АНАЛІЗ ПОКАЗНИКІВ ЯКОСТІ ВИМІРЮВАНЬ

ANALYSIS OF THE MEASUREMENT QUALITY INDEXES

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Annotation. The article focuses on the main problems of methodology of the measurement quality evaluation in the context of introduction into metrological practice of the International Dictionary of Metrology VIM 3. The generalized definition of the notion of measurement quality is given. A separate analysis of measurement quality indexes as a process and quality indexes of measurement result as a product of this process is carried out. The analysis and systematization of the functional quality indexes and quality indexes of the efficiency of the measurement process and the measurement result are performed. The recommendations for the development of the measurement quality methodology evaluation as one of the tasks of ensuring the uniformity of measurement are work out.

Key words: metrology, measurement, measurement result, measurement quality, measurement accuracy, measurement quality indexes, quality indexes of measurement result, measurement quality level.

Анотація. Розглянуто основні проблеми методології оцінювання якості вимірювань у контексті із упровадженням у метрологічну практику Міжнародного словника метрології VIM 3. Наведено узагальнене означення поняття “якість вимірювання” – це ступінь, до якого сукупність характеристик вимірювання (засобів вимірювань, методу і методики вимірювань, умов вимірювання і стану єдності вимірювань) задовольняє вимоги вимірювальної задачі щодо точності вимірювання, техніки безпеки, екологічних та інших чинників. Розглянуто номенклатуру показників якості вимірювань, яка у сучасній метрології не є остаточно встановленою і постійно змінюється та модернізується. Обгрунтовано доцільність роздільного аналізу показників якості вимірювання як процесу і показників якості результату вимірювання як продукту цього процесу. Здійснено аналіз і систематизацію показників, які, на думку авторів, найповніше характеризують якість вимірювань. Зокрема, це функціональні показники якості та показники ефективності процесу вимірювання і результату вимірювання, які розділено на дві групи. До першої групи зараховано показники, які характеризують якість процесу вимірювання загалом, а саме точність, правильність, прецизійність, повторюваність і відтворюваність вимірювань. До другої групи – показники, які характеризують якість результатів вимірювань, а саме метрологічну простежуваність, метрологічну порівнянність, метрологічну сумісність і достовірність результатів вимірювань. Запропоновано рекомендації щодо методології ефективного оцінювання якості вимірювань як одного із завдань забезпечення єдності вимірювань.

Ключові слова: метрологія, вимірювання, результат вимірювання, якість вимірювання, точність вимірювання, показники якості вимірювання, показники якості результату вимірювання, рівень якості вимірювання.

1. Introduction

One of the main tasks of metrology is assurance of the uniformity of measurement, that is, the state of measurement, in which their results are expressed in measurement units established by law, and the characteristics of errors or uncertainty of measurement are known with a certain probability and do not exceed the established limits [1]. The uniformity of measurement is achieved by the organization of metrological assurance of measurement, one of the tasks of which is measurement quality evaluation. In particular, objective quality estimates of measurement make it possible to compare the results of measurement obtained under different conditions. The issue of measurement quality evaluation has always attracted the attention of specialists in the field of metrology. This topic became especially relevant today due to the introduction into metrological practice of the International Dictionary of Metrology VIM 3 [2]. This normative document reflects the development of conceptual and terminological assurance for modern metrology and significantly expands the scope of its research. Accordingly, a substantive expansion of the functions of metrology and the scope of its research can be traced, namely in such areas of human activity as psychology, medicine, trade, industry, education, sociology, qualimetry etc. Establishing the unity of the measurement quality evaluation methodology in the above-mentioned areas is one of the key conditions for ensuring of the uniformity of measurement.

