Vasyl PARAKUDA
STATE ENTERPRISE SCIENTIFIC RESEARCH INSTITUTE FOR METROLOGY OF MEASURING AND CONTROL SYSTEMS,
6 Kryvonos str., Lvov, 79008, Ukraine

Estimation of the error of temperature measurement channels, taking into account the performance reliability of their elements during operation

Ph.D. Vasyl PARAKUDA

Graduated from Lviv Polytechnic Institute, Department of Information Measuring Technique. Defended his thesis in 1989. He is a deputy of the director of State Enterprise «Scientific Research Institute for Metrology of Measuring and Control Systems». Scientific interests - Metrology of Measuring and Control Systems; methods and means of temperature measurement

e-mail: parakuda@dndi-systema.lviv.ua

Abstract

This paper deals with a technique for estimating the error of a measurement system by taking into account the performance reliability of individual measuring instruments (MI) – measurement channel components. In the measurement system, the metrological characteristics of these components (e.g. sensors) vary in time, and sometimes they are defective. It introduces the error into the entire system. Determination of this error has been based on the information theory and statistical methods for estimating the variances of MI and temperature measurements.

Keywords: measurement channel, temperature measurement, reliability of individual measuring instruments, calibration characteristics of primary measuring transducers.

Ocena dokładności toru pomiarowego temperatury i niezawodności jego elementów

Streszczenie

W artykule przedstawiono metody oceny błędu kanałów pomiarowych z uwzględnieniem niezawodności i błędów wprowadzanych przez poszczególne urządzenia pomiarowe – elementy kanałów pomiarowych. Do określenia tego błędu zastosowano teorię informacji i wybrane metody statystyczne do szacowania wariancji sygnałów pomiarowych wytwarzanych przez urządzenia pomiarowe. Praca dotyczy głównie systemów do pomiaru temperatury. W kanałach do pomiaru temperatury powstają problemy wynikające głównie z zawodności poszczególnych elementów wyposażenia pomiarowego – elementów kanałów pomiarowych. Można do nich zaliczyć na przykład elementy termoelektryczne i inne sensory, które mogą zmieniać swoje właściwości metrologiczne w czasie eksploatacji. Zmiany właściwości metrologicznych prowadzą do powstania błędów pomiarowych. Istnieje więc potrzeba oceny parametrów metrologicznych i niezawodności systemu pomiarowego, która uwzględnienia zmiany właściwości metrologicznych poszczególnych urządzeń. Do oceny związku między niezawodnością urządzeń pomiarowych i rozrzutem wyników pomiaru temperatury zaproponowano wykorzystanie wartości rozrzutu sygnałów pomiarowych, w tym temperatury za pomocą odchylenia standardowego wartości wyników pomiaru. Na podstawie odchylenia standardowego wyników pomiarowych, możliwe jest wyznaczenie błędu ekwiwalentnego całego toru pomiarowego. Jako przykład, w pracy przedstawiono obliczenia dla toru pomiarowego temperatury, w którym poszczególne elementy systemu zostały uszkodzone określoną liczbę razy w ciągu określonego czasu pracy systemu.

Słowa kluczowe: pomiary temperatury, niezawodność elementów torów pomiarowych, kalibracja urządzeń pomiarowych.

1. Introduction

In temperature measuring channels there occur gradual failures in addition to random ones.

These failures are mostly caused by unreliability of the individual elements of measuring instruments – measuring chain components, in particular, of the primary measuring transducers, for example, the hot junctions of temperature thermo-transducers, due to changes in metrological characteristics compared to the standardized values.

Since such a change leads to inaccurate measurement results, there is a need to evaluate the influence of gradual failures on the reliability of a primary measuring transducer – measuring chain component, and to select a method for taking into account any change in metrological characteristics of a measurement result.

This especially concerns temperature measurements on sites where primary measuring transducers are not accessible.

