METROLOGICAL RISKS AND STATE OF THE MONITORED OBJECTS

Svyatoslav Yatsyshyn, *Dr. Sc., Prof.;* ***Roman Baitsar,*** *Dr. Sc., Prof.;*
Serhiy Lazarenko, *PhD Student;* ***Nadiia Lazarenko,*** *PhD Student;*
Lviv Polytechnic National University, Ukraine;
Rostyslav Mastylo, *PhD, Sen. Sc. Fellow, TU-Ilmenau, Germany;*
e-mail: sviatoslav.p.yatsyshyn@lpnu.ua

https://doi.org/10.23939/istcmtm2022.01.017

Abstract. The metrological risks of goods production are studied in the work. They are estimated conjugating with the existing technology as well as its metrological support. It is confirmed that in addition to the factors due to the processing of measurement results, the peculiarities of metrological support should be taken into account. One of the characteristic parameters of the metrological instruments is the variance of the measured value.

Multiple measurements of the electrical resistance of the mentioned instruments – high-precision resistors designed for indirect measurement of current by measuring the voltage on them, using a DC bridge, were performed. The variance of obtained results is estimated, depending on the number of repeated measurements, the time interval between them, etc.

Key words: Metrological support; Risks; Product quality; Metrological instruments; RMS deviations.

1. Introduction

In 2012, guidelines were published on the consideration of measurement uncertainty regarding decision-making in conformity assessment [1]. The Measurement System Analysis (MSA) Manual of the standard [2] has focused on the statistical analysis of data recorded by the measurement system. This is a method that allows concluding on the acceptability of the measuring system through the quantification of its indicators. Measuring systems (MSs) are considered as a set of instruments, standards, operations, methods, personnel, computer programs, the influence of the environment that are necessary to provide quantitative characterization to the measured values. The major MS task is to obtain data, the analysis of which is applied to make the management decisions about the products or processes. The MS consists of: the monitored object, measuring device, the measure of physical quantity; operational conditions (humidity, pressure, temperature, etc.) operator together with the measurement procedures. It is noted [3] that the MS must comply with a monitored process to ensure product quality within acceptable standards. Changes in measurement objects affect process variation, MSA. Therefore, the appropriate choice of research methods becomes quite important for measurement capabilities improvement. Many different quality measurement methods have been developed to enhance the accuracy required for different types of measuring instruments.

The ultimate goal of analyzing the various measurement capabilities of the estimated methods is to establish the total standard deviation of the measurement, known as measurement uncertainty [4]. Most data on processes are obtained with the help of measuring instruments, and the instruments themselves contain their uncertainties. Thanks to MSA, it is possible to ensure the reliability of measurement results, which helps to improve the product quality. That is, reliable analysis of the MS not only provides accurate capabilities of the controlled process but also contributes to scientific and industrial development. The quality of the MS and the quality of the product are conjugated. In particular, the MS effective monitoring is crucial for quality assurance [5].

2. Drawbacks

During the objects' examination (while monitoring the quality parameters), when the results obtained must be under a pre-established specification it is not always possible to avoid errors of type I (acceptable product is considered defective) and errors of type II (defective product is considered acceptable). These two types of incorrect decisions mean, respectively: the risk of the manufacturer (deviation of the characteristics of the product from the optimal values) and the risk of the customer (acceptance of the wrong product).

3. The Goal of the Work

The purpose of the current paper is to study the relationship of metrological risks with the parameters of metrological equipment while monitoring the electrical resistance of the specific objects that are the naturally-aged working standards.

4. Metrological Risks

Let's focus on the errors of type II, since then the risk goes directly to customers, causing their complaints and costs due to poor quality. Effective management of MSs has become a priority, as they play a key role in efforts to improve product quality. Increasing variability (standard deviations) degrades the values of the index and product quality, reducing the ability to monitor statistical schemes of the production. If the MS is not accurate enough, the true value of the monitored characteristic is distorted. This is an impetus for improving MS.

