AUTOMATIC METROLOGICAL DIAGNOSTICS OF SENSORS

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Summary

As the number of sophisticated technical complexes with automatic control systems grows, the number of embedded sensors increases. The specific scientific problems that emerge while developing the sensors characterized by fault tolerance and long-term lifetime without metrological maintenance are considered. The possible ways of solution of these problems are outlined. The features of metrological diagnostics are demonstrated.

Keywords: automatic metrological diagnostics, sensor, fault tolerance.

AUTOMATYCZNA DIAGNOSTYKA METROLOGICZNA CZUJNIKÓW

Streszczenie

W miarę wzrostu liczby skomplikowanych technicznych kompleksów z automatycznymi systemami sterowania zwiększa się liczba wbudowanych czujników. Rozpatrywane są problemy naukowo-techniczne związane z konstrukcją czujników charakteryzujących się długim czasem pracy bez obsługi metrologicznej i odpornością na uszkodzenia. Zostały zarysowane drogi rozwiązania tych problemów i mozliwosci diagnostyki metrologicznej.

Słowa kluczowe: automatyczna diagnostyka metrologiczna, czujnik, odporność na błędy.

1. INTRODUCTION

Development of industrial equipment and increasing number of sophisticated technical complexes goes with complication of automatic control systems (ACS) and with increase in the number of in-built sensors. At the same time:

- participation of personnel in the equipment control decreases;
- expenditures on metrological assurance of ACS grows;
- intervals between scheduled outages become longer;
- probability that invalid information can pass to ACS increases;
- risk of accident or failure grows.

More and more, trouble-free operation and production quality depend on sensor condition.

In many cases in order to carry out metrological assurance procedures such as calibration or verification (hereinafter referred to as calibration), it is necessary to interfere in a technological process. Meanwhile, the experience shows that calibration does not ensure the sufficient credibility of measurements over calibration period.

In current situation, modern technological processes require industrial sensors which are expected to provide many years of operation without metrological maintenance while ensuring a high level of confidence in their measurement data [1].

First of all, such sensors are necessary for technical systems with long-term technological cycle. However, in the near future, the other high duty objects including transport equipment, power units, etc., will need the sensors with enhanced metrological reliability. Moreover, the development of diagnostic systems depends, to a great extent, on the possibilities of their application.

The distinctive features of such sensors are:

- specified lifetime of many years without metrological maintenance (the lifetime should be proved experimentally);
- ability to self-diagnosing and revealing the growing uncertainty;
- the ability of a sensor to keep the measurement uncertainty for the most of single sensor defects within an enlarged, but permissible, range as defined by the user (fault tolerance), as well as to correct the uncertainty automatically (in a number of cases).

The set of these features affords ground for considering the corresponding sensors as "intelligent" [2].

2. ABOUT ASSESSMENT OF QUALITY OF SENSORS INTENDED FOR LONG-TERM OPERATION

The first problem the solution of which predetermines the possibility of intelligent sensors development is elaboration of the methods for sensors quality control with respect to their design and technology, taking into account the long-term lifetime. There is no point in complicating sensors by introduction of the diagnostic features if the sensors fail in a short period. Customers need to know the estimate of the sensor lifetime *T* during which the sensor uncertainty is kept within the specified limits. This value is equal to the sensor calibration interval. We could not find any special requirements for quality check of the sensors with a specified long-term lifetime neither in current standards, nor in any guides, including ISO documents.

Fridman in [3] proved that it is inexpedient to apply fundamental assumptions of the classical reliability theory (independence of failure rates and failure rate stability) to measuring instruments. Therefore, the lifetime estimation should be based on certification tests.

Taking economical reasons into account, sensor lifetime tests should be chosen at least 50 – 150 times shorter than the planned sensor lifetime without maintenance, while the number of tested sensors should be minimal. Test influencing factor values are limited: they are to be within the limits which provide that the sensor degradation mechanisms under test conditions and during actual operation are adequate. The plan of the certification tests should take the sensor design, technology and operation conditions into consideration.

Taking into account [4], in order to evaluate *T*, it is possible to recommend a technique which includes: determination of influencing factors that characterize sensor operating conditions; study of degradation processes; detection of probable reasons for the uncertainty increase; ranging of the uncertainty components according to their contribution; after that, certification tests themselves.

For the certification tests plan, one should choose only those influencing factors that give rise to the most "dangerous" (significant) uncertainty components of the sensor, i.e. predominant components or those tending to rise quickly.

Estimate of *T* can be obtained by processing the results of complex tests consisted of a simulation test and accelerated test.

In simulation test, harsh operation conditions that may take place during operation are simulated. At the stage of the accelerated test, it is expedient to expose the sensors to influencing factors by equal cycles. One cycle may include exposure to one or several factors, e.g. vibration and temperature of a maximum permissible level [5].

