The object of research is multiple measurements. The research aims to improve the accuracy of multiple measurements with a non-linear and unstable sensor transformation function. It is proved that the redundant measurement equation ensures the independence of the measurement result from the parameters of the transformation function and their deviations from the nominal values. It was found that the result of redundant measurements is affected by the reproduction errors of normalized temperatures T1 and T2. It is shown that the best accuracy results are obtained with a reproduction error of normalized temperature T2 within ±1.0 % and temperature T1 within ±0.1 %. This makes it possible to reduce the accuracy requirements for the source of reproduction of normalized temperature T2.

The possibility of processing the results of multiple measurements by two approaches is presented. Computer modeling using the first approach found that with a reproduction error of normalized temperature T2 within ±0.5 %, the relative measurement error is 0.003 %. When modeling the second approach, the relative error is 0.05 %. It was also found that with an increase in the reproduction error of normalized temperature T2 to ±1.0 %, the value of the relative error is 0.04 %. Due to this, when applying the second approach, it becomes possible to choose a non-high-precision source of reproduction of normalized temperature T2. In addition, the sensitivity of the second approach to the digit range of measuring devices was found, which leads to the dependence of the measurement result on their accuracy.

There are reasons to assert the possibility of increasing the accuracy of multiple measurements by processing the results of intermediate measurements according to redundant measurement equations using two approaches

Keywords: redundancy, multiple measurements, quadratic transformation function, function parameters, accuracy improvement

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COMPUTER ANALYSIS OF MULTIPLE MEASUREMENTS WITH THE SENSOR'S QUADRATIC TRANSFORMATION FUNCTION

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1. Introduction

When conducting a technological process or in production, it is extremely important to obtain reliable information about measurement parameters, characteristics or the object of research. The accuracy of the obtained data is one of the main problems that must be considered during any measurement. This is due to the fact that the accuracy of the data obtained affects the quality and reliability of the product [1, 2], as well as the effectiveness of the research or process as a whole. On the other hand, obtaining inaccurate data, especially at the beginning of the measurement, can disrupt the entire subsequent process and lead to product shortages. Since a sensor is the first element of the technical system that converts the measured input value into an output signal, the accuracy of this conversion will affect the accuracy of the entire subsequent process. So, the sensor must meet high requirements for accuracy, measurement range width, sensitivity, etc. In addition, the measurement accuracy of the sensor is also affected by the type of transformation function. This is due to the fact that with a non-linear transformation function of the sensor, there is a need to linearize it or work only on its linear sections. All this leads to either a nonlinearity error or a decrease in the operating measurement range. It should be noted that the issue of accuracy improvement is particularly acute in multiple measurements or when measuring a certain parameter (quantity). In addition, the measurement accuracy is also affected by the environment and aging of the technical elements of the measurement system, leading to instability of the sensor parameters. In this case, special attention is paid to both the accuracy of the sensor and the improvement of existing measurement methods in order to reduce not only the systematic, but also the random error component. All this is the basis for further improvement of methods and approaches to increase measurement accuracy.

In view of the need to generate reasonable data on the measurement process, research aimed at increasing the accuracy of multiple measurements with a non-linear and unstable sensor transformation function is considered relevant.

2. Literature review and problem statement

Various approaches and methods are used to solve the issue of increasing measurement accuracy: circuit solutions, calibration, correction of the design parameters of measuring instruments, increasing sensitivity, methods to reduce the impact of the environment, etc. All measures used in measurements have certain advantages and disadvantages. Thus, the studies conducted in [3] noted an increase in accuracy due to the circuit solution. It was noted that compensation for the effect of the reactive component of the shunt link resistance was achieved by adding a resistive divider. However, with such a circuit, there are difficulties in its metrological verification, as well as manufacturing low resistance of shunt parts with high accuracy. The increase in accuracy due to circuit solutions was also considered in [4]. A method for measuring the RMS value of AC voltage was presented, making it possible to perform measurements under additive interference. However, issues related to the reduction of the systematic component of the measurement error caused by the influence of the environment remained unresolved. To overcome one of the components of this problem, the work [5] proposed an approach that consists in compensating the measurement result of an infrared thermal imager from dust exposure. Reducing the influence of external aspects on measurement accuracy was also considered in [6]. It is shown that with the obtained theoretical formula, the effect of angular field, contrast, and atmospheric transmittance on the measurement accuracy is reduced. However, it should be noted that the increase in accuracy was achieved in the works only by reducing the influence of the environment, and the issue of measurement with a non-linear transformation function was not considered. In [7], an increase in the accuracy of the temperature sensor was achieved by measuring the nonlinear curvature correction for several reference temperature values. In [8], the accuracy of the digital temperature sensor was increased due to the correction of its nonlinear response. It is shown that the calibration method involved comparing the readings of the temperature sensor with a high-precision reference temperature sensor before and after applying linear regression. Increasing accuracy through calibration was also considered in [9]. The studies were aimed at determining the deviation characteristics of the waterproof sensor in accordance with the reference one.

