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Metrological self-check as a perspective trend of technical diagnostics

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Abstract – **The need for changing a traditional procedure of metrological maintenance of measuring instruments (MIs) and multichannel measuring systems (MMSs) within an operation process, is growing quickly. It is practically impossible to realize the Internet of Things without the wide use of facilities that can provide increase in measurement results reliability and decrease of maintenance costs. The general features and opportunities of automatic diagnostics of MI and MMS health, are considered. Such diagnostics is called a metrological diagnostic check. It is noted that the standardization is a necessary condition for the wide application of the metrological self-check. Some statements from the Russian state standards concerning terminology in this field and methods of metrological self-checking are given. The paper shows the ways for overcoming difficulties that impede industrial production of MIs and MMSs with the function of the metrological self-check.**

I. INTRODUCTION

Equipment that is subject to diagnostics is operated, as a rule, with the help of multichannel measuring systems (MMSs) containing a great number of sensors.

Usage of embedded diagnostic systems in the equipment usually results in an increase of the sensor number since the diagnostics is based on measurement results too. However, sometimes operation conditions for sensors and other measuring instruments (MIs) are so harsh that it is impossible to ensure sensor metrological health in the course of the whole production cycle. Correspondingly, one cannot be firmly convinced that the measurement information including diagnostics results is credible.

Over a few decades electronic technologies, computers and software has improved significantly. This fact resulted in intensive application of automatic control systems in industrial enterprises, power units, transport, scientific equipment, and even in public utilities sector.

These systems are based on information obtained from hundreds of sensors.

It is logical that the problem related to checking the validity of measurement information including

diagnostics results has arisen. At present, the solution of this problem is of current importance, particularly for many objects of nuclear power, space and defense engineering. In these fields the situation is aggravated when the operation cycle of the equipment is longstanding (10 years or more) and if over this period the participation of personnel in testing the metrological health of sensors embedded in equipment is prohibitive.

In the near future with its characteristic features such as Internet of Things, development of "smart cities", "smart healthcare" and so on, when in many cyber-physical systems there will be used tens and hundreds of thousands of sensors, the demand to solve the above problem will become critical.

It is impossible to address this problem using traditional methods of metrological maintenance. The reasons are as follows:

- Ignoring individual features of MIs and individual operation conditions results in the situation where the uncertainty of 10-15 % of MIs exceeds the maximum permissible limits at the end of a calibration interval (CI).

- If an average CI value is not changed, the observed annual (10-20) % increase of the number of sensors built in equipment will result in the unacceptable growth of operational costs connected with metrological maintenance. If the average CI value is increased, it will lead to damages, defective products, accidents, or even human victims.

In several scientific centres independently of the others (in the first place, in the USA, USSR, and UK) the idea was formed how it is possible to overcome the stalemate. A corresponding approach relied upon supplementing periodical calibration with an inexpensive procedure intended for checking the stability of MI metrological characteristics.

While the periodic calibration should be performed as seldom as possible, this additional procedure should be realized in the course of the CI with required frequency [1-5]. The efficiency of the latter procedure can be provided since in many cases it is useful to evaluate not a total uncertainty, but the most dangerous component of uncertainty or a group of components.

In the USA Prof. Hashemian and his team emphasized the development of simple methods of non-automatic checking of the stability of characteristics of temperature

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sensors, pressure sensors as well as other mass-produced sensors included into MMSs of NPPs [6, 7].

In Russia the majority of works were concentrated in the leading scientific centre D.I.Mendeleyev Institute for Metrology where the authors work. Here taking into account technology trends the main attention was drawn to the development of theoretical basis and methods of metrological self-check (automatic diagnostics of metrological health) of sensors and MMSs. Proposed decisions were tested by realization of the function of the metrological self-check in various developed sensor devices as well as MMSs [2, 8 - 13].

The text given below focuses on the issues concerning the metrological self-check.

II. METROLOGICAL SELF-CHECK

In Russia the metrological self-check (MSC) was recognized to be a promising area in the 80s of the last century. Upon the initiative and with active participation of the authors of this paper some instruments measuring displacement of tools in flexible manufacturing systems were modernized. The gained experience enabled a guide to be issued that gave an opportunity to increase the CI of embedded measuring instruments with the function of the MSC [3].