Stability of sensor manufacturing technology should be proved by periodic and extraordinary (in case of modification of the sensor design or technology) tests. For these tests, the cycles like those that were chosen for the accelerated test can be applied [6].

At present, approaches for the plan of the tests to evaluate *T* are different in different companies. Therefore, the results of *T* evaluation can be different. In order to obtain comparable results, it is necessary to work out international guides that will include corresponding test procedures. Before the necessary documents become operational, it is expedient to specify the test procedure on the basis of which the lifetime of sensors would be assigned.

3. METHODS OF AUTOMATIC DIAGNOSTICS OF SENSORS

In general, there are the following differences between metrological diagnostics and conventional procedures of metrological assurance of sensors:

- the value estimated in diagnostic procedure is the parameter defined by a set of uncertainty components (not the overall instrumental uncertainty);
- diagnostics conditions are identical with the technological process conditions (not the reference conditions);
- the sensor diagnosed remains in-situ (not in a calibration laboratory);
- metrological diagnostics envisage on-line method which does not require interruption of technological parameter measurements, while the conventional procedures are out-of-process methods.

The first way of organizing the metrological diagnostics is integration of sensors in a system with common diagnostic means. This system can be organized by several methods.

The most wide-spread method is application of a number of identical sensors and comparison of their output signals [7].

However, for mass-produced sensors of the same type, a drift of metrological parameters in the same direction and with a close speed is the most probable [2, 8]. If integration of such sensors is used, this drift cannot be revealed. The drawback is also in the necessity to place several (e.g., three) sensors in the equipment, which, in many cases, is impermissible by an argument of engineering limitations.

The second method implies integration of sensors that measure various quantities characterizing physical field parameters that correlate between each other.

The drawbacks of this method are:

- presence of the uncertainty components due to the diagnostic method, which depends on the accuracy of relationship between the measurements,
- necessity to apply more accurate sensors.

The third method involves application of a more accurate sensor in addition to other sensors.

However, in order to organize the effective diagnostics using this method, it is necessary to set a stationary state of technological equipment, on one hand, and on the other hand, to keep a comparatively short calibration interval for the most accurate sensor of the system.

Nevertheless, in a number of cases, metrological diagnostics of mass-produced sensors by their integration in a system ensures a higher confidence in measurements.

The other way is development of sensors with the in- built capability of self-checking [2].

There are two different ways of realization of this function. The first consists in embedding a reference standard (a reference measure or additional sensor, which is more accurate than the sensor under check) in the equipment and comparing output signals of the reference standard and checked sensor. The second way is associated with sensor intellectualization. It consists in comparison of several signals or parameters, which are close in accuracy, i.e. metrologically equivalent. We call the latter method metrological diagnostic check (MDC) [1, 2, 5].

If the metrological self-check is accompanied by a quantitative evaluation of measurement quality, it is usually called self-validation [9].

Development of the intelligent sensor requires a deep metrological investigation to be carried out. This investigation should result in determination of the limited number of the most dangerous uncertainty components and formation of the required dependence of diagnostic parameters on influencing factors. The distinguishing features of sensors capable of performing the metrological diagnostic checking are presence of:

- structural and/or information redundancy which afford ground for obtaining an additional signal regarding ambient conditions and/or sensor "health",
- microprocessor that provides processing of measurement and diagnostic data.

Metrological diagnostics allows to determine whether the sensor uncertainty is being kept within the specified limits. If the uncertainty exceeds the specified limits, it is possible to diagnose the uncertainty variation specifics and to localize a defect.

As a rule, on the basis of metrological self-diagnostics, the specified calibration interval can be considerably increased in comparison with its value which can be set on the basis of conventional method of metrological assurance.

The method requires the sensor sensitivity to be higher than it is required for usual measurements in the technological process. However, fulfilling this requirement, as a rule, does not cause serious difficulties.

The efficiency of the method is proved by the measuring and diagnostic system with an eddy current sensor of the DPL-KV type (MS). The MS was developed at the VNIIM [10] in order to apply it in the linear stepping drive that move a control rod in the WWER-1000 nuclear reactor. The sensor of the MS realizes a combinatory code chain. Besides measuring the control rod position, the MS performs metrological and technical diagnostics of the sensor and microprocessor unit. The MDC generally consists in comparison between:

- the code combinations identified and the code combinations specified;
- the code combinations related to consequent control rod positions and the specified code combinations;
- the control rod position and the number of steps made by the rod.

In various countries, new self-diagnosing, self-checking, or self-validating devices have been developed, for example [11-20]. Since recently, along with conventional devices, a number of companies have started mass-production of measuring instruments which can perform metrological self-diagnostics. Such instruments are double thermocouples or resistance thermometers in the same housing, a temperature transmitter which can accept 2 independent temperature sensor inputs (either Pt100 or thermocouples), as well as self-diagnosing electromagnetic and ultrasonic flow meters.