In an ideal system, correct results should be obtained as a result of each measurement. Otherwise, the ideal MS is inherent in the zero statistical error for the objects to be checked. Since there is no perfect measurement, you should rely on the MS in terms of analysis and control of data scatter to get them in a reasonable range. Then MSA is the main tool in the quality management system [2].

It applies the statistic and graphic methods to perform design as well as MSA of errors to estimate the tolerances of the whole MS. Based on this is possible to determine the deviations due to both measuring instruments and the activities of service personnel [6]. However, ISO/TS 16949 placed instrument calibration and MSA specification in one paragraph 7.6, and the main objectives for MSA are the measuring instruments. Therefore, it is not possible to correctly identify MSA and calibration, given that MSA means calibration plus statistics of measurement results.

MSA, instrument correlation, and calibration are methods of measuring system evaluation. Regardless of the method, they are all used to assess the reliability of the MS and to ensure the stability of the measurement process, evaluation, and interpretation of the obtained results.

4.1. Risks due to the measurement uncertainty

In 2017, the ISO 17025 standard [7] on calibration and testing laboratories was revised to document the adopted decision rule, considering the level of risk (e.g. erroneous acceptance and erroneous rejection, and statistical assumptions), and apply this rule in the context of decision-making on the conformity of the considered object.

In addition, EURAMET funded the EMPIR 17SIP05 “CASoft” project (2018–2020) to make the statistical methodology available to conformity assessment decision-makers: calibration and testing laboratories, industrialists, and regulators [8]. This project helps them with software for computing the associated risks, which is intended to cover common cases, consideration of the distribution, in the presence or absence of prior information, as well as some life situations (other options for the probability distribution, two-dimensional case, etc.).

The updated ISO 17025: 2017 [9] makes it even more important to address the issue of conformity assessment due to uncertainty, as it opens the possibility for entities involved in the mentioned problem to agree before measuring the decision-making rules that will be used for testing and calibration.

4.2. Decision-making in conformity assessment

The problem arises in various industries immediately after the measurement: the obtained measurement value is compared to the tolerance interval of the desired value; then they decide whether the good (product, tool, material, etc.) can be considered to meet the specifications. In this case, the uncertainty of measurement contributes to the wrong decision, i.e. the acceptance of the wrong product or the rejection of the proper product. Such risks (incorrect decisions) are estimated [8] using single or double integrals. These include:

– specific risk, defined as the probability of making the wrong decision for appropriate goods;

– global risk, defined as the probability of a wrong decision based on the future measurement result.

The peculiarity of application is following. The decision is performed based on counting the common amount in percentages. Only binary decision-making rules are applied: a) the product must be accepted (declared as appropriate) or b) it must be rejected (declared as inappropriate). That is, percentages, which form the “area of uncertainty”, are not considered. Given that the only possible solutions are acceptance or rejection of the product, study the two combined risks, namely the risk of a particular consumer, referred to here as R_S, which is the probability that the studied product does not meet the requirements;

and the risk of a particular manufacturer R_V, which is the probability that the rejected product meets the requirements ($R_S + R_V = 1$).

5. Repeated Study of the Same Object as the Further Development of the MSA Method

The disadvantage of traditional methods is the involvement of the far from obvious approach to the a priori accepted identity of the studied objects. This, in turn, contributes to the determination of the variance of the measurement results, and then forms our relationship to the object (product, tool, material, etc.), concluding that it meets or does not meet the pre-established specification.

The stated task changes significantly when the same object is subject to repeated research. Then a drift/shift in its characteristics indicates the presence of certain impacts or processes that cause it.

The task of studying a special highly-exact object can change even more significantly. Then we get changes in the same characteristic of the object to detect effects of higher-order of sensitivity. The latter are usually hidden by some other factors that are considered independent in origin, i. e. uncorrelated and commensurate with the results of the impact, and therefore random factors of influence in estimating the standard deviation.

When analyzing the results of statistical measurements of the parameters of the same objects, it is advisable to ensure the conditions of equality of measurements. Then the differences between the variances of the measurement results should be minimal. However, in practice, the differences between the variances can differ significantly. The question arises whether the condition of equality of measurements is observed.