In [10], the use of a CMOS temperature sensor with built-in calibration was proposed for the linearization of the curve. This improves measurement accuracy through both linearization and calibration. However, it should be noted that such approaches to improving accuracy through calibration require the use of exemplary sources, which implies certain material costs for their implementation. In addition, the influence of non-informative factors arising in the measurement process was not taken into account. The issue of increasing accuracy under the influence of non-informative factors on sensor signals was considered in [11], where, the method of reducing the calibration points of multisensors made it possible to significantly reduce the number of calibration points. Despite the expediency of the conducted research, the issue of choosing a method for processing measurement results remains unresolved. In [12], the impact of processing methods on measurement accuracy was investigated. It is shown that due to the improvement of the midline method, the absolute measurement error is reduced. However, the work did not address the instability of sensor parameters caused by the external environment during multiple measurements. Therefore, in [13], to reduce the effect of the environment on the uncertainty of sensor parameters, the general uncertainty propagation equation and the Monte Carlo method were used.

Despite the practical significance of the given results, the issue of comprehensively solving the problem of increasing the accuracy of multiple measurements with a non-linear and unstable transformation function has not been considered sufficiently. Therefore, the expediency of using redundant measurement methods in solving this issue was demonstrated [14]. According to the author [14], this is due to the use of appropriate systems and equations of redundant measurements, thereby increasing the accuracy of multiple measurements with an unstable transformation function in a wide range of values. The main theoretical aspects of redundant measurement methods were presented in [15]. The universal redundant measurement equation in general form was mathematically presented in [16]. However, the possibility of the practical application of redundant measurements with a non-linear transformation function was not shown. Therefore, the work [17] presented the use of redundant methods with a nonlinear function with the possibility of metrological self-control of the sensor. However, it should be noted that this paper did not consider the impact of destabilizing factors on the results of multiple measurements. This may cause difficulties related to the impact of the random component of the measurement error on the measurement result. To overcome this problem, the work [18] proposes two approaches to process measurement results. It is shown that this allows increasing the accuracy of measurements by eliminating the systematic component of the error due to changes in the parameters of the transformation function, as well as reducing the random component of the error. Redundant measurements with a nonlinear transformation function were further developed in [19]. It is shown that due to the regularity between the normalized and sought quantities, the range of high-precision measurements is significantly expanded. Despite the practical significance of such results, the practical application of redundant measurement methods for sensors with a quadratic transformation function (transistor, thermistor, etc.) was not considered. Therefore, in [20], the issue of increasing the measurement accuracy with a quadratic transformation function by adjusting the values of normalized quantities was considered. However, it should be noted that this paper does not provide methods for processing the results of multiple measurements with changes in the parameters of the transformation function and reproduction errors of normalized quantities.

Therefore, there are reasons to believe that the lack of certainty in research on processing the results of multiple measurements with a quadratic transformation function, as well as on determining the features of their application, necessitates research in this direction.

3. The aim and objectives of the study

The conducted studies aimed to improve the accuracy of multiple measurements with a quadratic transformation function using redundancy due to various approaches to processing measurement results. This will make it possible to determine the optimal version of the mathematical model of multiple measurements with a quadratic transformation function (TF), as well as the features of its application.

To achieve the aim, the following objectives were accomplished:

– to perform computer modeling and analysis of the effect of changes in TF parameters and reproduction errors of normalized quantities on the result of redundant measurements with a quadratic transformation function;

– to perform computer modeling of multiple measurements with a quadratic transformation function using the first approach with changes in TF parameters and with selected reproduction errors of normalized quantities;

– to perform computer modeling of multiple measurements with a quadratic transformation function using the second approach under conditions similar to the first approach;

– to make a comparative analysis of the results obtained when applying the two proposed approaches.

4. Materials and methods

4. 1. Object and hypothesis

The object of the study is multiple measurements.

The hypothesis of the study is that processing the results of multiple measurements by the proposed algorithms will help to increase the measurement accuracy by reducing not only the systematic, but also the random component of the measurement error.

Accepted assumptions and simplifications – during the measurement cycle consisting of 5 measuring steps, the change in the parameters of the transformation function remains constant.

4. 2. Modeling materials and tools

In the study of multiple measurements, as a sensor with a quadratic transformation function, a silicon bipolar transistor KT3132 A-2 (Ukraine) was used.

Mathcad 15.0 (USA) was chosen as a software tool for mathematical modeling and analysis of the results, and the MS Excel data analysis package (USA) was used for statistical data processing.

4. 3. Method of studying redundant measurements with a quadratic transformation function

As is known [21], the equation describing the dependence of the transistor base-emitter voltage on temperature has the following form:

$$U'_{bet}=U'_{bet0}-\Delta U'_A T_x-\Delta U'_B T_x{}^2, \tag{1}$$

where U'_{bet0} – the value of the base-emitter voltage at t=0 °C;

$\Delta U'_A$ – the linear coefficient of base-emitter voltage change as a function of temperature;

$\Delta U'_B$ – the quadratic coefficient of base-emitter voltage change as a function of temperature;

T_x – the value of the desired temperature.

In the equation of quantities (1), the value of the desired quantity T_x depends on the values of the parameters $\Delta U'_A$, $\Delta U'_B$, U'_{bet0} of the nonlinear transformation function (TF), and therefore on their deviations from the nominal values. This dependence of the measurement result on changes in the TF parameters contributes to an increase in systematic error, which negatively affects the measurement quality. In addition, direct application of a non-linear transformation function requires measures to linearize it, leading to nonlinearity error or requires work on the linear part of the sensor input characteristic, which limits the measurement range.