2. Theoretical fundamentals

It is known that during their operation, the primary measuring transducers are subjected to physical aging which results in changes in the metrological characteristics of a measuring channel due to metal evaporation, its structure alteration, etc.

The primary measuring transducers in operation are impacted by a set of factors (time, temperature, vibration, aggressive environment).

These factors are independent of each other.

Taking this into account allows us to consider that the variation of the calibration characteristics of primary measuring transducers in operation, to fall outside the permissible limits, is normal, i.e. the function of gradual failure density is subjected to normal distribution law.

The above mentioned fact gives rise to a problem of estimating the reliability values of primary measuring transducers, taking into account the random and, especially, gradual failures. In our opinion, this problem can be solved based on information theory.

In particular, with the equivalent error estimate of the temperature measuring chain, and with the appropriate data on the variances of the measuring chain (σ^2_{BK}) and of the temperature being measured σ^2_θ, taking into account the failure rate λ of primary measuring transducer elements – measuring chain component, during their operation.

It is known that the temperature measuring channels are typically qualified for application following the results of official metrological confirmation that yields specific accuracy indicators established against the determined values of measuring chain variances (σ^2_{BK}), while the variances of the temperature error estimate σ^2_θ are determined in the process of measurement procedure validation.

These indicators are established taking into account the metrological failure rate **λ** of the measuring chain at the time of performing official metrological confirmation, and measurement procedure validation. However, over time, gradual failures cause changes in these error values.

Below there is a procedure for determining the relationship between the corresponding variances and reliability indicators.

To determine these relationships, it is necessary to:

– determine, in the process of official metrological confirmation, the variance values σ^2_{BK} of the measuring chain against the mean square deviation to be obtained from the results of experimental investigations into the measuring chain in the process of official metrological confirmation, according to GOST 8.009, from the formula:

$$\tilde{\sigma}\left[\overset{o}{\Delta}\right]=\sqrt{\frac{\sum_{i=1}^{2n}\left(\Delta_i-\tilde{\Delta}_s\right)^2}{2n-1}}, \qquad (1)$$

where: $\tilde{\sigma}\left[\overset{o}{\Delta}\right]$ is the mean square deviation of a random component of the error for a specific temperature measuring chain; 2n is the number of investigations in determining $\tilde{\Delta}_s$ which must be as high as to allow for $\tilde{\Delta}_s$ being close to mathematical expectation of Δ-value; Δ_i is the *i*th realization (readout) of the error.

The number *n* is regulated by the metrological confirmation programme and methodology.

– determine the variance value, σ_θ^2, for temperature measurement from the value of the mean square deviation of the results of experimental investigations.

This value is to be obtained from the results of experimental investigations performed in validating the temperature measurement procedure against GOST 8.207, using the formula

$$\tilde{\sigma}(\theta)=\sqrt{\frac{\sum_{i=1}^{2n}\left(x_i-\tilde{A}\right)^2}{n(n-1)}}, \qquad (2)$$

where: x_i - the *i*-th result of observations; $\tilde{A}$ - the measurement result (arithmetic average of the corrected results of observations); *n* - the number of observation results; $\tilde{\sigma}(_\theta)$ - the mean square deviation of the measurement result.

Based on these data, and using information theory, we can obtain its number for the time interval *T*, of failure-free operation of the measuring chain, using one of the following formulae

$$I=WT\lg\frac{\sigma^2{}_{BK}}{\sigma^2{}_\theta}, \qquad (3)$$

from the variance data or from the formula with known mean square deviations.

$$I=2WT\lg\frac{\sigma_{BK}}{\sigma_\theta}, \qquad (4)$$

where: W is the occupied frequency bandwidth for signalling over the time interval, *T*.

It is known [3] that in the presence of random and gradual failures, the total reliability, *P*(*T*), is a function of time, *T*, and is given by

$$P(T)=P_1(T)\cdot P_2(T), \qquad (5)$$

where: $P_1(T); P_2(T)$ is the reliability of the primary measuring transducer at random and gradual failures, respectively.

