further, MIs are often used in different operating conditions within the standard range, and sometimes, beyond this range.

If we denote the full range of conditions for using MIs as

$$R = R\ \{\ \alpha_1, \alpha_2, \ldots, \alpha_m\ \},\ \alpha_i\ \mathrm{X} D_i,\ I = 1\ldots m,$$

then, in the foregoing, the instrument is used on a part of a set of conditions:

$$R_0 = R\ \{\ \alpha_{10}, \alpha_{20}, \ldots, \alpha_{m0}\ \},\ \alpha_{i0}\ \mathrm{X} D_{i0}\ \mathrm{T}\ D_i,\ I = 1\ldots m,$$

or beyond it:

$$\overline{R} = R\ \{\overline{\alpha}_1, \overline{\alpha}_2, \ldots, \overline{\alpha}_m\},\ \ \overline{\alpha}_i \in \overline{D}_i,\ \ \exists k:\ \overline{D}_k \cap D_k = \varnothing.$$

Besides, calibration of MIs gives a lot of individual data on their MCs, which are hardly ever used. All this suggests that MCs can and should be modified, and their norms need refining too.

In addition to it, as a rule, increase in accuracy of MIs leads to increase in their cost, which results in reduction of production MIs. This reinforces the tendency of giving up the so-called technical measurements, when users are guided by the MIs type (standard MCs), in favour of laboratory measurements, each of which uses a particular MI with individual MCs.

Thus, the tendency for MI individualization is reinforced by wider possibilities provided by information technologies used in estimation procedures and compliance tests.

Using the data on individual MCs through their monitoring and modification makes it possible to improve the efficiency of MIs. Therefore, the problem of standardization of MCs should be addressed with due account for modern design engineering, and realization of metrological procedures for conformity assessment.

The analysis and methods given below used to solve the specified tasks are stated in the terms of errors,

[1] In what follows we only consider MCs involved in estimation of errors (partial uncertainties) of the result (a priori in choosing MIs and a posteriori in data processing)

since in the context of methodology, the notion of error as an attribute of the factors contributing to the accuracy is more appropriate than the notion of uncertainty used for representation of measurement accuracy. Besides, the MI error obtained in calibration is based on an exactly known measurand and, therefore, this error is measurable in principle. Hence, the main argument in favour of abandoning the notion of error based on an unknown “true value” of measurand is no longer valid. However, the discussion below remains valid both in the terms of errors and uncertainties.

2 OBJECTIVES AND PRINCIPLES OF STANDARDIZING METROLOGICAL CHARCTERISTICS OF MEASURING INSTRUMENTS

The aims of standardization of MCs are formulated differently by manufacturers, users, and metrologists.

For a manufacturer, the aim is to attain uniformity of MCs for MIs of the same pattern.

For a user, the aim is to be able to choose MIs suitable for measurements and tests, i.e., to compare them with each other, to make sure that they are suited for specific measurements, and to form the result of measurements, including the error estimates, based on standardized MCs.

For a metrologist, the aim is a maximum possible efficiency of measurements performed with the chosen measurement instruments, which is attainable through revealing all metrological properties of MIs with their adequate representation and reliable testing.

Achieving these goals requires compliance with the following principles for norms establishing for MCs of MI [1, 2]:

– completeness of a set of MCs: all of the MI properties that affect determination and accuracy of measurement results should be standardized;

– MC separability: each of the MI properties to be normalized should be standardized separately;

– MC testability: methods for norm setting for MCs of MI should allow for experimental check for compliance of each MI with adopted norms;

– effectiveness of MC norm setting procedures: the procedure should be adequate to the objective stated above, for example, it should ensure MI compliance tests by a rather simple and efficient way.

It is easy to see that these principles are contradictory, which is a consequence of the contradictions in goals of manufacturers, users, and metrologists. For example, the principle of completeness is in contradiction with the principles of testability and effectiveness, the separability principle is obviously in conflict with that of testability. Lastly, efficiency is a complex principle. It includes a number of partial requirements which present different aspects that contradicting the previous principles to some extent.

As regards manufacturers, they are interested in emphasizing the market advantages of MIs and minimizing expenditures. Users want to simplify the employment of MIs at a required level of their efficiency. On the other hand, the purposes of metrologists and, partially, users call for a more detailed description of individual properties of the MIs and MCs. Among the others, the metrologists have the most objective position, because they present the interests of the measurement system as a whole.