The motivation to develop economically efficient technical decisions supported by the development of microprocessors has resulted in forming the theoretical basis of the MSC [14-16] relying upon the independence (invariance) theory [17]. It was demonstrated that the MSC (sometimes it is called "self-validation") can be realized by using supplement information received on the basis of structural (spatial), temporal, functional, or combined redundancy. The redundancy can be inherent in the MI or MMS. It can be formed especially with the aim of self-checking too.

Structural redundancy is characterized by the use of additional components (built-in material measures and/or measuring transducers), the number of which exceeds the minimally needed number that is necessary for performing measurements with the accuracy required.

Temporal redundancy is provided by additional measurement operations carried out at the operating transducer frequency or within the frequency band which exceeds the measurement frequency needed to control and/or operate the technological process concerned, based on its time constant.

Functional redundancy arises from the application of additional correlation between a measurand or measurands, or their derivatives, on one hand, and sensor device output signals, on the other hand.

The MSC can be performed as a direct or diagnostic self-check.

The direct self-check, to some extent, is similar to calibration. It is carried out by a combination of a measuring transducer under check and an additional (redundant) element (a sensor or material measure) of a higher accuracy ("reference standard")

For example, the metrological direct self-check can be realized in a temperature sensor device that contains an embedded cell (capsule) with a metal, the fixed point of which is known with a high accuracy [9]. This fixed point is taken as the reference value. When the environment, the temperature of which is measured, is heated or cooled and the metal melts or hardens in the capsule, the speed of measured temperature changes significantly decreases, forming a "plateau" in a diagram "temperature – time". It is possible to estimate the sensor device uncertainty or error (hereinafter referred to as error) on the basis of the deviation of the temperature value measured, when the temperature corresponds to the metal fixed point, from the reference value.

However in practice, the application of a material measure for checking is limited to several points of measurement range. Such approach is possible to use only for measurements of temperature, distance, electrical quantities, and some others. Moreover, the stability of those redundant elements of a higher accuracy ("reference standards") cannot be guaranteed in the course of time.

Sometimes metrological direct self-check is realized combining thermocouple as the main thermometer and platinum resistance thermometer as the "reference standard" in the same sensor device [20]. This approach enables the sensor device:

• to measure temperature with rather small delay on the basis of thermoelectric effect when the temperature changes quickly,

• check the metrological health of the thermocouple when the temperature mode is stable,

• correct a thermocouple error if necessary.

The CI of this sensor device can be increased and brought closer to the corresponding CI value for platinum resistance thermometers.

The metrological diagnostic self-check does not require for the usage of embedded elements of a higher accuracy. It relies upon a concept of critical error component, which with the maximum probability is the reason of unreliable measurement results. The critical error component is the most "dangerous" component, i.e., a predominant error component or that tending to rise quickly. This component determines mostly a risk of getting an unreliable result of measurement.

To choose the critical error component for a measuring instrument, it is necessary to analyze the processes of origination and growth of error components as well as to study:

• influence quantities under expected operation conditions of the measuring instruments (taking into account both a transient mode and steady run);

• errors of measurement instruments that can be considered to be analogs;

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- information on metrological failures of analogs within operation process;

- design and manufacturing technique of main components and units that can contribute noticeably to the error growth n the course of time (accelerated testing can be very useful in this study).

After such analysis, error components should be ranged in the probability of exceeding the permissible limit within the process of long-term operation.

Then, the critical error component or a critical group of components should be chosen from them.

This stage is very important since the efficiency of the metrological diagnostic check depends on whether the choice of the critical error component is correct.

The metrological diagnostic check is performed by evaluating the deviation of an additional diagnostic parameter characterizing the critical error component from the reference value of this parameter established at the stage of a previous calibration.

Thus, the level of the critical error component (components) is checked within the operation process automatically and can be corrected if necessary. This circumstance gives grounds to assign a significantly longer CI of the sensor device, taking into account only error components that are not included into the critical error components.

Examples given below can illustrate the metrological self-check method.

In the pressure sensor device with the Bourdon tube one end of such a tube is rigidly fastened in the device construction and the second end is free. Measuring displacement of the free end, the pressure supplied to the tube is determined.