Some metrological self-check modes (under various names) have been used in industry for many years. The first national regulations [21, 22] were published in Russia (1989) and the UK (2001). Their main statements were developed in new documents [23-25]. Attempts to systematize such methods were made, for instance, in [9, 26-28].

4. SELF-CORRECTION AND FAULT TOLERANCE

The capability of self-diagnostics which is the inherent feature of the intelligent sensor allows to increase metrological reliability significantly by the application of measures of active character. These measures are aimed at self-correction of the external influences and ageing of components as well as at the support of fault tolerance.

Structural and Information redundancy of sensor as well as computer technology afford ground for these measures.

The simplest example for self-correction in the presence of transient errors is frequency filtration or time filtration. In order to apply such a correction, it is sufficient to use a priori information on the parameters of a signal coming from the sensor and on the specified limits of the signal.

If a fault occurs, the intelligent sensor shell:

- register the fact of fault,
- inform the human operator that the measurement reliability decreased,
- correct the measurement result and continue operating.

An example of how the sensor fault tolerance is assured is the MS [10] mentioned above. The sensor of the MS contains a set of inductance coils. If a fault occurs, e.g. any signal wire breaks or any coil fails, the sensor is keeping operation.

In the most part of the position range, due to incorporating a redundant number of coils into the sensor (in comparison with minimally needed), the code combination is distorted, but it keeps information regarding the control rod position. In addition, the position of the rod can be corrected on the basis of the known number of steps made by the rod from the nearest position that was reliably measured.

In many cases, it is not possible to obtain a quantitative estimation of the uncertainty. For a considerable part of applications, it is expedient to estimate the quality of measurement results using measurement value status (MVS) [9]. In [9] the following status values were recommended: secure, clear, blurred, dazzled, and blind.

In the joint paper of Oxford and St.Petersburg scientists [29] a comprehensive justification of the necessity to introduce the measurement value status was given and some details were proposed. It was noted that the number of status states should depend on the number of human operator's actions required in response to information about the measurement value status. The number of MVS states is comparatively small:

A) Firm confidence, that a measurement value is reliable, corroborated by an additional information source, i.e. it is based on redundant information. The sensors are fault-free.

B) Assumption that a measurement value is reliable, but there is no corroboration from any additional information sources.

C) Understanding that measurement confidence has been decreased due to some fault. Measurement value was corrected for this fault condition, but the uncertainty is not too great. The measurement confidence is sufficient to get operator's bearings in the technological process and technological equipment condition.

D) Conception that measurements are not reliable for a short period of time. This relates to carrying out a special test, technological operation, or data filtration. In such a situation the measurement values are projected from the past history.

E) Confidence that measurement values are not reliable. This situation obliges, if necessary, to stop the technological process. If the substituted data concerning the measurements are available, step must be taken to move the process away from any critical technological constraints.

5. CONCLUSION

In order to provide reliable functioning of sophisticated technical complexes with automatic control systems, besides technical diagnostics of the equipment, it is necessary to apply high-reliability sensors. They must provide long-term operation and realization of automatic metrological diagnostics.

Development of such sensors should go with development of specific methods for assessment of quality of sensors in respect of their design and technology. Automatic diagnostics should be provided on the basis of structural and/or information redundancy and computer technologies.

Success in developing such sensors depends, to a great extent, on elaboration of international regulatory documents which can establish the requirements for sensors characterized by long- term lifetime.

REFERENCES

[1] Tarbeyev Yu., Kuzin A., Taymanov R., Lukashev A.: *New Stage of Development of Sensors Metrological Assurance*, Measurement Technique, 3, 2007. p. 69-72.

[2] Taymanov R., Sapozhnikova K.: *Problems of Developing a New Generation of Intelligent Sensors*, Proc. of the 10th IMEKO TC7 Symposium, St.Petersburg, 2004, p. 442-447.

[3] Fridman A. E.: *Theory of Metrological Reliability, Measurement Technique*, 1991, 11, p. 3-10.

[4] Efremov L., Sapozhnikova R.: *Assessment of the Sensors Lifetime on the Basis of Test Results*, Proc. of the 10th IMEKO TC7 Symp., St. Petersburg, 2004, p. 448-453.

[5] Sapozhnikova K., Taymanov R.: *Development of Sensors Distinguished by Enhanced Reliability*, Proc. of Conf. "Nuclear Power Instrumentation, Controls, and Human Machine Interface Technology", Albuquerque, New Mexico, USA, 2006.

[6] Taymanov R., Moiseeva N.: *Application of the Metrological Investigation to the Development of the Manufacturing Technology of High-reliable Sensors*, Proc. of the 10th IMEKO TC7 Symp., St. Petersburg, 2004, p. 433 - 436.