Verification of the condition of equality of measurements can be performed by statistical criteria, for example, by Fisher's test F, comparing the values of variances of measurement results with the critical value F_{CR}. For $F > F_{CR}$ it can be argued that the condition of equality of measurements is violated and the measurements are no equilibrium. However, statistical criteria do not answer the question of the cause of measurement inequality and under what conditions the difference between variances becomes minimal. That is, in which cases the condition of measurement inequality must be met. That is why we study highly-exact objects of electrical nature, that's the working standards of electrical resistance (p. 5.1) and the noise thermometers with resistance sensitive elements (p. 5.2).

5.1. Study of the Working Standards of Electrical Resistance

The object of the study is unique, highly-exact measures of electrical resistance – electrical resistance coils, 1960. During storage in the metrological laboratory of Lviv Polytechnic, they were subject to natural aging. This makes it possible to state that the mechanical stresses in them are minimized, and the values of electrical resistance are maximally stabilized. Accordingly, one can expect the minimum values of the dispersion while repeated measuring of their resistance values by a DC bridge.

· **Model of study**

The study was carried out with the help of the mentioned metrological instruments: the differences between the variances of the electrical resistance of the same objects under the same conditions were determined. The energy spectrum of fluctuations of their measured values in the frequency range of repeated measurements was established within: a) minutes' range; b) hours' range. Then, we believe, the quasi-equilibrium object is measured and the variance of the obtained results has to be minimal.

The main reasons for such measurements can be both changes in measurement conditions and the non-equilibrium (quasi-equilibrium) state of the studied object. If the latter is in thermodynamic equilibrium, then the variance of the measurement results is not a function of time t. Therefore, the standard deviation does not depend on the time interval between the particular measurements or on the time during which n measurement results are obtained. The energy spectrum of fluctuations $S_{xp}(f)$ of the parameter $x_p(t)$ of the equilibrium system is the same in the frequency range from $f \to 0$ to ultrahigh frequencies (i.e. the spectrum is in the form of "white" noise) [10].

Measurements have been performed for 10 s and 3 hours (10 000 s) intervals. The results of repeated 10-fold measurements were fulfilled over 10 seconds (Δt) after which they were averaged. Similarly, the average value of 10-fold measurements was obtained for over 3-hour duration (ΔT) of measurements. These values were slightly different. In this case, the energy spectrum $S_{xn}(f)$ of fluctuations of the parameter $x_N(t)$ is altering within the whole frequency range; it contains the flicker component of the spectrum (Fig. 1). The latter is more characteristic for the energy spectrum of the object $x_N(t)$ when 10 measurements have been performed at an interval of 1 s between successive measurements (a) and less typical for the same object, when these 10 measurements have been performed at an interval of 100 s between successive measurements (b).

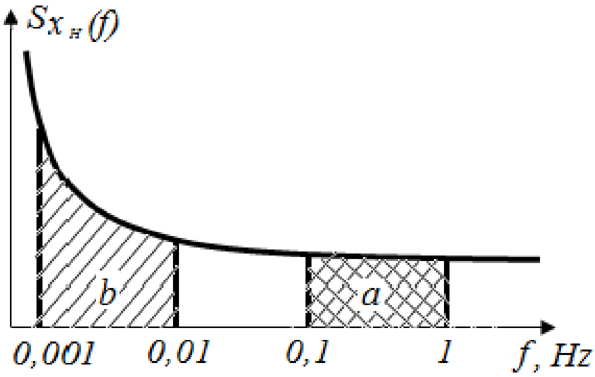

Fig. 1. The energy spectrum of fluctuations of electrical resistance of Measure $S_{xn}(f)$ for 10 measurements performed at intervals of 1 s (a) and 100 s (b) [11] (model)

When measuring, the relationship should be fulfilled: $f_B \geq F_C$, where F_C is the upper frequency of the spectrum of the variable. The variance of the results of the parameters, as we consider of the non-equilibrium system, depends not only on the number of measurements n but also on the duration between the measurements δt: the smaller δt, the greater f_B. The range of measurement frequencies is shifted to the high-frequency band and the process of measuring the parameter of the object in the quasi-equilibrium state is realized (Fig. 2, f_H = 0.1 Hz, f_B = 1.0 Hz). As the time interval between measurements δt increases, the frequency f_B decreases. The range of measurement frequencies is shifted to low frequencies and the process of measuring the parameter of the object in the non-equilibrium state is realized (Fig. 3, f_H = 0.001 Hz, f_B = 0.01 Hz).