Currently (with rare exceptions), specialists use the sets of MCs and **norms** for a particular MI pattern. The paradox is that if manufactures prefer using the notion of “pattern”, norms go into the background, whereas ensuring uniformity within the pattern comes into the foreground. However, the norm established to cover a current MI totality would rather conceal the problem of ensuring uniformity than contribute to its solution. The correct approach is to ensure stable manufacturing of MIs and, on this basis, the uniformity of the totality obtained, and then, after examining the statistical properties of this totality, to substantiate the norms.

3 GOALS AND METHODS FOR STANDARDIZING METROLOGICAL CHARCTERISTICS OF MESURING INSTRUMENTS

The main contradiction, which brings the standardization problem discussed here, lies in the fact that the MI is manufactured (designed) as an element of **a certain type**, and exists and operates as an **individual** instrument.

Therefore, the notion of type is important for MI manufacturers only. For any user, the type is relevant but it does not prevail. Primarily the type is of interest to a user if the MI is obviously defective and should be replaced with an equivalent one.

Also, we can distinguish simple batch-produced MIs with a short life cycle and simple typical application. The notion of type remains significant for them, in particular, type estimates, i.e., limits of errors, are sufficient for MI application.

However, for a majority of universal MIs used in a wide range of applications and measurement conditions, when high-accuracy measurement and/or precise estimation of errors are required, it is desirable to know individual MCs of this very instrument. Therefore, there is a need to use individual MCs and keep track of their evolution; hence, the notion of pattern becomes fuzzy and it is no longer significant.

To go from type to individual MCs in the process of instrument exploitation, a new approach to standardization based on the formulated principles should be developed. In other words, standardization methods should be optimized. We mean formulation of criterions suitable for optimal solution of each of the problems being considered. Further, we consider the following standardization problems associated with different stages of instrument life cycle.

Developing an MC set

On the whole, the choice of MCs of MIs should be based on a detailed model of MI properties and their instrumental errors [7]. In so doing, we can trace the logic of MC introduction:

$\{\text{MI properties}\} \Rightarrow \{\text{models of MI properties}\} \Rightarrow \{\text{MCs}\}$.

In the formal statement, a set of MI MC is represented as a certain basis in space determined by an MI model. This brings the questions of basis completeness and equivalence of different basis.

These issues should be solved in the context of the adopted MI model, which is conditioned, among other factors, by goals, aims, conditions of measurements, and requirements for measurement errors. It implies that we can introduce different measurement models for MIs of similar designs, and, therefore, prescribe different sets of MCs if they are intended for different aims and goals.

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Then, the criterion of MC completeness for a set of MCs may have the following meaning: a set of MCs is considered complete if the introduction of a new MC does not lead to any significant (from the standpoint of measurement objectives) refinement of estimates of the MI accuracy, taking into consideration uncertainty of source data needed for this refinement.

Similar questions arise concerning detailed representation of MCs. In particular, we can choose the adequate form of calibrating curve or influence function for MI [2] (such as linear and quadratic dependencies for temperature error).

Apparently, it is also appropriate only if it is possible to refine estimates of MI accuracy, taking into account other factors that limit the attainable estimation accuracy and feasibility of MC testing.

Establishing norms for MI MC

It is the most common practice that norms for MI MCs are established on the basis of initial requirements for the development of MIs with consideration for the design features. The established norms are experimentally verified prior to MIs release to the market, which is usually done in the process of development testing prior to pattern approval. For processing of data obtained in experimental verification, it is preferable to use statistical methods based on tolerance intervals.

Since many of the MCs are probabilistic in nature (e.g., RMS error of certain deviations or error components), their application involves various problems. For individually manufactured (super complicated and expensive) MIs, for example, there arises the problem of approval, which involves, above all, interpretation of statistical MCs. The essence of this interpretation lies in guessing the general totality of MIs.

For series-produced MIs, stability (controllability) of the MI manufacturing process ensures that a lot of MIs is a sample of real or conceivable general totality.

Confirmation of the statistical norm for an MI depends on whether the process of "accuracy unfolding**"** (error realization) is ergodic. The ergodic process suggests using statistical estimates of the parameters of a random process based on its realization. If the process is non-ergodic, it makes sense to take into account the results of a statistical prediction.

In solving these questions, manufacturers and users make use of data that belong to different categories: manufacturers lean on physical laws and test results, whereas users rely on experimental data only.