As a rule, the critical error component is caused by the residual deformation of the tube originated within operation process. In one of the versions, the structural redundancy was organized using information on the displacement of an additional point of the tube, which is located at some distance from the free end. A ratio of output signal values determined in various points of the tube can be applied as the diagnostic parameter [11].

Sensor devices measuring specific electrical conductivity of liquid contain a conductivity cell that includes a group of electrodes immersed into a liquid to be checked. To determine a measurand it is necessary to know a precise value of the distance between electrodes.

The critical error component involves electrode contamination with the products of corrosion and other substances. To organize the metrological self-check, the structural redundancy was realized by the increase in the number of the electrodes with various distance between them. Electrodes were connected in pairs. A ratio of electric conductivity values measured by various electrode pairs became the diagnostic parameter. [11]

In a ball flow meter the volume flow is determined by the value of a period or frequency of ball rotation.

Usually, in such a measuring instrument, a critical error component is determined by bearing degradation. In the course of time, movement of the ball becomes less and less stable.

Using the temporal redundancy of information on the ball movement, a statistical evaluation of short-time deviations of the period or amplitude of the output signal from the average value calculated before (at a previous calibration) can be accepted as the diagnostic parameter [2].

The MSC of MMSs can use different types of redundancy too [21]. At that, two alternative versions can be applied:

- check of separate measuring channels or their components (an element or "componentwise" check);

- check of all channels at the same time (a complex check).

The element MSC, in particular, can be organized by using sensor devices with the MSC.

The complex MSC can be provided on the basis of analyzing the correspondence between the results of measuring the technological process parameters changing with time and along space, on one hand, and physical patterns intrinsic to this process and MMS itself, on the other hand.

The efficiency of the complex MSC is limited to the accuracy and stability of the assumed physical patterns in the course of time and along the space. This concerns both measurands and influence quantities.

A characteristic example of the MSC on the basis of the structural redundancy organized in MMSs is a system of flow meters installed in pipeline branches. The diagnostic parameter here is the difference between flow values being measured in inlet and outlet branches.

Another example is a MMS that provides diagnostics of threaded connections fastening a cover to a turbine unit body at a hydroelectric power plant [12, 13].

It includes a set of 8 load washers mounted under internal screws on double-end bolts fastening the cover.

The complex MSC is organized taking into account that the pressure under the cover effects all the load washers at the same time, but variations of a compression force, which are determined by a defect in some measuring channel or by weakening of some threaded connection, do not take place in several load washers concurrently.

The MSC includes the correlation analysis of the output signals of load washers and estimation of metrological health of the measuring channels. If necessary, a correction of measuring channel characteristics is performed with changing a data processing algorithm.

III. STANDARDIZATION IN THE FIELD OF THE METROLOGICAL SELF-CHECK

To put the metrological self-check into general practice, just the availability of scientific publications devoted to the metrological self-check theory is

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insufficient. The first normative documents [3, 22-26] could not take into consideration various problems concerning application of the non-traditional approach.

It is necessary for customers as well as specialists in instrument engineering and metrology to understand and recognize the topicality of this new paradigm of metrological maintenance.

The MSC application results in some increase in the costs of MIs and MMSs, decrease in the number of the metrologists dealing with maintenance of them as well as growth of the requirements for the competence and role of the metrologists at the stage of development.

The experience of the development of various MIs and MMSs with the MSC has shown that organization of this function increases the costs of sensor devices approximately by (30-40) % [27], while the costs of the MMS increase even less. At the same time, reduction in maintenance costs, damages, and defective products associated with its implementation, as a rule, results in a fast payback.

However, the industrial production of such MIs and MMSs increases slowly.

The difficulties of application of the scientific achievements to production are partly of a psychological character. According to the Kuhn's law [28], they are caused by expected consequences of the "paradigm shift" that are undesirable for certain groups of metrologists.

To overcome these difficulties, besides popularization of the MSC concept as an essential feature of the transition to the Internet of Things, it is necessary to provide normative support, including:

• terminology vocabularies that enable engineers and developers, on one hand, and customers, on the other hand, to understand each other;

• standards formulating the requirements for MIs and MMSs with the MSC as well as for testing of them.

