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Computer Implementation of Algorithmic Components of Redundant Measurement Methods

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***Abstract*—**This article demonstrates the implementation of the proposed algorithm for computer modeling of redundant measurement methods to solve problems to improve the accuracy of measurements of a controlled quantity with a nonlinear and unstable transformation function. Improving accuracy is achieved by processing the results of redundant measurements which are an array of data according to the proposed measurement equations. In addition, the article presents the possibility of determining the time variation of the parameters of the transformation function. A comparative analysis of the results of computer simulation of redundant and direct methods with unstable parameters of the linear and nonlinear sensor transformation functions is carried out. It was proved that, in the case of an increase in deviations of the parameters of the transformation function from the nominal values, the use of redundant methods provides a significantly higher measurement accuracy compared to direct methods. This became possible due to the automatic elimination of the systematic component of the error of the measurement result due to a change in the parameters of the transformation function under the influence of destabilizing factors. It was also found that, in contrast to direct methods, methods of redundant measurements allow working with a nonlinear transformation function without additional linearization or dividing it into linear sections, which also contributes to increased accuracy.

In general, the application of the proposed approach in the modeling system proves its effectiveness and feasibility.

Thus, there is reason to argue about the prospects of redundant measurements in the field of improving accuracy with a nonlinear and unstable transformation function, as well as the possibility of identifying deviations of the parameters of the transformation function from their nominal values.

***Index Terms*—**Computer simulation, redundant measurements, mathematical model, increasing accuracy, function instability, parameter prediction.

I. Introduction

In the automation of any technological process, as you know, it is necessary to strictly observe the conditions for its implementation. Even a slight deviation from the established rules and regulations can lead to unreliability of the measurement result obtained, to product rejection, and in some cases even to an accident. Improving control systems is impossible without increasing the reliability of technical means of measurement and control. One of the main conditions for obtaining reliable information about a controlled quantity is the accuracy of its measurement. Therefore, the accuracy and reliability of the information received from sensors or control systems determines the effectiveness of the entire process.

In this regard, the task of increasing the accuracy of measurement in difficult conditions of the technological process remains relevant.

One of the main reasons for the appearance of measurement errors is the deviation of the parameters of the sensor transformation function (or the measuring channel with the sensor) from their nominal values under the influence of external destabilizing factors (temperature, pressure, ionizing radiation, etc.). Therefore, in real conditions, the values of the parameters of the transformation function (TF) differ from their nominal values, which leads to a decrease in the measurement accuracy. To do this, periodically calibrate the sensors, which requires material (especially with a large number of production sensors), time costs, or leads to a delay in the process. According to [1], about 12% of the measuring instruments arriving for calibration have an unacceptable error. Many scientific works were directed to overcome these problems [2–6].

In addition, the nonlinearity of the transformation function affects the measurement accuracy. So, with the non-linear function of the sensor conversion, it is necessary to linearize it, which leads to the appearance of an additional error from linearization. The issues of combating non-linearity were considered, for example, in the article [7], which proposed a high-precision calibration method based on linearity adjustment. Existing methods and approaches do not provide a comprehensive solution to the measurement problem. If linear methods ignore the nonlinearity problem, then nonlinear methods can cause the problem of re-equipment during the calibration process, which can also serve as a decrease in accuracy. Thus, studies aimed at improving the accuracy of measurements with unstable parameters of the transformation function with the possibility of analyzing the parameters of the transformation function should be considered relevant. Therefore, a new approach was chosen - the use of redundancy to obtain accurate information with the ability to determine the nature and rate of change in time of the characteristics of the transformation function. When applying the method of redundant measurements, an increase in accuracy is achieved due to the automatic elimination of the systematic component of the error in the measurement result due to changes in the parameters of the transformation function under the influence of destabilizing factors. In addition, MRM provide the opportunity to obtain the values of the parameters of the transformation function, which allows you to determine their deviation from the permissible values and, thus, to predict the adequacy of the use of this transformation function.

The aim of the work is: 1) to increase the accuracy of measuring physical quantities based on redundant measurements by increasing the resistance to changes in the parameters of the sensor transformation function; 2) providing the ability to determine the parameters of the transformation function.