To comprehensively solve the problem of increasing the accuracy of measurement with a non-linear and unstable transformation function, methods of redundant measurements (MRM) were proposed. One of the necessary conditions for the implementation of MRM is the measurement, in addition to the desired physical quantity, of several normalized physical quantities, which have the same physical nature as the desired one and are in a certain regularity with it. Thus, there is a need to perform several measurement steps that make up a measurement cycle. The mathematical model of MRM is a system of equations of quantities, where each of the equations describes the measurement step, as well as the equation of redundant measurements of the desired physical quantity, which is obtained as a result of solving this system.

As a result of research conducted in [20], a system of equations of quantities describing five measurement steps was chosen:

$$\begin{cases} U'_{bet1}=U'_{bet0}-\Delta U'_A T_1-\Delta U'_B T_1^2; \\ U'_{bet2}=U'_{bet0}-\Delta U'_A T_2-\Delta U'_B T_2^2; \\ U'_{bet3}=U'_{bet0}-\Delta U'_A T_x-\Delta U'_B T_x^2; \\ U'_{bet4}=U'_{bet0}-\Delta U'_A 2T_1-\Delta U'_B \left(2T_1\right)^2; \\ U'_{bet5}=U'_{bet0}-\Delta U'_A \left(T_1+T_x\right)-\Delta U'_B \left(T_1+T_x\right)^2; \end{cases} \tag{2}$$

where U'_{beti} – voltage in each i-th (i=(1÷5)) measurement step;

T_1 and T_2 – normalized temperatures, formed using standard sources with normalized characteristics.

The solution of system (2) is the equation of redundant measurements of the desired temperature T_x:

$$T_x=\frac{\left(U'_{bet5}-U'_{bet3}\right)\left(3T_1T_2-2T_1^2-T_2^2\right)-\left(U'_{bet4}-U'_{bet1}\right)\left(T_1T_2-T_2^2\right)-2T_1^2\left(U'_{bet2}-U'_{bet1}\right)}{2\left(T_2-T_1\right)\left(U'_{bet4}-U'_{bet1}\right)-T_1\left(U'_{bet2}-U'_{bet1}\right)}. \tag{3}$$

The value of the desired temperature found by the equation of redundant measurements (3) does not depend on the values of the parameters $\Delta U'_A$, $\Delta U'_B$, U'_{bet0} and their deviations from the nominal values. In addition, the redundant measurement equation (3) is applied directly to the quadratic transformation function without additional linearization, which also contributes to increasing the accuracy of MRM. However, it should be noted that such results are obtained if changes in the parameters of the quadratic transformation function remain constant during five measurement steps.

4. 4. Method of studying multiple measurements

The presented mathematical model of MRM, described by the system (2) and equation (3), is used when the random error component is insignificant. In the presence of significant random errors or the need to conduct multiple measurements in order to control a physical quantity, two approaches are used in the theory of redundant measurements [14, 18]. These approaches differ in the method of processing the results of multiple measurements. So, in the first approach, the value of the desired quantity is found by averaging its values obtained by the redundant measurement equation for n measurement cycles. In the second approach, the voltage values in each step over n measurement cycles are first averaged, and the results are substituted into the redundant measurement equation. Thus, the redundant measurement equation of the desired temperature T_x for the first approach has the following form:

$$T_x=\sum_{i=1}^{n}T_{xi}=$$
$$=\frac{\sum\limits_{i=1}^{n}\frac{(U'_{beti5}-U'_{beti3})(3T_1T_2-2T_1^2-T_2^2)-(U'_{beti4}-U'_{beti1})(T_1T_2-T_2^2)-2T_1^2(U'_{beti2}-U'_{beti1})}{2(T_2-T_1)(U'_{beti4}-U'_{beti1})-T_1(U'_{beti2}-U'_{beti1})}}{n}. \quad (4)$$

The redundant measurement equation of the desired temperature T_x for the second approach has the following form:

$$T_x=$$
$$=\frac{\left(\sum\limits_{i=1}^{n}U'_{beti5}-\sum\limits_{i=1}^{n}U'_{beti3}\right)(3T_1T_2-2T_1^2-T_2^2)-\left(\sum\limits_{i=1}^{n}U'_{beti4}-\sum\limits_{i=1}^{n}U'_{beti1}\right)(T_1T_2-T_2^2)-2T_1^2\left(\sum\limits_{i=1}^{n}U'_{beti2}-\sum\limits_{i=1}^{n}U'_{beti1}\right)}{2(T_2-T_1)\left(\sum\limits_{i=1}^{n}U'_{beti4}-\sum\limits_{i=1}^{n}U'_{beti1}\right)-T_1\left(\sum\limits_{i=1}^{n}U'_{beti2}-\sum\limits_{i=1}^{n}U'_{beti1}\right)}. \quad (5)$$

As can be seen from the redundant measurement equations (4) and (5), standard methods of statistical data processing are used to determine the desired temperature T_x during multiple measurements, which makes MRM flexible for application.