Standardization of the above requirements has to contribute to the removing unfair competition and expanding the market of the products and services in this field. For example, various manufactures can choose critical error components with different level of significance. The choice is directly connected with the product price. To provide the comparability and interchangeability of MIs and MMSs produced by different manufacturers, it is necessary to standardize:

• parameters demonstrating the efficiency of the applied method of the MSC in specifications,

• test methods confirming that the specified parameter values have been realized.

Taking into account the above ideas and gained experience, the authors prepared several national standards that came into force. The standards relate to terminology [29], methods of MSC organization and requirements for corresponding specifications [30] as well as accelerated testing of MIs and MMSs with the metrological self-check [31].

In particular, in [29] on the basis of international discussion results and evolutional analysis [14-16], the MIs and MMSs with the metrological self-check are defined as intelligent ones.

In [29] the concept of a "measurement value status" proposed in [5, 32] is also introduced. The measurement value status can be applied for quantitative assessing the measurement information reliability. It can be automatically formed in intelligent MIs or MMSs and gives ground to perform metrological maintenance according to the technical condition of the MIs or MMSs taking into consideration a technological cycle of equipment. The number of status values is determined by the number of possible reactions of customer to this information.

The status called "confirmed" indicates that a measurement result has been confirmed by additional information on the metrological health of a sensor device or MMS, and a risk to use an unreliable measurement result is negligible.

The status called "normal" indicates that the risk of using an unreliable measurement result is small.

The status called "orienting" indicates that a risk to use an unreliable measurement result has increased, but the measurement result can be applied for an orienting estimate of the equipment condition and that of the technological process under control.

The status called "extrapolated" indicates that a measurement result was obtained by extrapolating the data from the preceding time interval, since a lag effect of the process under control is significant and metrological fault appeared quite recently.

The status called "unreliable" indicates that the risk is high that a measurement error is unacceptable.

In [30] it is stated that in the MI and MMS specifications information should be given on:

• applied method of the metrological self-check;

• critical error component if the metrological diagnostic check is used;

• diagnostic parameter and permissible limits of its variation;

• time interval between the automatic procedures of self-checking;

• availability of a self-correction function;

• maximal recommended CI;

• measurement value statuses;

• other supplement information.

While using the MSC results, one faces with a dilemma that is characteristic for technical diagnostics as a whole. It is necessary to find a balance between the risks of an undetected fault and false fault.

A corresponding choice should be made depending on the requirements with regard to measurement reliability. These requirements in turn are determined by the necessity to provide safety of an object and exclude significant economic losses.

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IV. CONCLUSIONS

Traditional methods of the metrological maintenance of MIs and MMSs within their operation process cannot meet either the requirements of the coming Internet of Things for measurement information reliability, nor also present requirements related to a number of science-based units of industry.

The analysis of tendencies in instrument engineering gives ground for the statement that the concept of the metrological self-check developed with the active participation of the authors of this paper, supported by a number of the national normative documents, opens the prospect to combine the high reliability of measurement information with multiple reduction in maintenance costs that are required for obtaining this information.

However, the transition to the serial production of MIs and MMSs with the function of the metrological self-check and to the new methods of metrological maintenance is not as quick as it would be necessary.

In the first place, the insufficient awareness of potential customers and, as a consequence, underestimation of the expected market by investors and potential manufacturers, hampers this process. Certainly, the Kuhn's law influences the process too.

Nevertheless, the number of publications devoted to this topic has increased about twice since the beginning of the 21st century and continues to grow.

In a number of countries, several teams dealing with the development of intelligent MIs and MMSs have been formed. For example, in Russia such teams work in Chelyabinsk, Ufa, Omsk, St. Petersburg, etc. Interesting works are performed in Great Britain, Germany, USA, Ukraine, China, and other countries.

To accelerate the move to the new paradigm of metrological maintenance, together with popularization of the advantages of the metrological self-check, it appears to be necessary to widen an international cooperation in this field. This cooperation should provide preparing international standards on the basis of national standards, introducing required additions into [33], as well as organizing a special technical committee or subcommittee to deal with these problems.

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