2. Problems of the measurement quality evaluation

Today, the issue of the measurement quality evaluation is reflected by the relevant terms in a number of current normative documents – DSTU 2681-94 [3],

ISO 9000:2015 [4], DSTU 2925-94 [5], ISO 5775-1:2005 [6], ISO 10012:2003 [7], ISO/IEC 17025:2017 [8], ISO/IEC Guide 98-3:2008 [9], etc. However, it should be noted that the definition of a number of the same terms in different normative documents is different, especially compared with their interpretation in VIM3 [2]. First of all we are talking about an expanded interpretation of key concepts of metrology – "*measurement*", "*quantity*" and "*measurand - quantity to be measured*", as well as the notions "*measurement result*" and "*measurement error*", what, in particular, is indicated in [10]. Using in metrological practice of the identical, internationally recognized terms provides an adequate approach to understanding and measurement quality evaluation, and, respectively, mutual recognition of measurement results. Consequently, ensuring the unity of metrological terminology in the field of the measurement quality evaluation is an actual metrological task, which determined the subject and relevance of this article.

3. The purpose of the work and the principal tasks of the research

The *purpose* of this work is analysis and systematization of the measurement quality indexes, as a certain type of product, and to make recommendations for their optimal using. To achieve the stated objective, the following tasks have been identified:

• to make a definition and separate analysis of the measurement quality as a process and of the measurement result quality as a product of this process;

• to make an analysis and systematization of the functional quality indexes and quality indexes of the efficiency of the measurement process and the measurement results;

• to work out recommendations for the development of the methodology of the measurement quality evaluation as one of the tasks of ensuring the uniformity of measurement.

NOTE. The peculiarities of the quality evaluation of the measuring instruments and methods of measurement are not considered in the work.

4. Analysis of the main concepts and terms of the measurement quality estimation

4.1. Analysis of the key notions of the measurement process

This question is analyzed in accordance with the new terminology pointed in the International Vocabulary of Metrology VIM 3 [2]. First of all, these are the key notions of metrology mentioned above, which are used in the following analysis in the article:

• *measurement* – process of experimentally obtaining one or more quantity values that can reasonably be attributed to a quantity;

• *measurand* – quantity intended to be measured;

• *quantity* – property of a phenomenon, body, or substance, where the property has a magnitude that can be expressed as a number and a reference. The reference can be a standard, a measurement unit, a measurement procedure, a reference material, or a combination of such;

• *measurement result* – set of quantity values being attributed to a measurand together with any other available relevnt information.

Usually such available relevant information is the estimation of the measurement result accuracy. That is, a measurement result is generally expressed as a single measured quantity value and a measurement uncertainty. In so doing, specify which value is attributed to the measured quantity – either the uncorrected result or the corrected result, according to the context.

Such an approach to the field of modern metrology studies reflects the departure from the narrowed interpretation of the notion of "*measurand – quantity to be measured*" only as a "*physical quantity*" in accordance with the current DSTU 2681-94 [3]. Physical quantity is only one of a number of possible quantities to be measured – chemical, biological, psychological, sociological, economic, as well as product quality estimations. Respectively, the application of terms and concepts has its own characteristics in different types of measurement.

4.2. Definition of the notion of "*product*" in the measurement process

This analysis has been completed on the substantive provisions of the Law of Ukraine on Metrology and Metrological Activity [1], the International Vocabulary of Metrology VIM3 [2], the above-mentioned regulatory documents [3–9] and literary sources [10–16]. According to the ISO 9000:2015 [4], *product* – is the planned result of the process, and the *process* is a combination of interconnected or interactive works that use inputs to generate the planned result. The inputs of one process are, as a rule, the outputs of another process, and the "*planned result*" of the process is called the "*product*".

In general, measurement is a certain kind of activity (a process), as result of which a certain product is obtained – the result of measurement. That is, the *result of measurement* is an intellectual product, which consists of information. Respectively, the measurement process and the measurement results are evaluated by certain qualitative characteristics.

4.3. Definition of the notion of "*measurement quality*"

According to generally accepted definitions, ***product quality*** – the degree to which a set of own characteristics of a product satisfies the requirements [4]. *Requirement* is a formulated need or expectation, and a *quality requirement* is a requirement related to quality. Respectively, we will formulate the basic notions and terms of the measurement quality evaluation.

Measurement quality is the degree to which the set of measurement characteristics satisfies the requirements of the measurement task.