5. Results of computer modeling to increase the accuracy of multiple measurements

5. 1. Computer modeling and analysis of the influence of the reproduction error of normalized quantities

Computer modeling was performed in the Mathcad 15 environment for the KT3132 A-2 transistor [21] with a measurement range from 10 °C to 200 °C, U_{bet0}=0.6 V and at ΔU_A=1.882 mV/°C, ΔU_B=0.41 μV/°C^2.

Based on the recommendations given in [20], T_x=100 °C was set as the desired value, and the values of normalized temperatures, respectively, $T_1=T_x(0.0005\cdot T_x+1)$=105 °C and T_2=10 °C. Limits of change for the parameters $\Delta U'_A$, $\Delta U'_B$, U'_{bet0}, lying within ±1.0 % were also set for computer modeling, and the values of the reproduction error of normalized temperatures T_1 and T_2 were chosen at +0.1 % and –0.1 %. As a result of computer modeling, it was found that the relative measurement error δ is 0.1 %. Increasing change limits for the parameters $\Delta U'_A$, $\Delta U'_B$, U'_{bet0} from ±1.0 % to ±10.0 % does not change the values of the relative measurement error δ.

The effect of reproduction errors of normalized temperatures T_1 and T_2 was investigated. Studies were carried out with a change in the parameters $\Delta U'_A$, $\Delta U'_B$ and U'_{bet0}, lying within ±1.0 %. An increase in the reproduction error of normalized temperature T_1 from ±0.1 % to ±0.2 % leads to an increase in the relative measurement error δ from 0.1 % to 0.2 %. However, an increase in the reproduction error of normalized temperature T_2 from ±0.1 % to ±0.2 % leads to a decrease in the relative measurement error δ from 0.1 % to 0.088 %. A further increase in the reproduction error of normalized temperature T_2 to ±0.5 % leads to a decrease in the relative measurement error δ already to 0.05 %. An increase in the reproduction error of normalized temperature T_2 to ±1.0 % leads to a decrease in the relative measurement error δ already within (0.009÷0.010) %. However, increasing the reproduction error of normalized temperature T_2 to ±2 % already leads to an increase in the relative error δ within (0.12÷0.13) %.

In addition, it was found that a simultaneous increase in the reproduction errors of both normalized temperatures T_1 and T_2 from ±0.1 % to ±0.2 % leads to an increase in the relative measurement error δ from 0.1 % to 0.2 %.

The studies revealed that the best results in accuracy were obtained with a reproduction error of normalized temperature T_1 at ±0.1 % and temperature T_2 at ±1.0 %. That is, when applying MRM with a quadratic transformation function, high accuracy requirements can be imposed only on the reproduction source of normalized temperature T_1. On the other hand, high accuracy requirements may not be applied to the reproduction source of normalized temperature T_2.

Studies on the effect of instability of TF parameters on the measurement result with a reproduction error of normalized temperature T_1 of ±0.1 % and temperature T_2 of ±1.0 % were also carried out. It was found that a further increase in changes the parameters $\Delta U'_A$, $\Delta U'_B$ to ±10 % and the parameter U'_{bet0} within ±1.0 % does not lead to an increase in the measurement error. That is, the value of the relative error δ does not change and remains within (0.009÷0.010) %. In addition, it was found that increasing the value of changes in the parameter U'_{bet0} up to ±10 % also does not lead to an increase in the measurement error. It should be noted that such results are obtained when, during the measurement cycle consisting of 5 measurement steps, the change in the parameters remains constant.

To determine the effect of the parameters of the transformation function on the relative measurement error, a graph of such dependence was plotted (Fig. 1). When constructing the graph, reproduction errors of normalized temperature T_1 were chosen at the level of ±0.1 % and temperature T_2 at ±0.5 %. On the graph (Fig. 1), along the z-axis there are values of the relative error δ (%), along the i- and j-axes – ordinal numbers of changes in the parameters, respectively $\Delta U'_B$ and $\Delta U'_A$. Moreover, the change in the parameter $\Delta U'_B$

from the nominal value occurs in the range from –10 % to +10 %, and the change in the parameter $\Delta U'_A$ in the range from –10 % to +10 %.

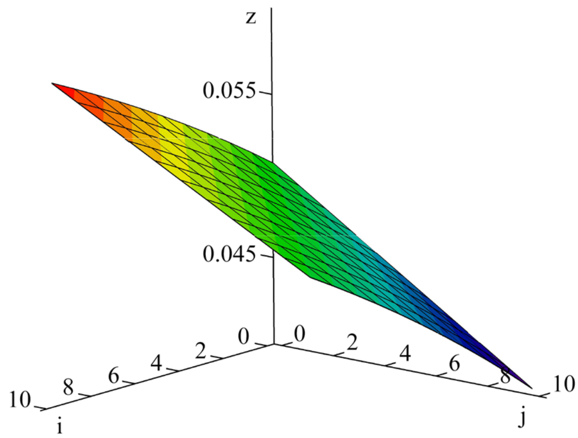

Fig. 1. Graph of the relative measurement error against changes in the parameters of the transformation function with a reproduction error of normalized temperature T_2 at the level of ±0.5 %

From the given graph (Fig. 1), it can be seen that the influence of the parameter $\Delta U'_B$ is more significant than that of the parameter $\Delta U'_A$. The best results in terms of measurement accuracy occur when the parameter $\Delta U'_B$ is changed by –1.0 % and the parameter $\Delta U'_A$ is changed by +10 %.