Considering [3] that the random failure reliability is estimated by

$$P_1(T)=e^{-\lambda T} \qquad (6)$$

and the gradual failure reliability is estimated by

$$P_2(T)=\frac{1+\Phi\left(\frac{TCP_2-T}{\sigma}\right)}{1+\Phi\left(\frac{TCP_2}{\sigma}\right)}, \qquad (7)$$

then, according to Expression (5), the probability of the simultaneous effect of random and gradual failures is equal to

$$P(T)=\frac{1}{2}e^{-\lambda T}\left[1+\Phi\left(5-5\frac{T}{T_{CP_2}}\right)\right], \qquad (8)$$

where: $\Phi(T)$ is the Laplace's function.

Taking into account that, according to the data from reference tables, the Laplace's function $\Phi(T)$ (equation (8) term in round brackets) is approximately equal to 1, then, for further calculation, the failure probability will be determined by formula (6), and the average time of failure-free operation within the time interval (0,T), under operating conditions, by the known formula

$$\overline{T}_1=T_0[1-P(T)], \qquad (9)$$

where: $\overline{T}_0=\frac{1}{\lambda}$ is the average time of failure-free operation within the time interval (0,*T*).

As the presence of failures results in reducing the actual operation time of the measuring chain, i.e. down to T_1, compared to the time T of measuring chain operation, then, in this case, the average amount of information obtained at the measuring chain output, taking account expression (4), is given by

$$I_1=2WT_1\lg\frac{\sigma_{BK}}{\sigma_\theta}= \\ =2WT_0[1-P(T)]\lg\frac{\sigma_{BK}}{\sigma_\theta} \qquad (10)$$

In this case, there is an information loss which can be determined by the formula

$$\Delta I_1=I-I_i= \\ =2W\left[T-T_0[1-P(T)]\lg\frac{\sigma_{BK}}{\sigma_\theta}\right] \qquad (11)$$

this leading to an increase in the measurement error.

This equivalent error σ_E, which affects the measurement result, can be obtained from a hypothetical measuring chain that operates without a failure during the time *T*, and yields an amount of information I_2, which, with the known variances, is calculated from the formula

$$I_2=2WT\,lg\frac{\sigma_{BK}}{\sigma_E}. \qquad (12)$$

The value of this error is to be determined from the information loss condition under reliable operation of the hypothetical measuring chain with the real measuring chain equivalent error of information loss, taking into account its reliability.

The information loss at the measuring chain output, with the equivalent error, equals

$$\Delta I_2 = I - I_2 = 2WT\,lg\frac{\sigma_{BK}}{\sigma_\theta} - 2WT\,lg\frac{\sigma_{BK}}{\sigma_E} = 2WT\,lg\frac{\sigma_E}{\sigma_\theta} \qquad (13)$$

By equating Equations (11) and (12)

$$2W\left[T - T_0\left[1 - P(T)\right]lg\frac{\sigma_{BK}}{\sigma_\theta}\right] = 2WT\,lg\frac{\sigma_E}{\sigma_\theta} \qquad (14)$$

after appropriate reductions, division by *T*, and its solution, we obtain

$$\sigma_E = \sigma_\theta \cdot \left(\frac{\sigma_{BK}}{\sigma_\theta}\right)^{1-\frac{\overline{T}_0}{T}\left[1-P(T)\right]} . \qquad (15)$$

At $\lambda T << 1$ *or* $T << T_0$, with expression (10) being multiplied by $б_0$, we obtain

$$\sigma_E = \left(\frac{\sigma_{BK}}{\sigma_\theta}\right)^{1-\frac{\overline{T}_0}{T}\left[1-P(T)\right]} = \sigma_{BK}^{1-\frac{\overline{T}_0}{T}\left[1-P(T)\right]} \sigma_\theta^{\frac{T_0}{T}\left[1-P(T)\right]} \qquad (16)$$