Characteristics of measurement – measuring instruments, method of measurement and measurement procedure, measurement conditions and the state of measurement uniformity.

Measurement task – a task which is to determine the value of a quantity to be measured with the necessary accuracy in the given measurement conditions.

Requirements – formulated requirements for the accuracy of measurement, safety, environmental and other factors.

Consequently, we obtain a generalized definition – ***measurement quality*** – the degree to which the set of the measurement characteristics (measuring instruments, method of measurement and measurement procedure, measurement conditions and the state of unity of measurements), meet the requirements of the measurement task in relation to measurement accuracy, safety, environmental and other factors.

4.4. Quality indexes of measurement as a certain product type

Quality today does not have a specific numerical expression. The term "*quality*" may be used with adjectives such as high, low, excellent, etc. [4]. Numerical quality estimations are quality indexes and quality level. By well-known definition [5], the *quality index* is a quantitative characteristic of one or several product properties that characterize its quality, which is considered in relation to certain conditions for its creation and operation or consumption.

In general, the nomenclature of measurement quality indexes in modern metrology is not completely established and is constantly changing and modernizing. The article deals with the indexes which, according to the authors, most fully characterize the quality of measurement. In particular, these are functional quality indexes and performance indexes of the measurement process and of the measurement results, which are divided into two groups (see Table 1).

However, it should be noted that the systematization of the measurement quality indexes, given in the table, is not absolutely rigid. Some of the above quality indicators are characteristic of both the measurement process in general and the measurement results in particular. A detailed analysis of measurement quality indexes is given below.

5. Analysis of the quality indexes which are characteristic of the measurement process

As noted above, the main indexes that characterize the quality of the measurement process in general are accuracy, trueness, precision, repeatability, and reproducibility and interval of the measurement.

5.1. Measurement accuracy

5.1.1. Measurement accuracy, accuracy of measurement, accuracy – closeness of agreement between a measured quantity value $x_{meg},1_x$ and a true quantity value of a measurand [2, p. 2.13] or a conventional reference quantity value $x_{ref},1_x$ [6].

Accuracy, in general, is an assessment of the quality of both the measurement process and the measurement results. Accuracy is a purely qualitative measurement characteristic and does not have a specific numerical expression. Numerical estimates of accuracy in metrology are the *error* and *uncertainty* of measurement. It should be noted that the theory of measurement errors is applied to the theoretical analysis of the accuracy of the measurement processes and the verification and calibration of the measuring instruments. The theory of measurement uncertainty is used for practical analysis of the accuracy of measuring processes, namely, the accuracy of measurement results [11].

Table

Measurement Quality Indexes

Indexes that characterize the quality of the **measurement process** in general	Indexes that characterize the quality of the **measurement results**
• *measurement accuracy*; • *measurement trueness*; • *measurement precision*; • *measurement repeatability*; • *measurement reproducibility*; • *measuring interval*	• *metrological traceability of measurement results*; • *metrological comparability of measurement results*; • *metrological compatibility of measurement results*; • *metrological reliability of measurement results*

5.1.2. Measurement error, error of measurement, error $\Delta x, 1_x$ – measured quantity value $x_{meg}, 1_x$ minus a reference quantity value $x_{ref}, 1_x$ [2, p. 2.16]:

$$Dx = x_{meg} - x_{ref}, 1_x . \quad (1)$$

Measured quantity value, value of a measured quantity, measured value $x_{meg}, 1_x$ – quantity value representing a measurement result $x, 1_x$ [2, p. 2.10].

Measurement result, result of measurement – set of quantity values being attributed to a measurand together with any other available relevant information [2, p. 2.9]. A measurement result $x, 1_x$ is generally expressed as a single measured quantity value $x_{meg}, 1_x$ and a measurement uncertainty $u(x), 1_x$.

Reference quantity value, reference value $x_{ref}, 1_x$ – quantity value used as a basis for comparison with values of quantities of the same kind [2, p. 5.18]. A reference quantity value can be a *true quantity value* of a measurand $X, 1_x$, in which case it is unknown, or a *conventional quantity value* $x_{con}, 1_x$, in which case it is known.