Based on the defined $S(f)$ for the known f_H and the given δt, it is possible to determine the number of measurements n for which the difference between variances is minimal, and, accordingly, the condition of equivalence of measurements, and to determine whether the object is in equilibrium or no equilibrium:

$$SH(f) = \frac{\exp(f + t)}{\exp(f + t) - 1} S_0, \qquad (1)$$

where S_0 is the energy spectra of resistance fluctuations at medium and high frequencies; τ is the relaxation time (the time at which the value of $S_H(f)$ changes to $1.58 \cdot S_0$, where $f_0 = 1/\tau$). The criterion for the state of the object is the value of τ: for $\tau \to \infty$, $S_H(f)$ @ S_0 the is in equilibrium; for $\tau < \infty$ the thermodynamic system of the object under study is in a non-equilibrium state (Fig. 2).

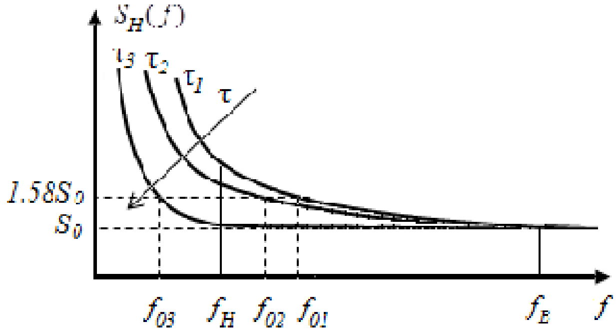

Fig. 2. The energy spectrum of fluctuations of electrical resistance of the object under study as a nonequilibrium thermodynamic system [11] (model)

As can be seen, in the frequency range from f_H to f_B, $S_H(f)$ changes the least for an object with τ_3, and $S_H(f)$ changes the most for an object with τ_1. Therefore, depending on the state of the object under study (on the τ) the measurements of its parameters in the mentioned frequency range occur in quasi-equilibrium (τ_3) or non-equilibrium (τ_1) state at the same interval between measurements δt ($f_B = 1/\delta t$) and at the same number of measurements n ($f_H = 1/n\delta t$). Therefore, the variances of the results under different measurement conditions are different. Otherwise, under the same conditions of measuring the resistance of the resistors of one batch, the different value of the variance is most likely not an error of the experiment, but a consequence of different thermodynamic states of the tested resistors.

· **Experiment**

To test this assumption, the electrical resistance of two 1-ohm resistance coils was measured. They were connected to a DC Bridge according to a 4-wire circuit. Measurements were performed under the same conditions (with the same methodological errors and with the same environmental impacts – temperature, humidity, etc.). One coil was conventionally denoted as measure A, the other as measure B. One hundred measurements were performed for each coil. The average value of resistance R_m and standard deviation σ were obtained (Table 1). To determine the influence of external factors on the measurement results, the correlation coefficient κ was determined. A small value of κ indicates that the measurement results are independent and the influence of external factors is minimal.

Table 1

Measurement results of measures A and B

	R_m, Ω	σ, Ω	$R_m \pm 3\sigma$, Ω	κ
Measure A	0.9967	$1.8524\cdot10^{-4}$	$0.9967 \pm 5.5572\cdot10^{-4}$	0.2271
Measure B	0.9969	$1.2978\cdot10^{-4}$	$0.9969 \pm 3.8934\cdot10^{-4}$	

The difference in the variances of the results for measures A and B is ≈ 40 %. This may be due to the difference of non-equilibrium thermodynamic states of the materials of these measures. The energy spectra of fluctuations of their resistances within the frequency range from 0 to $f_D/2$ are shown in Fig. 3. Here, for measurements that have been performed with time interval δt = 25 s, the sampling frequency f_D ($f_D = f_B$) was 40 MHz. It is seen that the spectra of measures A and B decrease with frequency, thus resembling the spectrum of flicker noise that is inversely proportional to frequency.