To achieve this goal it is necessary: 1) to submit an algorithm for the operation of redundant measurements; 2) to develop a mathematical model of redundant measurements, with the help of which it is possible to obtain equations of redundant measurements of both the desired value and the parameters of the sensor transformation function; 3) show the advantages of the methods of redundant measurements in the field of increasing the accuracy of measurements with unstable parameters of the sensor transformation function.

A review of the works related to improving the measurement accuracy and the possibility of determining the parameters of the transformation function will be discussed in Section 2. The proposed algorithmic component of the method of redundant measurements is explained in Section 3. The development of mathematical models of redundant measurements with linear and polynomial transformation functions is described in Section 4. Computer modeling and their study is given in section 5. Conclusions on the results of the simulation and research are given in times case 6.

II. Literature Review

Improving the accuracy of the measurement result is one of the important tasks for mathematical and algorithmic methods of data processing.

Many scientific works are directed to solving problems of increasing the accuracy of measurements. For example, works [2–4] are aimed at reducing the influence of environmental factors on the measurement result. In [5], an increase in the measurement accuracy was achieved by introducing a calibration coefficient, and in [6], by applying statistical processing of multiple measurements. In [8], an approach is proposed to increase accuracy by combining the method of infinite integrals with the Boltzmann method due to their characteristics with opposite errors. However, the indicated works did not take into account the influence of noise and distortion that arise in interface circuits under the influence of changes in the external environment. As a result, the performance of any measuring system is greatly degraded. Ways to reduce the effect of noise on the signal throughout the system were considered in [9]. In this paper, by using corrective methods and filters, an increase in the measurement accuracy was achieved. However, the issue of improving the accuracy of measurements with non-linear characteristics of the sensors remained unresolved. So, in [10], the problem of compensating for the nonlinearity of a transformation function using a radial basis artificial neural network was considered, since neural networks are nonlinear in nature and have good approximating properties. It is also proposed to use the method of multi-segment approximation of the transformation characteristics of a microprocessor sensor to reduce the measurement error in nonlinear TF of transitions [11, 12]. In these works, the TF is replaced by a system of local surfaces so that they repeat its spatial configuration. However, in these studies, it is proposed to use an approximating local surface, which also introduces additional errors from the approximation of the TF. In addition, the indicated works did not show the possibility of obtaining the independence of the measurement result from the instability of the parameters of the TF under the influence of external destabilizing factors, as well as the possibility of determining the parameters of the TF.

Therefore, to comprehensively solve the problem of increasing the measurement accuracy with a nonlinear and unstable transformation function, it was proposed to use the method of redundant measurements [13–16]. A distinctive feature of the use of MRM is to obtain redundancy and process the obtained measurement results according to the equations of redundant measurements.

III. Algorithm for Redundant Measurements

The application of the method of redundant measurements (MRM) occurs in a mode that does not interrupt the measurement process, based on structural, temporal or functional redundancy. In the general case, for their implementation, MRM require additional measurement steps, in which, in addition to the measured value, several, normalized by value, quantities of the same physical nature are measured. As a result of such measurement clocks, a system of equations of quantities is obtained, each of which describes the state of the measuring channel (or sensor) at discrete time instants. The subsequent solution of this system makes it possible to derive the equation of redundant measurements of the desired physical quantity (DPQ) and parameters of the transformation function (TF). As will be proved below, the equation of redundant measurements of a controlled quantity is obtained invariant to the spread of the parameters of the transformation function. In turn, the equation of redundant measurements of the parameters of the transformation function allows you to find the values of these parameters, which are compared with their nominal values. Based on the results of this analysis, we can conclude that they are deviated.

The algorithm of the MRM will look like this, presented in in Fig. 1.