Further studies showed that the reproduction error of normalized temperature T_2 at the level of ±1.0 % leads to a change in the graph of the functional dependence of the relative measurement error on changes in the parameters of the transformation function (Fig. 2).

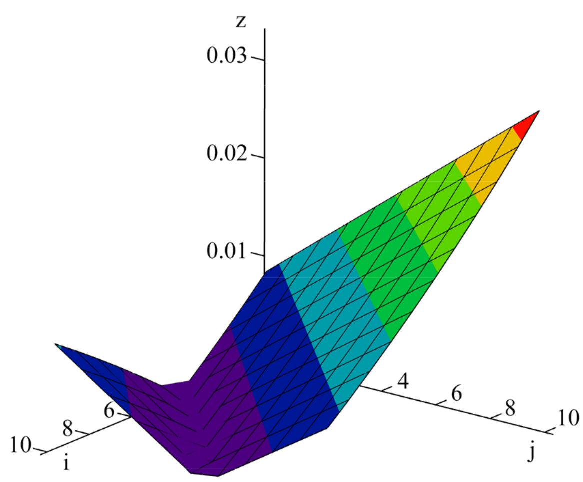

Fig. 2. Graph of the relative measurement error against changes in the parameters of the transformation function with a reproduction error of normalized temperature T_2 at the level of ±1.0 %

From the given graph (Fig. 2), it can be seen that the growth of the reproduction error of normalized temperature T_2 leads to changes in the dependence of the relative measurement error on changes in the parameters of the transformation function. The best results in terms of measurement accuracy (δ=0.0002 %) are obtained when the parameter $\Delta U'_B$ is changed by –1.0 % and the parameter $\Delta U'_A$ is changed by –10 %.

Thus, from the above graphs (Fig. 1, 2), it can be seen that the measurement error is more influenced by the reproduction error of normalized temperatures T_1 and T_2 than by the change in the parameters $\Delta U'_A$, $\Delta U'_B$. So, further research was aimed at determining this dependence.

As a result of computer modeling, a graph of the functional dependence of the relative measurement error on the reproduction errors of normalized temperatures T_1 and T_2 was also built (Fig. 3). Calculations were performed when the parameters $\Delta U'_A$, $\Delta U'_B$ and U'_{bet0}, lying within ±10.0 % were changed. In Fig. 3, along the z-axis there are the values of the relative measurement error, along the *i*-axis and *j*-axis – the corresponding ordinal numbers of changes in the reproduction errors of normalized temperatures T_1 and T_2. It is noted that the change in the reproduction error of normalized temperature T_1 occurs in the range from –0.1 % to +0.1 % and temperature T_2 from –0.5 % to +0.5 %.

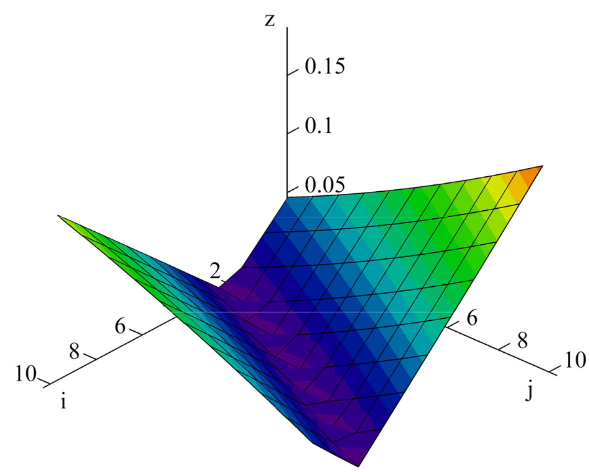

Fig. 3. Graph of the relative measurement error against the reproduction errors of normalized temperatures T_1 and T_2 (when T_2 changes within ±0.5 %)

It was determined that the minimum value of the relative measurement error (δ=0.0003 %) is obtained when the value of the reproduction error of normalized temperature T_1 is within (+0.046) % and temperature T_2 within (+0.41) %.

A surface graph (Fig. 4) of the functional dependence of the relative measurement error on the reproduction errors of normalized temperatures T_1 and T_2 was also constructed. In Fig. 4, along the z-axis there are the values of the relative measurement error, along the *i*-axis and *j*-axis – the corresponding ordinal numbers of changes in the reproduction errors of normalized temperatures T_1 and T_2. Moreover, the change in the reproduction error of normalized temperature T_1 occurs in the range from –0.1% to +0.1 % and temperature T_2 from –1.0 % to +1.0 %.

From the given graph (Fig. 4), it can be seen that the best results in terms of measurement accuracy occur with symmetrical changes in the reproduction errors of normalized quantities T_1 and T_2. It was determined that the minimum value of the relative measurement error (δ=0.0013 %) is obtained when the value of the reproduction error of normalized temperature T_1 is within (–0.048) % and temperature T_2 within (–0.043) %.