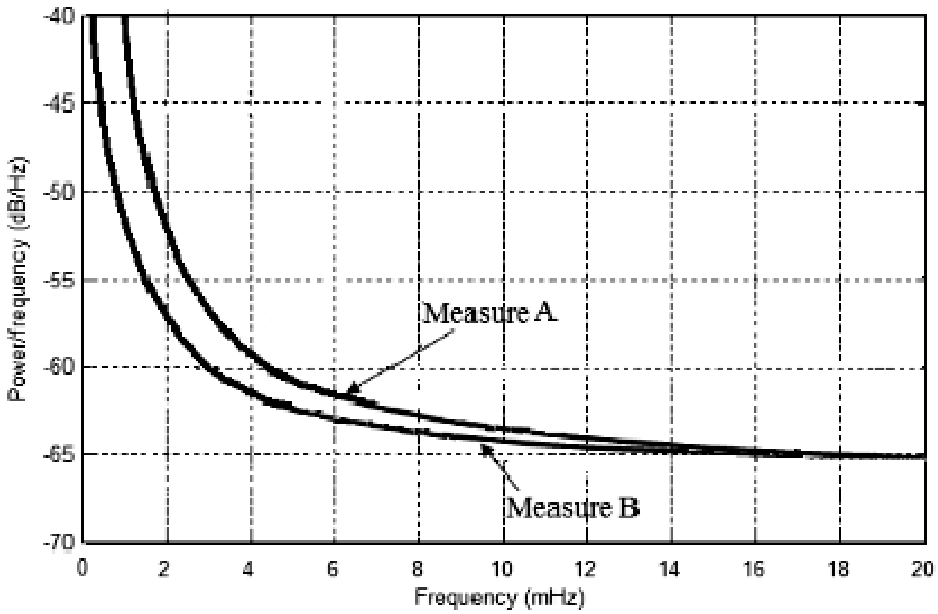

Fig. 3. The energy spectrum of fluctuations of electrical resistance Mir A and B [11] (experiment)

For certain spectrum values, the lower frequency f_H ($f_H < f_H = 1/n\delta t$) in the range from f_H to f_B, in which measures A and B are in the quasi-equilibrium state, is defined as: $f_H = 10\cdot10^{-3}$ Hz; $f_H = 1/\delta t = 40\cdot10^{-3}$ Hz. That is, at $f_H = 10\cdot10^{-3}$ Hz and the intervals between readouts δt = 25 s. the number of results n for which the measurements were performed while the object of study was at the quasi-equilibrium state the difference between the variances is minimal, the condition of equality of measurements is met. Then the number of measurements is defined as $n' = 1/f_H\cdot\delta t = 4$.

This thesis was confirmed by determining the variances for 4 consecutively measured resistances of measures A and B, performed with the interval δt = 25 s: the mean of standard deviations of measure A: $\sigma_{Am} = 1.0210\cdot10^{-4}$ Ω, and measure B: $\sigma_{Bm} = 1.0087\cdot10^{-4}$ Ω (σ_{Am}/σ_{Bm} – 1) ≈ 1 %. For comparison, the difference between the standard deviations of the resistance of measures A and measures B was determined for a larger number of measurements performed after 25 s. as ~8 %. That is, with a larger number of measurements over the same period, the difference between the variances increases (measurements are made for a resistor in the non-equilibrium state: $f_H = 1/n\cdot\delta t = 1.6\cdot10^{-3}$ Hz).