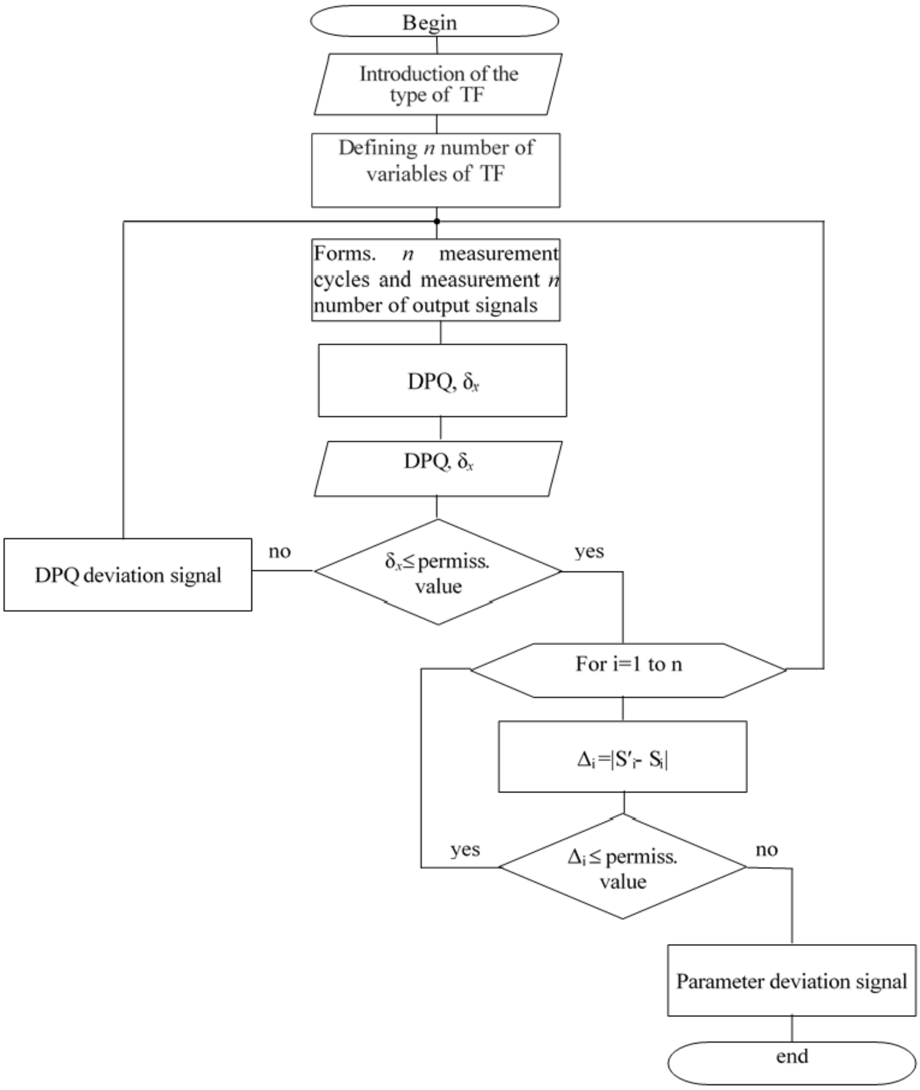

Fig.1. Algorithm of MRM

Consider the main stages of the MRM algorithm.

1. The type of the TF and the number n of unknown parameters of the TF are determined.
2. A system is made up of such a number of equations in order to derive n or more number of measurement equations. The number of equations depends on the number of possible ways to form redundancy and on the complexity of the type of TF.
3. The equation for measuring the desired physical quantity (DPQ) is derived.
4. Displays the measurement equation for each of the

parameters of the TF.

5. Compare the obtained values of the DPQ with the specified.

6. Compares the obtained values of the parameters of the TF with their values.

7. According to the results obtained in Clause 5 and Clause 6, decisions are made to adjust the technological process or to replace the sensor.

Based on the proposed algorithm, we will develop mathematical models that underlie the method of redundant measurements.

IV. Development of Mathematical Models of Redundant Measurements with Linear and Polynomial Transformation Functions

The proposed MRM is based on the mathematical features of the transformation of the measured value. Based on the proposed algorithm, we will develop a mathematical model of the MRM. For the study, we take the linear and nonlinear (polynomial) TF.

A. Study of linear TF

As is known, the mathematical model determines the measurement result and is represented as a functional dependence of one parameter on another. Let us consider such a functional dependence on the example of a linear TF:

$$y'_l = S'_l x_i + \Delta y' \tag{1}$$

where y'_l – is the signal at the sensor output;

x_i – is the desired physical quantity (DPQ);

S'_l – is the sensitivity (slope) of the transformation of the linear component of the transformation function;

$\Delta y'$ – is the shift of the transformation function with the additive component of the error.