True quantity value, true value of a quantity, true value $X, 1_x$ – quantity value consistent with the definition of a quantity [2, p. 2.11].

Conventional quantity value, conventional value of a quantity, conventional value $x_{con}, 1_x$ – is quantity value attributed by agreement to a quantity for a given purpose [2, p. 2.12]. A conventional quantity value $x_{con}, 1_x$ is generally accepted as being associated with a suitably small measurement uncertainty $u(x_{con}), 1_x$, which might be zero. *Conventional quantity value* is set in the procedure of theoretical analysis of the accuracy of measuring processes and in the verification and calibration procedures of measuring instruments [8]. In this case, it is denoted as the *standard reference value* $x_{st}, 1_x$, i.e. $x_{con} = x_{st}, 1_x$. Standard reference value $x_{st}, 1_x$, can be found experimentally using of reference measuring instruments. It can also be the *nominal quantity value, nominal value* $x_{nom}, 1_x$ – rounded or approximate value of a characterizing quantity of a measuring instrument or measuring system that provides guidance for its appropriate use [2, p. 4.6].

Consequently, in practice, the absolute error of measurement is found by the formulas:

$$Dx = x_{meg} - X, 1_x , \text{ or } Dx = x_{meg} - x_{st}, 1_x . \quad (2)$$

The concept of "*measurement error*" $Dx, 1_x$, in general, is one of the key concepts of metrology, what, in fact, is reflected in the definition of measurement accuracy. In the case of obtaining the measured value $x_{meg}, 1_x$, the first question as far it is close to the true quantity value $X, 1_x$. The problem of practical use of the concept of "measurement error" is due to the fact that the true quantity value $X, 1_x$ is always unknown. However, in such metrological procedures as verification and calibration of measuring instruments, the reference quantity value $x_{ref}, 1_x$ is known and error $Dx, 1_x$ can be calculated by the formula (2).

5.1.3. Measurement uncertainty, uncertainty of measurement, uncertainty – non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used [2, p. 2.26]. The main parameter of the theory of measurement uncertainty is *standard uncertainty* (*standard measurement uncertainty, standard uncertainty of measurement*) $u(x), 1_x$, namely the uncertainty of the measurement result $x, 1_x$, expressed in the form of a standard deviation $s(x), 1_x$ or a standard deviation estimate $s(x), 1_x$ [2, p. 2.30]. Measurement uncertainty is a numerical estimate of the result accuracy of the measurement performed. On the whole, the result of a measurement is only an approximation or estimate of the value of the measurand and thus is complete only when accompanied by a statement of the uncertainty of that estimate [9, p. 3.1.2].

5.2. Measurement trueness

Measurement trueness, trueness of measurement, trueness – closeness of agreement between the average of an infinite number of replicate measured quantity values and a reference quantity value [2, p. 2.14]. Measurement trueness is not a quantity and thus cannot be expressed numerically. Measurement trueness is inversely related to the systematic measurement error, but is not related to the random measurement error. It reflects the closeness to zero of a systematic measurement error.

5.3. Measurement precision

5.3.1. Measurement precision, precision – closeness of agreement between indications or measured quantity values obtained by replicate measurements on the same or similar objects under specified conditions [2, p. 2.15].

Also, precision of measurement is a characteristic of the measurement quality, which reflects the proximity between independent measurement results obtained under certain accepted conditions. *Independent* *measurement results* – these are results obtained without the influence of previous results on the following on the same or identical investigated object [6, p. 3.12].

Precision depends only on the distribution of random errors and is not related to either the true quantity value or the reference quantity value. The precision is expressed by the characteristics of scattering of measurement results. Its numerical estimate is the standard deviation or variance of the measurement results under the specified conditions of measurement. The precision reflects the closeness a random measurement error to zero.

The measurement results can not be corrected by eliminating a random error. But its value can be reduced by carrying out repeated measurements and finding the measurement result as an average value.

The "*specified conditions*" can be, for example, repeatability conditions of measurement, intermediate precision conditions of measurement, or reproducibility conditions of measurement. Accordingly, such assessments of the measurements quality are related to precision as:

- measurement repeatability;
- intermediate measurement precision;
- measurement reproducibility.