[7] Hashemian H. M.: *Maintenance of Process Instrumentation in Nuclear Power Plants*, Springer - Verlag, Berlin Heidelberg, 2006.

[8] Reed R. P.: *Possibilities and Limitations of Self-validation of Thermoelectric Thermometry, Proc. of the Conf.* "Temperature: Its Measurement and Control in Science and Industry", 7, D. C. Ripple et al. eds., AIP Conference Proceedings, Melville, New York, 2003, p. 507-512.

[9] Henry M. P., Clarke D. W.: *The Self-validating Sensor. Rationale, Definitions, and Examples*, Control Eng. Practice, v. 1, 1993, 4, p. 585-610.

[10] Taymanov R., Sapozhnikova K., Druzhinin I.: *Measuring Control Rod Position*, Nuclear Plant Journal, 2007, 2, USA, p. 45-47.
[11] Henry, M.P., Clarke, D. W., et al.: *A Self-validating Digital Coriolis Mass-flow Meter: an Overview*, Control Engineering Practice, 8, 2000, 5, p. 487-506.
[12] Yang J. C.-Y., Clarke D. W.: A Self-validating Thermocouple, IEEE Transactions on Control Systems Technology, v. 5, 1997, 2.
[13] Bernhard F., Boguhn D., et al.: *Application of Self-calibrating Thermocouples with Miniature Fixed-point Cells in a Temperature Range from 500 °C to 650 °C in Steam Generators*, Proc. of the XVII IMEKO World Congress, 2003, Dubrovnik, Croatia, p. 1604-1608.
[14] Feng Z.-G., Wang Q., Shida K.: *Structure Design and Finite Element Analysis of Self-Validating Pressure Sensor*, Chinese Journal of Sensors and Actuators, 20, 2007, 2, p. 279-282.
[15] Belevtczev A. B., Karzhavin A. V., et al.: *In-built Method for Estimation of Confidence in Thermocouple Measurements*, Mir Izmerenii, 2005, 3, p. 12-15.
[16] Hans V., Ricken O.: *Self-monitoring and Self-Calibrating Gas Flow Meter*, Proc. of 8th International Symposium on Measurement Technology and Intelligent Instruments, Sept 24-27, 2007, p. 285-288.
[17] Barberree D.: *Dynamically Self-validating Contact Temperature Sensors, Proc. of the Conf. "Temperature: Its Measurement and Control in Science and Industry*", 7, D. C. Ripple et al. eds, AIP Conference Proceedings, Melville, New York, 2003, p.1097-1102.
[18] WO2007097688, *Redundant Level Measurement in Radar Level Gauging System*, G01F23/284; G01F23/14; G01F25/00, Haegg L., Larsson L.O., et al, Rosemount Tank Radar AB, 2007.08.30.
[19] Kao I., Zhang K.: *Miniaturized Sensors for Intelligent System Fault Detection and Diagnosis (FDD)*, Proceedings of SPIE, 2007, part 1, art. No. 65290U.
[20] Frolik J., Abdelrahman M.: *A confidence – based Approach to the Self-validation, Fusion and Reconstruction of Quasi-redundant Sensor Data*, IEEE Transactions on Instrument and Measurement, v.50, 2001, 6, p. 1761-1769.
[21] MI Recommendation 2021-89, *Metrological Assurance of Flexible Manufacturing Systems. Fundamentals*, Committee on Standard. and Metrology, Moscow, 1991.
[22] BS 7986:2001, *Data Quality Specification for Industrial Measuring and Control Systems*, British Standards Institute, London, 2001.
[23] MI Recommendation 2233-00. *Assurance of Measurement Efficiency in the Control of Technological Processes*. Fundamentals, VNIIMS, Moscow, 2000.
[24] BS 7986:2005. *Specification for Data Quality Metrics of Industrial Measurement and Control Systems*, British Standards Institute, London, 2005.
[25] NAMUR Recommendation NE 107, *Self-monitoring and Diagnosis of Field Devices*, 2005.
[26] Sapozhnikova K. V.: *Metrological diagnostic check*, Metrological Service in the USSR, 1991, 2, p.18-24.
[27] Werthschutzky R., Muller R.: *Sensor Self-Monitoring and Fault-Tolerance, Technisches Messen*, v.74, 2007, 4, p. 176-184.
[28] Feng Z., Wang Q., Shida K.: *A review of self-validating sensor technology*, Sensor Review, 27, 2007, 1, p. 48-56.
[29] Sapozhnikova K., Henry M., Taymanov R.: *Proc. of the Joint IMEKO TC1+ TC7 Symp.*, Ilmenau, Germany, 2005, p. 71-72.

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