In equation (1), all quantities (y'_l, S'_l $\Delta y'$) are indicated with strokes, which indicates their real (not ideal) values, that is, values with an error.

Following item 1 of the algorithm, we determine the number of unknown parameters of TF. For equation (1) there are 3 unknowns (y'_l, S'_l, $\Delta y'$), therefore, we can compose a system of 3 equations of redundant measurements. Thus, it is necessary to form two more equations. To do this, use the normalized (or normalized) value of the physical quantity x_1. The formation of a normalized value occurs using a calibrated source. As a result, the system of equations will look like:

$$\begin{cases} y'_{l1} = \Delta y'; \\ y'_{l2} = S'_l x_1 + \Delta y'; \\ y'_{l3} = S'_l x_i + \Delta y'. \end{cases} \tag{2}$$

As a result of solving the system of redundant equations (2), an equation is obtained DPQ

$$x_i = x_1 \frac{(y'_{l3} - y'_{l1})}{(y'_{l2} - y'_{l1})} \tag{3}$$

and parameter equations TF:

$$S'_l = \frac{(y'_{l2} - y'_{l1})}{x_1} \tag{4}$$

$$\Delta y' = y'_{l1} \tag{5}$$

To verify the correctness of the derived equations (3-4), it suffices to substitute instead of the quantities y'_{l1}, y'_{l2} and y'_{l2} their expressions from the system (2).

As can be seen from equation (3), the obtained result x_i does not depend on the parameters TF (S'_l $\Delta y'$). Thus, by measuring only the signals at the output of the sensor and processing them according to the proposed equation (3), it is possible to achieve independence from changes in the parameters of the TF.

B. Study of polynomial TF

Following the proposed algorithm, we will compose a mathematical model for the TF that has the form of a 3rd degree polynomial:

$$y'_n = S'_{n2} x^3{}_i + S'_{n1} x^2{}_i + S'_l x_i + \Delta y' \tag{6}$$

where S'_{n2}, S'_{n1} – is the nonlinear component of the transformation function.

Since equation (6) has a complex structure, as well as 5 unknowns, we will form redundancy with the help of values normalized by the value x_0 and Δx. It should be noted that it is enough to have one calibrated source, with the possibility of forming several values normalized by value. As a result, we obtain a system of equations of the form:

$$\begin{cases} y'_{n1} = S'_{n2}(x_1)^3 + S'_{n1}(x_1)^2 + S'_l(x_1) + \Delta y'; \\ y'_{n2} = S'_{n2}(x_2)^3 + S'_{n1}(x_2)^2 + S'_l(x_2) + \Delta y'; \\ y'_{n3} = S'_{n2}(x_3)^3 + S'_{n1}(x_3)^2 + S'_l(x_3) + \Delta y'; \\ y'_{n4} = S'_{n2}(x_4)^3 + S'_{n1}(x_4)^2 + S'_l(x_4) + \Delta y'; \\ y'_{n5} = S'_{n2}(x_5)^3 + S'_{n1}(x_5)^2 + S'_l(x_5) + \Delta y'; \\ y'_{n6} = S'_{n2}(x_6)^3 + S'_{n1}(x_6)^2 + S'_l(x_6) + \Delta y'; \\ y'_{n7} = S'_{n2}(x_7)^3 + S'_{n1}(x_7)^2 + S'_l(x_7) + \Delta y'; \\ y'_{n8} = S'_{n2}(x_8)^3 + S'_{n1}(x_8)^2 + S'_l(x_8) + \Delta y', \end{cases} \tag{7}$$

where $\{x_1\}=\{x_0\}-\{\Delta x\}$, $\{x_2\}=\{x_0\}-2\{\Delta x\}$, $\{x_3\}=\{x_0\}+\{\Delta x\}$, $\{x_4\}=\{x_0\}+2\{\Delta x\}$, $\{x_5\}=\{x_i\}+\{x_1\}=$ $=\{x_i\}+\{x_0\}-\{\Delta x\}$, $\{x_6\}=\{x_i\}+\{x_2\}=\{x_i\}+\{x_0\}-2\{\Delta x\}$, $\{x_7\}=\{x_i\}+\{x_3\}=\{x_i\}+\{x_0\}+\{\Delta x\}$, $\{x_8\}=\{x_i\}+\{x_4\}=\{x_i\}+\{x_0\}+2\{\Delta x\}$.