Estimates of measurement repeatability and intermediate measurement precision are obtained in the same laboratory.

5.3.2. Measurement repeatability, repeatability – measurement precision under a set of repeatability conditions of measurement [2, p. 2.21].

Repeatability condition of measurement, repeatability condition – condition of measurement, out of a set of conditions that includes the same measurement procedure, same operators, same measuring system, same operating conditions and same location, and replicate measurements on the same or similar objects over a short period of time [2, p. 2.20].

Measurement repeatability is often used as an estimate of scattering of measurement results in the middle of a batch of investigated objects.

5.3.3. Intermediate measurement precision, intermediate precision – measurement precision under a set of intermediate precision conditions of measurement [2, p. 2.23]

Intermediate precision condition of measurement, intermediate precision condition – condition of measurement, out of a set of conditions that includes the same measurement procedure, same location, and replicate measurements on the same or similar objects over an extended period of time, but may include other conditions involving changes [2, p. 2.22]. In particular, measurements can be carried out by different operators using different equipment.

Intermediate measurement precision is often used as an estimate of scattering of measurement results between different batches of investigated objects.

5.3.4. Measurement reproducibility, reproducibility – measurement precision under reproducibility conditions of measurement [2, p. 2.25].

Reproducibility condition of measurement, reproducibility condition – condition of measurement, out of a set of conditions that includes different locations, operators, measuring systems, and replicate measurements on the same or similar objects [2, p. 2.24] In some cases, different measuring instruments can be used in accordance with different measurement methods.

Consequently, the measurement reproducibility reflects the proximity between the results of measurements of the same quantity performed in different laboratories, at different times, by different methods and means.

5.4.4. Measuring interval

Measuring interval, *working interval* - set of values of quantities of the same kind that can be measured by a given measuring instrument or measuring system with specified instrumental measurement uncertainty, under defined conditions [2, p. 4.7].

Within the measuring interval, it is possible to measure the quantity (for example, the mass concentration) with the specified uncertainty, using the given measurement method. In some areas of practical metrology, the term is used as an analogue of "*measuring range*" or "*measurement range*". The lower limit of a measuring interval should not be confused with detection limit.

Detection limit – measured quantity value, obtained by a given measurement procedure, for which the probability of falsely claiming the absence of a component in a material is β, given a probability α of falsely claiming its presence [2, p. 4.18] The term "sensitivity" is discouraged for "detection limit".

6. Analysis of the quality indexes which are characteristic of the measurement results

As is shown above, in the clause 4.4., the main indexes that characterize the quality of the measurement results are metrological traceability, metrological comparability, metrological compatibility and metrological reliability of measurement results.

6.1. Metrological traceability – property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty [2, p. 2.41].

For this definition, a "*reference*" can be a definition of a *measurement unit* through its practical realization, or a *measurement* procedure including the measurement unit for a non-ordinal quantity, or a *measurement standard.* Metrological traceability requires an established calibration hierarchy. *Calibration hierarchy* – sequence of calibrations from a reference to the final measuring system, where the outcome of each calibration depends on the outcome of the previous calibration [2, p. 2.40]

Unbroken chain of calibrations – it is *metrological traceability chain, traceability chain* – sequence of measurement standards and calibrations that is used to relate a measurement result to a reference [2, p. 2.42]. A metrological traceability chain is defined through a calibration hierarchy and is used to establish metrological traceability of a measurement result.

For most of the measurement results, the "*reference*" for comparison is the *measurement unit. Metrological traceability to a measurement unit* – metrological traceability to a unit metrological traceability where the reference is the definition of a measurement unit through its practical realization [2, p. 2.43] Practical realization of the definition of a measurement unit is a *procedure* according to which the definition can be used to determine the value of the quantity of the same kind as a unit, together with the associated uncertainty of measurement.

The concept of "*metrological traceability*", which is a key in the measurement unity ensuring, is directly related with concepts such as "*metrological comparability of measurement results*" and "*metrological compatibility of measurement results*".