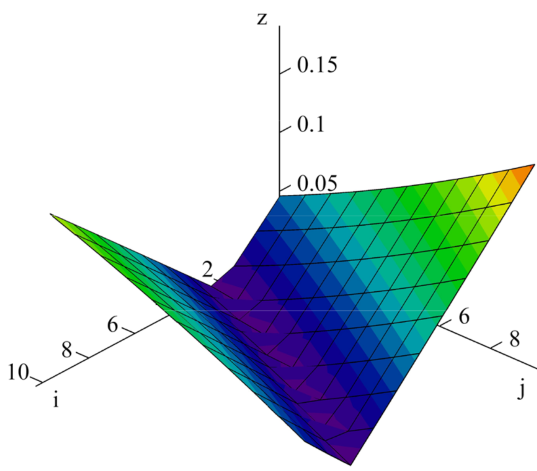

Fig. 4. Graph of the relative measurement error against the reproduction errors of normalized temperatures T_1 and T_2 (when T_2 changes within ±1.0 %)

Thus, it was found that the result of redundant measurements is more affected by the reproduction errors of normalized temperatures T_1 and T_2 than by changes in the TF parameters. In addition, it can be seen from the given data that the best results in terms of accuracy are obtained when the temperature T_2 changes within ±0.5 %.

5. 2. Computer modeling using the first approach

It was found that the accuracy of measurements when using MRM is affected by reproduction errors of normalized temperatures T_1 and T_2, as well as changes in the TF parameters under the influence of the environment. To reduce the influence of these errors, especially, in multiple measurements, an algorithm for processing measurement results, represented by expression (4), is proposed.

Computer modeling according to the first approach was carried out when the parameters $\Delta U'_A$, $\Delta U'_B$ and U'_{bet0}, lying within ±10.0 % were changed, and with the reproduction error of normalized temperatures: T_1 within ±0.1 % and T_2 within ±0.5 %. Also, in the computer modeling of multiple measurements according to the redundant measurement equation (4), 144 measurement cycles (n=144) were used. Moreover, each such cycle consists of determining the values of five output voltages U'_{bet1}, U'_{bet2}, U'_{bet3}, U'_{bet4}, U'_{bet5} of the system of equations of quantities (2). As a result, 144 values of the desired temperature T_{xi} were obtained. The obtained statistical data were exported to Excel, where their average value was found according to the redundant measurement equation (4).

Thus, when processing the results of the first approach, the value of the desired temperature T_x was obtained, which is 100.003 °C, and, accordingly, the value of the relative error δ is 0.003 %.

Computer modeling carried out with a reduced number of measurement cycles n=36 showed that the value of the desired temperature T_x is 100.007 °C, and the value of the relative error δ is 0.007 %. This confirms the classical application of statistical data processing methods when using MRM.

Studies were also conducted at the reproduction error of normalized temperature T_2 within ±1.0 % and with the number of measurement cycles n=144. When processing the results of the first approach, the value of the desired temperature T_x was obtained, which is 100.01 °C, and, accordingly, the value of the relative error is 0.01 %.

Thus, when performing multiple measurements using the first approach, it is recommended to choose a reproduction source of normalized temperature T_2 with an error within ±0.5 % and temperature T_1 – no more than ±0.1 %.

5. 3. Computer modeling using the second approach

For computer modeling by the second approach, changes in the parameters $\Delta U'_A$, $\Delta U'_B$ and U'_{bet0}, lying within ±10.0 % similar to the first approach were set. In addition, reproduction errors of normalized temperatures were set: T_1 within ±0.1 % and T_2 within ±0.5 %. Processing of multiple measurements was carried out according to the redundant measurement equation (5). During the calculations, 144 measurement steps (n=144) were also selected, and each value of the output voltages U'_{beti} of the system of equations of quantities (2) was measured 144 times. The obtained statistical data for each of the output voltages U'_{beti} were exported to Excel, where their average values were found: $\bar{U}'_{bet1}=0.80585$ V, $\bar{U}'_{bet2}=0.99095$ V, $\bar{U}'_{bet3}=0.81578$ V, $\bar{U}'_{bet4}=0.59256$ V, and $\bar{U}'_{bet1}=0.60293$ V. After substituting the obtained average voltage values into equation (5), the value of the desired temperature T_x=99.946 °C and the corresponding value of the relative error δ of 0.054 % were obtained.

In addition, the second approach revealed a certain feature – dependence of the measurement result on the digit range of the average voltage values $\left(\bar{U}'_{beti}\right)$. It was found that the reduction of the average voltage values from five to four decimal places leads to an increase in the value of the desired temperature T_x from 99.946 °C to 101.518 °C. Thus, at $\bar{U}'_{bet1}=0.8058$ V, $\bar{U}'_{bet2}=0.9909$ V, $\bar{U}'_{bet3}=0.8158$ V, $\bar{U}'_{bet4}=0.5926$ V, and $\bar{U}'_{bet1}=0.6029$ V, the value of the relative error δ increased from 0.054 % to 1.518 %. Further reduction of the digit range to three decimal places leads to a further increase in the value of the desired temperature T_x from 99.946 °C to 105 °C and a relative error to 5 %.