As a result of solving the system of redundant equations (7), the DPQ equation (8) and the corresponding parameters are obtained (9-12):

$$x_i = \frac{\Delta x((y'_{n8} - y'_{n6}) - (y'_{n4} - y'_{n2}) - 4((y'_{n8} - y'_{n4}) - (y'_{n7} - y'_{n3})))}{-3((y'_{n8} - y'_{n6}) - 2(y'_{n7} - y'_{n5}))} \quad (8)$$

and

$$S'_{n2} = \frac{((y'_{n8} - y'_{n6}) - 2(y'_{n7} - y'_{n5}))}{12 \cdot \Delta x^3} \quad (9)$$

$$S'_{n1} = \frac{2\Delta x\left[(y'_{n4} + y'_{n2}) - (y'_{n3} + y'_{n1})\right]}{12\Delta x^3} - \frac{3x_0\left[(y'_{n8} - y'_{n6}) - 2(y'_{n7} - y'_{n5})\right]}{12\Delta x^3} \quad (10)$$

$$S'_l = \frac{6\Delta x^2 (y'_{n3} - y'_{n1}) - 4\Delta x \cdot x_0\left[(y'_{n4} + y'_{n2}) - (y'_{n3} + y'_{n1})\right]}{12\Delta x^3} + \frac{(3x_0^2 - \Delta x^2)\left[(y'_{n8} - y'_{n6}) - 2(y'_{n7} - y'_{n5})\right]}{12\Delta x^3}, \quad (11)$$

$$\Delta y' = y'_{n1} - \frac{(x_0 - \Delta x)}{12\Delta x^3}\Big[6\Delta x^2 (y'_{n3} - y'_{n1}) - 2\Delta x(x_0 + \Delta x)\left[(y'_{n4} + y'_{n2}) - (y'_{n3} + y'_{n1})\right] + x_0(x_0 + \Delta x)\left[(y'_{n8} - y'_{n6}) - 2(y'_{n7} - y'_{n5})\right]\Big]. \quad (12)$$

To check the correctness of the derived equations, it suffices to substitute the output signals y'_{ni} for their values from the system (7) instead of the output signals.

Using the obtained equations, we will carry out computer simulation of the MRM and the method of direct measurements for linear and polynomial TF. Based on the obtained results, we will conduct a comparative analysis of these methods in the field of measurement accuracy and the possibility of self-control of the TF parameters.

V. Computer Simulation of a Mathematical Model

Computer simulation with linear and polynomial TF will allow to evaluate and make a comparative analysis of the errors in the determination of DPQ using MRM and direct methods.

A. Simulation of linear TF

1) Comparative analysis of errors

When applying MRM, it is necessary to form and carry out at least 1 measurement cycle, which consists, according to system (2), of 3 intermediate measurements of the sensor output signal. For computer simulation, we will set the following nominal values of parameters for the compared approaches: S_l = 2,0; Δy=0,1; x_1=1,8; x_i=2,2.

It should be noted that the physical quantity x_1 normalized by value is set such that it is of the same order as the DPQ. In addition, we will set the reproduction error of the parameter x_1, which will be ± 0.1%. This error is due to the fact that the normalized value of x_1, as a rule, is formed using a calibrated source of high accuracy. We will also set the limits of changes for each of the parameters of the TF (S'_l, $\Delta y'$): at ± 1.0%, and also at ± 10.0%. At the same time, it was assumed that during the conduct of intermediate measurement cycles (1 measurement cycle) the values of the parameters of the TF and their deviations remained unchanged.