6.2. Metrological comparability of measurement results, metrological comparability – comparability of measurement results, for quantities of a given kind, which are metrologically traceable to the same reference [2, p. 2.46].

The term "comparable" means "such that they can be compared", and not "close in size". Metrological comparability of measurement results does not necessitate that the measured quantity values and associated measurement uncertainties compared be of the same order of magnitude. For example, the results of measurements of the lengths of various objects are metrologically comparable when they are both metrologically traceable to the same measurement unit of length, for instance, up to a meter.

The concept of "metrological comparability" is related to the concept of "metrological compatibility".

6.3. Metrological compatibility of measurement results, metrological compatibility – property of a set of measurement results for a specified measurand $X,1_x$, such that the absolute value of the difference $|J_x| = |x_1 - x_2|,1_x$ of any pair of measured quantity values from two different measurement results $x_1,1_x$ and $x_2,1_x$ is smaller than some chosen multiple of the standard measurement uncertainty of that difference $u_c(J_x)$ [2, p. 2.47].

Therefore, the establishment of metrological compatibility of the measurement results requires a standardized method for finding their uncertainty. The correlation between the measurement results affects their meteorological compatibility.

If the measurements results $x_1,1_x$ and $x_2,1_x$ are completely uncorrelated, the condition of their meteorological compatibility is expressed by the formula:

$$|J_x| = |x_1 - x_2| \le k_p \cdot u_c(J_x) = k_p \cdot \sqrt{u^2(x_1) + u^2(x_2)},1_x, \qquad (3)$$

where k_p – a coverage factor, that corresponds to the given level of confidence p [9, p.6.3]; $u(x_1),1_x$ and $u(x_2),1_x$ – standard measurement uncertainties of the measurement results $x_1,1_x$ and $x_2,1_x$.

If the measurements results $x_1,1_x$ and $x_2,1_x$ are correlated, the condition of their metrological compatibility is expressed by the formula:

$$|J_x| = |x_1 - x_2| \le k_p \cdot u_c(J_x) = k_p \times$$

$$k_p \times \sqrt{u^2(x_1) + u^2(x_2) + 2u(x_1) \cdot u(x_2) \cdot r_{x_1,x_2}},1_x, \qquad (4)$$

where r_{x_1,x_2} – correlation coefficient between measurement results $x_1,1_x$ and $x_2,1_x$.

Metrological compatibility of measurement results replaces the traditional concept of "staying within the error", as it represents the criterion for deciding whether two measurement results refer to the same measurand or not. If in a set of measurements of a measurand, thought to be constant, a measurement result is not compatible with the others, then this means that:

• either the measurement was not correct (e.g. its measurement uncertainty was assessed as being too small);

• or the measured quantity changed between measurements.

Also, it should be noted that the establishment of metrological compatibility of the measurement results requires the fulfillment of the condition of metrological comparability of the measurement results.

6.4. Metrological reliability of measurement results, metrological reliability – a characteristic of the measurement quality, which characterizes the degree of confidence in the measurement results. The term "*metrological reliability*" is similar in content to the term "*measurement accuracy*" for evaluation the measurement quality and characterizes the degree of confidence that the value of the measurand lies within the specified range [11, 12]. The reliability of measurements results is established in accordance of the laws of probability theory and mathematical statistics. The numerical estimates of the measurement reliability are the confidence probability P (in the case of calculating the errors of measurement results) or the level of confidence p (in the case of calculating the uncertainty of measurement results).

Conclusions

1. The analysis and systematization of the measurement quality indexes on the basis of current normative documents is carried out. This makes possible to develop a generalized methodology for measurement quality evaluation in accordance with the concept of the uniformity of measurements.

2. It is expedient to carry out a separate analysis of quality indexes of measurement as a process and quality indexes of the measurement result as a product of this process. The determinants of the procedure of measurement quality evaluation are functional quality indexes and performance of the measurement process and the of measurement result.

3. The objective quality estimates of measurement make it possible to compare the results of measurement obtained in the different laboratories under different conditions.

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