5.2. Deviations of electrical parameters of the noise thermometer with resistive sensitive element

Deviations of electrical parameters can be directly studied on the sensitive element of the noise thermometer, which measures the temperature proportional to the power of the electrical noise signal dissipated on this element. The analysis is based on the fact that the studied sensitive element is a separate homogeneous thermodynamic system described by the basic equation of thermodynamics with thermal and electrical degrees of freedom [12]. While measuring temperature with methodical error ΔT_{met}, the internal energy U_{int} accumulated in the element practically does not change (dU_{int} = 0); the entropy coming from outside to the thermometric material at the established non-equilibrium process “flows” at the same speed. Therefore, the equation $T = bP_{el}$ describes the stationary non-equilibrium state of the object, where an irreversible process with a relaxation constant τ occurs.

Note that the constancy of temperature does not indicate the thermodynamic balance of the object with the environment: the aging occurs at a constant temperature. In the event of a non-stationary thermodynamic state in the sensitive element of the thermometer (as a consequence of thermal cycling, unrelaxed plastic deformation, transmission of electric current during measurement, etc.), the condition under which the Nyquist formula has been derived is violated. The rate of entropy dissipation increases, powering of electrical noise, and the error of the noise thermometer. The relaxation of micro stresses, when the internal energy is lowered to the minimum, occurs over time, depending on the temperature, type, and concentration of defects. Hence, the methodological error ΔT_{met} of the noise thermometer is due to the dissipation of the entropy flow entering the thermometric material from the outside. It does not matter whether this flow is related to heat transfer or deformation during the spiral winding of the sensitive element.

5.3. Modes of resistance measurements

The dissipation of the entropy flow coming from outside while conducting research, leads to noise, even due to heat exchange with the environment. In our case, the source seems to be the electrical measurements themselves. After all, balancing the bridge lasts a certain time (~1 s). The electric current during the balancing period averages 10^{-7} A (according to the galvanometer). During this time, with a continuous decrease in current to zero due to the balancing of the bridge, the studied 1 Ω coil dissipates electric power ~ 10^{-14} W, which forms a weakly non-equilibrium thermodynamic state that is manifested by fixed fluctuations of electrical resistance.

6. Conclusions

1. To reduce the metrological risks of manufacturing and operation of products should pay attention to the whole complex: product + measuring system + processing of results. Effective management and monitoring of the measuring system state are the main requirements to ensure the reduction of errors, aimed at ensuring compliance of products with the requirements of the specification. To produce high-quality products, the correct MSA concept should be followed, providing the involvement of the highly-exact and precision measuring equipment.

2. The variances of the measurement results permit to the generation of the attitude to the object (product, tool, material, etc.) and determine whether it meets/doesn’t meet the pre-established specification. A change in its characteristics over time, for example, a shift, indicates the presence of processes that cause it. In the study of highly stable objects (naturally aged resistance coils with minimal values of electrical resistance dispersions), we have got the opportunity, by the deviations of the repeatable-studied characteristics, to detect effects of higher-order of sensitivity. The latter are usually hidden by many other factors that are considered independent in origin, i.e. uncorrelated and commensurate with the results of the impact, and therefore random factors of influence in estimating the standard deviation.

3. Based on the study of energy spectra of fluctuations of electrical resistance and frequency range within which the energy spectrum changes slightly, the measurement conditions are determined – the time interval between subsequent measurements δt and their number n, for which the difference between the variances of the results is minimal. It is shown that in real conditions the obtained spectrum resembles the flicker-noise in frequency behavior. This means that the random error cannot be reduced to negligible values by averaging a certain number of measurement results.

4. A significant difference between the variances of the results under the same measurement conditions may be the result of different degrees of imbalance of the considered objects – measures of electrical resistance, as isolated thermodynamic systems. The reason for this difference may be the energy interference, as a consequence of the measurement, in the state of the measured object, namely the dissipation of electric power in the measure at the moment of balancing the DC Bridge.

7. Gratitude

The authors express their gratitude to the Staff of the Department of Information and Measuring Technologies of Lviv Polytechnic National University.

8. Conflict of interest

The authors state that there are no financial or other potential conflicts regarding this work.

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