As a result, we obtain the following relative errors (δ, %) of the DPQ, which are listed in Table 1:

Table 1. Relative definition errors DPQ

	δ, % when changing parameters (S'_l, $\Delta y'$) within ± 1,0%	δ, % when changing parameters (S'_l, $\Delta y'$) within ± 10,0%
Direct method	(1,00÷1,02)	(10,00÷10,23)
MRM	0,10	0,10

A comparative analysis of the results shows the advantage of the MRM over the direct method in the field of increasing the measurement accuracy by eliminating the influence of deviations of the parameters of the TF from their nominal values. It is shown that, in contrast to direct methods, an increase in the deviations of the parameters TF within ± 10% does not lead to a change in the results obtained with the use of MRM. This feature is achieved due to the processing of intermediate measurements according to the equation of redundant measurements (3). It should be noted that the value of the relative error in the determination of DPQ obtained with the use of MRM corresponds to the value of the error of reproduction normalized by the value of the physical quantity x_1. Thus, an increase in the reproduction error of up to 0.5% will lead to an increase in the relative error in the determination of DPQ also up to 0.5%. Thus, the methodological error of the MRM is due to the error in reproducing normalized values, which puts forward increased requirements for the source of physical quantities normalized by the value.

2) Determination of parameters of linear TF and study of their instability

Consider the possibility of determining the parameters of TF. For this, we use the equations of the TF parameters (4) and (5). This approach is used if external conditions are unstable or when it is necessary to check the value of parameters for deviation from their nominal values. In this case, it is necessary to carry out several cycles of measurements, since there may be a change in the parameters of the TF within different limits. Consider the following cases:

1. Changes in the parameters S_l and Δy occur within ±

1,0%.

2. Changes in the parameters S_l and Δy occur within ± 10,0%.
3. The change in the parameter S_l occurs within ± 1.0%, the parameter Δy within ± 10,0%.
4. The change in the parameter S_l occurs within ± 10.0%, the parameter Δy within ± 1,0%.

To determine the parameters for an unstable TF, it is necessary to make calculations using equations (4) and (5) in each measurement cycle, average them and, determining the difference between the calculated value and the nominal value, compare with the allowed norms of each of the parameters.

In the calculations, it was assumed that during the conduct of the intermediate measures of measurement, the values of the parameters of the TF and their deviations remained unchanged. So, with previously specified data, we get the following values of the change parameter S'_l:

1. When the parameters S_l and Δy change within ± 1.0%, the deviation of the parameter S'_l, is equal to 0.00002 measured units (or 0.001% of the nominal value).
2. When the parameters S_l and Δy change within ± 10.0%, the deviation of the parameter S'_l, is equal to 0.0002 measured units (or 0,01% of the nominal value).
3. When the parameter S_l varies within ± 1.0%, and Δy within ± 10.0%, the deviation of the parameter S'_l, is obtained, equal to 0.05 measured units (or 2.5% of its nominal value), the relative error of the direct method will be (0.77÷1.23)%, and the error of the MRM – 0.10%.
4. When the parameter S_l varies within ± 10.0%, and Δy within ± 1.0%, the deviation of the parameter S'_l, is obtained, equal to 0.12 measured units (or 6% of its nominal value), the relative error of the direct method will be (9.98÷10.02)%, and the error of the MRM – 0.10%.

Since equation (5) for the parameter $\Delta y'$ has a rather simple form, in this case, it is sufficient to simply average the obtained results of intermediate measurements. As a result, the deviation of the parameter $\Delta y'$ with the given data can be as high as 3% of its nominal value.

From the data obtained, it can be seen that any symmetric deviations of the parameters (case 1 and 2) affect only the measurement result by the direct method, and MRM, in this case, allow you to work with high accuracy (0.10%). However, it is necessary to verify the obtained parameter values with acceptable standards. If the parameter values are outside the permissible limits, then we can conclude that the sensor is replaced.

With asymmetric deviations of the parameters of the linear TF transition (case 3 and 4), we can conclude that the TF shift (it becomes inadequate) and the subsequent replacement of the sensor.

B. *Simulation of polynomial TF*

1) *Comparative analysis of errors*

In the classical approach to measurements with a nonlinear TF, it is usually necessary to express the complex dependence of the output signal on the input with a simple linear formula. To do this, the input range is divided into linear sections, which leads to the appearance of additional errors from nonlinearity, or work on the selected linear section, which leads to a narrowing of the input range. In contrast to the classical method, presented by the MRM allows to eliminate these shortcomings due to the redundant measurement equation (8). In this equation, by eliminating the influence on the measurement result of parameters of nonlinear TF, it is possible to work on the entire input signal range with high accuracy without dividing the range into linear sections.