Considering that

$$\overline{T}_0 = \frac{1}{\lambda} \quad \text{and} \quad P_1(T) = e^{-\lambda T} , \qquad (17)$$

and, under this condition, taking an approximate value

$$e^{-\lambda T} = \frac{1}{e^{\lambda T}} = \frac{1}{1+\lambda T} = 1 - \lambda T , \qquad (18)$$

then the power expression for the second term of equation can be given by

$$\frac{T_0}{T}\cdot\left[1 - P(T)\right] = \frac{1}{\lambda T}\cdot\frac{(1 - 1 + \lambda T)}{1 + \lambda T} = 1 - \lambda T . \qquad (19)$$

With this value being taken into consideration, expression (15) can be presented as:

$$\sigma_E = \sigma_{BK}^{\frac{\lambda T}{2}} \cdot \sigma_\theta^{\frac{(1-\lambda T)}{2}} . \qquad (20)$$

As may be inferred from expression (16), established is the relationship between the equivalent error of measurement and the failure rate of temperature measuring channels in operation.

3. Example

Data

Estimate the equivalent error of temperature measurement, with the measuring channels being in operation, against the following input data: number of temperature measuring chains (20 items) which have been operated under the same conditions within the temperature measurement range of 600 °C, during a period of 20 000 hours.

Experimentally there are determined 5 failures due to the hot junction failure of the primary measuring transducer.

According to the data from official metrological confirmation of measuring chains, the mean square deviation, in estimating the error within this range, is equal to 0,5°C, and according to the data from measurement procedure validation, the mean square deviation of temperature measurement is equal to 1,2°C.

The standardized value for the permissible bounds of the absolute error of temperature measurement is 3°C.

The duration of failure-free operation, according to the data from operational documentation, is 100 hours.

Solution

According to these data, the failure rate

$$\lambda = \frac{5}{20 \cdot 20000} = 0{,}0000125 .$$

Then, from formula (16), we obtain

$$\sigma_E = 0{,}5^{\frac{0{,}00025\cdot 100}{2}} \cdot 1{,}2^{\frac{(1-0{,}00025\cdot 100)}{2}} = 0{,}999 \cdot 1{,}199 = 1{,}98^0 C.$$

4. Conclusions

The proposed method allows defining the equivalent error of the temperature channel of a measuring system and implement the improvements to the results of measuring. The results of calibration and testing of the measuring channel are defined by its metrological reliability of the measurement uncertainty [5] and the possibility of future use of the measuring channel temperature.

5. References

[1] Norma ГОСТ 8.009-84 ГСИ, State system for ensuring the uniformity of measurements. Standardized metrological characteristics of measuring instruments, http://www.gosthelp.ru/text/GOST800984GSINormiruemyem.html.

[2] Norma ГОСТ 8.207-76. State system for en-suring the uniformity of measurements. Direct measurements with multiple observations. Meth-ods of processing the results of observations. Ba-sic principles, http://www.gosthelp.ru/gost/gost4226.html

[3] Metrologia i technika pomiarowa, podręcznik. E.S. Poliszczuk, M. M. Dorożowiec, V. O. Yat-suk i inni, pod. Red. Prof. E. S. Poliszczuka, Wydawnictwo Uniwersytetu narodowego „Politechnikf Lwowska", 2012, 544 str.

[4] Encyklopedia termometrii. Y. T. Lutsyk, L. K. Bunyiak, J. K. Rudawskij, B. I. Stadnyk, Lwów, Wydawnictwo Uniwersytetu narodowego „Politechnikf Lwowska", 2003, 428 str.

[5] ISO/IEC Guide 98-3:2008 Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement.

otrzymano / received: 24.06.2013
przyjęto do druku / accepted: 01.08.2013 *artykuł recenzowany / revised paper*