Thus, the establishment of norms is a problem of optimization. In our opinion**, t**he optimization criterion can be formulated as follows: the established norm must provide a certain contribution to attaining a highest total level of competitive advantages of the MI manufacturer (new MCs, improvement of traditional MCs, decrease of the manufacturer's risk, test cost reduction, and, as a result, a better price-quality relation) for a given a certain amount of required resources.

Verification of MC norms

Certification or calibration of MIs (primary or periodical) includes verification of the properties and MCs of an MI for compliance with the established norms. As this takes place, there may need to refine norms and it can be realized**.**

The main problem of verification of norms is minimization of the volume and/or time of operation. The solution to this problem is to accumulate and analyze information: to reduce the nomenclature of the MCs to be verified by their correlation, to reduce the time period by revealing stability (also to make the intervals between calibrations or verifications longer, to formulate criteria of capabilities and factors of decreasing the intervals).

Thus, the criterion for an optimal solution of the testing norms for MI MCs may be to achieve the maximum ratio of S/T, where S represents a saving of resources achieved by carrying out compliance approval procedures, and T is the amount of checks or the duration of this procedure.

Norms are usually verified by statistical methods, first of all, confidence intervals and hypothesis testing methods. In this case the adequacy of testing is due to the homogeneity of the data in two aspects. Stability of MI test results determines the representativeness of the sample for testing and reliability of the conclusions in hypothesis testing.

Using established MCs norms while using MIs on their purpose

When MIs are used according to their intended purpose, the established norms for MCs are used to solve different problems, including the choice of MIs for specific measurements, formation of measuring systems, finding the results of measurements and estimation of measurement errors.

In order to indicate the place and significance of MC in measurement error estimation, we could consider the simplest case of direct measurement.

A property of physical object under consideration is presented as a physical quantity with true value x_0; so measurand is defined by linear transformation:

$$Q = K_n x_0 ,$$

Table 1

Structural decompositions of the measurements errors into detailed components

Input signal	Measurement conditions	Structural decompositions of the measurements errors, if it is known for MI:	
		Individual MC	Type MC
Constant	Exactly known	$\varsigma_1 = (K_i. - K_n)\, x_0 + +K_i (\delta x_n + \delta x_r) + (w, u)\, x_0 + \mu$	$\varsigma_2 = (K - K_n)\, x_0 + K_t (\delta x_n + \delta x_r) + (w, u)\, x_0 + \mu$, within $K \in R(K_t)$, $w \in R(w_t)$
	Specified inaccurately	$\varsigma_1(\xi, u)$, within $\xi \in R(\xi)$, $u \in R(u)$	$\varsigma_2(\xi, u, K, w)$, within $\xi \in R(\xi)$, $u \in R(u)$, $K \in R(K_t)$, $w \in R(w_t)$,
Variable, specified functional kind	Exactly known	$\varsigma_3 = \delta B_{in}(x_0) + \delta B_r(x_0) + B_{ri}(\delta x_n) + B_{ri}(\delta x_r) + \mu$	$\varsigma_4 = \delta B_{tn}(x_0) + B_{rt}(\delta x_n) + B_{rt}(\delta x_д) + \mu$, within $x_0 \in R(x_0)$, $u \in R(u)$
	Specified inaccurately	$\varsigma_3(\alpha, x_0)$, within $x_0 \in R(x_0)$	$\varsigma_4(\alpha, x_0)$, within $\alpha \in R(\alpha)$, $x_0 \in R(x_0)$, $u \in R(u)$
Variable, unspecified functional kind	Specified inaccurately	$\varsigma_3(\alpha, x_0)$, within $\alpha \in R(\alpha)$, $x_0 \in R(x_0)$,	$\varsigma_4(\alpha, x_0, u)$, within $\alpha \in R(\alpha)$, $x_0 \in R(x_0)$, $u \in R(u)$

where K_n is a nominal scale factor of MI (often $K_n = 1$).

In fact, both the quantity x_0 and the factor K_n are subject to distortions. Considering interactions of MI with the object, a nominal input signal x_n differs from the true value x_0. Moreover, input noise ξ is added to it, so the real (actual) input signal of MI would be

$$x_r(t) = x_n + \xi(t).$$

In reality, MI transforms the actual input signal $x_r(t)$ into an output signal

$$y_r = K_r\, x_r,$$

where K_r is an actual scale factor of MI. The latter factor K_r usually differ from the nominal one K_n, and this sequence of transformations may be presented as follows:

$$K_n \rightarrow K_t \rightarrow K_i \rightarrow K_r,$$

where K_t is a type factor, corresponding to the MI type, and K_i is an individual factor, corresponding to the particular MI, which is used in measurement. The type factor K_t is defined by tolerance limits, which are usually based on nominal factor K_n.