Studies were conducted under the condition that the reproduction error of normalized temperature T_2 is ±1.0 %, and the number of measurement steps is 144, i.e. n=144. After exporting the obtained output voltage values to Excel, their average values were found: $\bar{U}'_{bet1}=0.89585$ V, $\bar{U}'_{bet2}=1.08093$ V, $\bar{U}'_{bet3}=0.90578$ V, $\bar{U}'_{bet4}=0.68256$ V, and $\bar{U}'_{bet1}=0.69293$ V. After substituting the obtained average values into equation (5), the value of the desired temperature T_x=99.959 °C and the corresponding value of the relative error δ of 0.041 % were obtained. Decreasing the average voltage values to four decimal places also leads to an increase in the value of the desired temperature T_x from 99.959 °C to 101.518 °C and the value of the relative error δ from 0.041 % to 1.518 %. Further reduction of the digit range to three decimal places leads to an increase in the relative error to 5 %. The same value of the relative error is obtained when the reproduction error of normalized temperature T_2 is ±0.5 %.

Thus, the digit range of the average voltage values when applying the second approach significantly affects the measurement accuracy.

5. 4. Comparative analysis of the two approaches

The comparison of the obtained results of multiple measurements by the two approaches, described by the redundant measurement equations (4) and (5), was carried out according to the following criteria:

1) measurement accuracy;

2) use of high-precision measuring devices;

3) reliability of implementation.

When considering the first approach described by the redundant measurement equation (4), the criteria for its evaluation are as follows:

1) the relative measurement error δ of temperature for 144 measurement cycles at the reproduction error of normalized temperature T_2 within ±0.5 % is 0.003 %. At the reproduction error of normalized temperature T_2 within ±1.0 %, the relative measurement error δ is 0.01 %;

2) when determining the desired temperature value by the first approach, there is no need to apply high-precision measuring devices. This is due to the fact that the value of the desired temperature, calculated by the redundant measurement equation (4), does not depend on the digit range of the intermediate values;

3) to implement the first approach, you need to have statistical data for a certain number of measurement cycles. So, the more statistics, the higher the accuracy. However, even with an unplanned stoppage of the measurement process (accident, breakdown, etc.), certain statistical data will be available for processing, which makes the first approach reliable for implementation.

When considering the criteria of the second approach described by the redundant measurement equation (5), the following can be distinguished:

1) the relative measurement error δ of temperature for 144 measurement steps with the reproduction error of normalized temperature T_2 within ±0.5 % is 0.054 %. The relative measurement error δ with the reproduction error of normalized temperature T_2 within ±1.0 % is 0.041 %;

2) when measuring by the second approach, there is a need to use high-precision measuring devices, since the accuracy of the measurement result also depends on the digit range of the calculated average voltages. When applying the second approach, it is necessary to obtain the values of average voltages with an accuracy of up to the fifth decimal place;

3) the reliability of the second approach is inferior to the first approach. This is due to the fact that in the event of an unplanned stoppage of the measurement process, all the necessary data for calculating the desired temperature value will not be available.

Thus, analyzing all the presented evaluation criteria for the proposed approaches, it can be concluded that the first approach is promising compared to the second one in determining the desired temperature value in multiple measurements with high accuracy.

6. Discussion of the results of computer modeling of multiple measurements with a quadratic transformation function

During the computer modeling of MRM with a quadratic TF, as follows from the results (Fig. 1), it was found that among the TF parameters, the greatest influence is exerted by the parameter $\Delta U'_B$. According to the authors, this is due to its location in the equation of quantities (1). In addition, it was found that increasing the value of the parameter U'_{bet0} from ±1 % to ±10 % does not lead to an increase in the measurement error. Obviously, this becomes possible due to the application of the redundant measurement equation (3), where the additive component of the measurement error is eliminated as a result of the operation of subtracting the output voltages. This does not differ from the practical data given in [12], the authors of which also associate the improvement of measurement accuracy with the method of processing measurement results.

When investigating the effects of reproduction errors of normalized temperatures T_1 and T_2, as follows from the results (Fig. 1, 2), it was found that they have a greater influence on the measurement error than the change in the parameters $\Delta U'_A$, $\Delta U'_B$ and U'_{bet0}. In this sense, the interpretation of the results given in Fig. 3, 4 is of particular interest, which confirms the influence of reproduction errors of normalized temperatures T_1 and T_2 on the measurement result. It was found that the best accuracy results are obtained with a reproduction error of normalized temperature T_2 within ±0.5 %, and temperature T_1 – with an error of no more than ±0.1 %. This means that when applying MRM with a quadratic transformation function, high accuracy requirements are imposed only on the source of reproduction of normalized temperature T_1, which requires certain material costs. This does not differ from the practical data given in [9, 10], where the increase in accuracy due to the use of exemplary sources also leads to an increase in material costs. However, it should be noted that high accuracy requirements cannot be applied to the reproduction source of normalized temperature T_2. This makes it possible to choose a non-high-precision source of reproduction of normalized temperature T_2 and thereby reduce the cost of the measurement process.

In the study of multiple measurements, two approaches to processing measurement results were proposed, as in [18]. In this sense, the interpretation of the results with the quadratic transformation function, which was studied in [20], is of particular interest. It is shown that due to processing the measurement results according to equations (4), (5), the measurement accuracy is increased by eliminating the systematic error component caused by changes in the parameters of the transformation function, as well as reducing the random error component. A comparison of the results of multiple measurements by two approaches allows us to assert that the first approach using equation (4) is promising compared to the second approach applying the redundant measurement equation (5). This does not differ from the practical data given in [18], where they also associate an increase in the accuracy of multiple measurements with the determination of the desired value through averaging its values over n measurement cycles. The feature of the second approach should be noted, in which the measurement accuracy will increase with an increase in the accuracy of measuring devices or with a decrease in the accuracy of the reproduction source of normalized temperature T_2.