The difference between K_i and K_r is primarily (mainly) caused by the influencing quantities, denoted by vector u. So K_r can be represented as follows:

$$K_r = K_i + (w, u),$$

where w is a vector of influencing factors (which are also standardized for MI).

On the output of MI (or while reading of the scale), the additional error μ arises; it should be also standardized. So the final measurement result is presented as follows

$$Q^* = y_r + \mu = K_r\, x_r + \mu.$$

Thus, the error of this result is presented as follows:

$$\varsigma = Q^* - Q = K_r\, x_r + \mu - Q.$$

Structural decompositions of this error into detailed components are presented in table 1. These decompositions differ in compliance with the nature of input signals, the information concerning MC of MI which is used, and information on measurement conditions.

In the first case, we assume that measurement conditions are known exactly, the input signal is constant, and the individual MC are known; then measurement error ς_1 could be decomposed as presented in table 1, with $\delta x_n = x_n - x_0$, $\delta x_r = x_r - x_n$.

In the second case, when the type MC are only known, we obtain the similar decomposition of error ς_2 into components as presented in table 1. When estimating this error, the factor K and the influencing factors **w** should be varied within their standardized type domains:

$$K \in R(K_t),\ w \in R(w_t).$$

While proceeding to the cases, when conditions are inaccurately specified, we should vary all the elements of the error decompositions within their standardized type domains. This is presented in table 1 as variations $\xi \in R(\xi)$, $u \in R(u)$.

Further, proceeding to the measurements with varying MI input signals, we also obtain the error decompositions by the similar way as presented in table 1. In the simple case of the signal transformation by linear operator B, the measurand is defined as follows:

$$Q = B_n [x_0 (t)],$$

where B_n is the nominal (required) operator.

Taking into consideration the MI interactions with the object and also the input noise, the actual input signal x_r and measurement result are formed as follows

$$Q^* = B_д [x_д (t)] + \mu(t).$$

The error decompositions for these cases are also presented in table 1. The norms for MC are introduced in similar way, but these are more complicated than in previous cases.

In the first place, if the measurement conditions, the input signal form and parameters are known exactly, and the individual MC are also known, then measurement error ς_3 could be decomposed as presented in table 1, with $\delta B_{in} = \delta B_i - \delta B_n$

In other case, when the type MCs are only known, we obtain the similar decomposition of error ς_4 into components as presented in table 1. When estimating this error, the signal x_i and the influencing quantities are varying within their standardized type domains: $x_i \in R(x_i)$, $u \in R(u)$.

While proceeding to the cases, when conditions are inaccurately specified, we should vary all the elements of the error decompositions within their standardized type domains. This is presented in table 1 as variations $\xi \in R(\xi)$, $u \in R(u)$.

Similar to previous cases, when conditions and signals are inaccurately specified, we should vary conditions and signals parameters within their standardized type domains. These variations are also presented in table 1: $\alpha \in R(\alpha)$, $u \in R(u)$.

4 CONCLUSIONS

Modern measuring instruments are becoming increasingly complex and expensive, which requires that ways to improve their efficiency be sought. A candidate solution is to individualize the metrological characteristics. Individualization implies modification of pattern metrological characteristics for particular instruments, their monitoring during the operation, and correction based on calibration results.

This method is attractive, since it doesn't require additional resources, but solves the problem using organizational measures.

5 REFERENCES

[1] Rabinovich S. G. Measurement errors and uncertainties. Theory and practice. – 2nd edition, Springer-Verlag, New York, 2000.

[2] Granovsky V. A., Siraya T. N. Methods for Data Processing in Measurement. - Energoatomizdat, Leningrad, 1990 (in Russian).

[3] Hofmann D. Rechnergestutzte Qualitatssicherung. – Verlag Technik, Berlin, 1988.

[4] International Vocabulary of Metrology – Basic and General Concepts and Associated Terms (VIM). JCGM 200:2008.

[5] Vocabulary of Legal Metrology – Fundamental Terms. - OIML.

[6] ISO 1101:2004 Geometric Product Specifications (GPS) - Geometrical Tolerancing – Tolerances of form, orientation, location and run-out.