Such conclusions can be considered appropriate from a practical point of view, because they allow a reasoned approach to increasing the accuracy of multiple measurements using redundancy. Moreover, it was found that the use of MRM in multiple measurements can reduce the accuracy requirements for the source of reproduction of normalized temperature T_2, which helps to reduce material costs for implementation. In addition, the application of the redundant measurement equation (3) ensures the independence of the measurement results from the parameters of the transformation function and their deviations from the nominal values. This is manifested in the possibility of using inexpensive transistors (sensors) without high requirements for their stability. From a theoretical point of view, MRM allow us to state that processing the results of multiple measurements with a quadratic TF using two approaches increases the measurement accuracy without additional measures to linearize it. This advantage is manifested primarily when using the first approach, which provides a relative measurement error of 0.003 %. However, it should be noted that such high accuracy results are obtained when the change in parameters remains constant during the measurement cycle consisting of 5 measuring steps. The impossibility to remove the mentioned restrictions within the framework of this study gives rise to a potentially interesting direction for further research. In particular, it can be focused on identifying new systems and corresponding equations of redundant measurements. Such detection will allow using MRM in complex and rapidly changing process conditions while ensuring high measurement accuracy.

7. Conclusions

1. Based on the mathematical model of MRM, computer modeling of the effect of changes in the TF parameters and reproduction errors of normalized quantities on the result of redundant measurements with a quadratic transformation function was carried out. It was found that among the TF parameters, a greater influence on the measurement error is exerted by the parameter $\Delta U'_B$. It was found that the result of redundant measurements is more influenced by the reproduction errors of normalized temperatures T_1 and T_2 than by changes in the TF parameters. The effect of reproduction errors of normalized temperatures T_1 and T_2 was investigated. The studies revealed that the best accuracy results were obtained with the reproduction error of normalized temperature T_1 within ±0.1 % and temperature T_2 within ±1.0 %. Thus, it can be stated that when applying MRM with a quadratic transformation function, high accuracy requirements can be imposed only on the source of reproduction of normalized temperature T_1. On the other hand, high accuracy requirements may not be applied to the source of reproduction of normalized temperature T_2.

2. Computer modeling of multiple measurements with a quadratic transformation function using the first approach with changes in the TF parameters and selected reproduction errors of normalized quantities was carried out. The feature of processing the results of multiple measurements by the first approach is the averaging of the values of the desired quantity obtained according to the redundant measurement equation (4) for n measurement cycles.

In computer modeling, two options were considered: with a reproduction error of normalized temperature T_2 within ±1.0 % and ±0.5 %. Each of the options was carried out with the number of measurement cycles of 144 (n=144) and 36 (n=36). As a result of the calculations, it was found that with the reproduction error of normalized temperature T_2 within ±0.5 %, the relative error is 0.003 % at n=144. Moreover, it was found that reducing the number of measurement cycles to 36 leads to a slight increase in the measurement error to 0.007 %. This testifies to the classical application of statistical data processing methods when using MRM. Computer modeling with a reproduction error of normalized temperature T_2 within ±1.0 % (at n=144) showed an increase in the measurement error to 0.01 %. Thus, it can be stated that when making multiple measurements, it is recommended to choose a source of reproduction of normalized temperature T_2 with an error within ±0.5 %.

This allows us to assert the effectiveness of the proposed first approach, which is manifested in a decrease in the accuracy of multiple measurements by an order of magnitude compared to the result obtained during only one measurement cycle.

3. Computer modeling of multiple measurements with a quadratic transformation function using the second approach under similar conditions was carried out. The peculiarity of the second approach is the averaging first of the voltage values in each step for n measurement cycles, which are then substituted into the redundant measurement equation (5).

In the calculations by the second approach, options of the reproduction error of normalized temperature T_2 within ±1.0 % and ±0.5 % were also considered. Similar studies were conducted under the condition that the reproduction error of normalized temperature T_2 is ±0.5 %, and the number of measurement steps is 144, i.e. n=144. As a result of the calculations, the relative error value of 0.054 % was obtained. With the reproduction error of normalized temperature T_2 within ±1.0 %, a relative error of 0.041 % was obtained. Thus, in contrast to the first approach, it is recommended to choose a reproduction source of normalized temperature T_2 with an error within ±1.0 %.

The studies of the second approach revealed its peculiarity, namely sensitivity to the accuracy of measuring devices. This is manifested in the dependence of the measurement result on the digit range of intermediate measurements.

Thus, when applying the second approach, on the one hand, it is possible to use a non-high-precision source of reproduction of normalized temperature T_2, but, on the other hand, to use high-precision measuring devices. This indicates the variability of the second approach depending on the available equipment.

4. A comparative analysis of the two proposed approaches was carried out, in accordance with criteria for evaluating their results on accuracy, reliability and the necessity to use high-precision measuring devices. It was found that when determining the desired temperature value in multiple measurements with high accuracy, the first approach has priority over all three criteria compared to the second one.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this study, including financial, personal, authorship, or any other, that could affect the study and its results presented in this paper.

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Data availability

Data can be provided upon reasonable request.

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