To carry out computer simulations, the same initial data were chosen as in the case of linear TF, but with the following dipole parameters: S_l = 1.5; S_{n2} = 2; S_{n1} = 3; Δy=0.1. When using the direct method for a polynomial TF, the input value sub-range was taken x_i = (1.98÷2.42), the error from which linearization is 1%. Thus, such a linearization leads to a narrowing of the measurement range or its splitting into linear sections, which increases the estimated time. For a comparative analysis of the direct method and the MRM, two cases were also considered: when the parameters of the TF were changed within ± 1.0% and within ± 10.0%. At the same time, it was assumed that during the conduct of intermediate measurement cycles (1 measurement cycle) the values of the parameters of the tf and their deviations remained unchanged. As a result, we obtain the following values of the relative errors (δ, %) of the DPQ, which are listed in Table 2:

Table 2. Relative definition errors DPQ

	δ, % when changing parameters (S'_l, $\Delta y'$) within ± 1,0%	δ, % when changing parameters (S'_l, $\Delta y'$) within ± 10,0%
Direct method	1,02	(1,02÷10,23)
MRM	0,10	0,10

As with linear TF, redundant methods have shown good results in reducing the error caused by the instability and non-linearity of the TF of the sensor. It is shown that the use of MRM allows one to increase the measurement accuracy by an order of magnitude compared to direct methods. Therefore, if the change in all parameters occurs within 10.0%, then the use of direct methods will increase the measurement error. The use of MRM, in this case, will allow obtaining a result without compromising accuracy.

In addition, MRM do not require work on a linear section or the division into sub-range of the input signal. This is achieved by processing the signals according to the equation of redundant measurements (8), in which the output receives a signal such as at the input. The methodological error of the MRM, as in the case of the linear TF, is determined by the error in reproducing the values normalized by the value of x_1 x_2, x_3, x_4.

2) Determination of parameters of polynomial TF and study of their instability

Consider the possibility of determining the parameters of the TF according to the redundant equations of the parameters of the TF (9) - (12). Consider the following cases:

1. Changes in the parameters S_{n2}, S_{n1}, S_l and Δy occur within ± 1.0%.
2. Changes in the parameters S_{n2}, S_{n1}, S_l and Δy occur within ± 10.0%.
3. Change in the parameter S_{n2} occurs within ± 10.0%, the parameters S_{n1}, S_l and Δy within ± 1.0%.
4. Changes in the parameters S_{n2} and S_{n1} occurs within ± 10.0%, and the parameters S_l and Δy within ± 1.0%.
5. Changes in the parameters S_{n2}, S_{n1} and S_l occurs within ± 10.0%, and the parameter Δy within ± 1.0%.
6. Changes in the parameters S_{n1}, S_l and Δy occurs within ± 10.0%, and the parameter S_{n2} within ± 1.0%.

In this case, as in the case of a linear TF, it is also necessary to carry out several measurement cycles, in each of which it is necessary to make calculations using equations (9) - (12), average the obtained values and determine the deviation of each parameter from the data obtained.

In the calculations, it was also assumed that during the measurement cycles, the values of the parameters of the TF and their deviations remained unchanged. As a result, the following values were obtained:

1. When changing the parameters S_{n2}, S_{n1}, S_l and Δy within ± 1.0%, the following deviations of the parameters are obtained:

– the deviation of the parameter S'_{n2} was 0.0003 measurable units (or 0.01% of the nominal value);
– the deviation of the parameter S'_{n1} was 0.0001 measurable units (or 0.005% of the nominal value);
– the deviation of the parameter S'_l was 0.00002 measurable units (or 0.001% of the nominal value);
– the deviation of the parameter $\Delta y'$ amounted to small order values.

2. When changing the parameters S_{n2}, S_{n1}, S_l and Δy within ± 10.0%, the following deviations of the parameters are obtained:

– the deviation of the parameter S'_{n2} was 0.003 measurable units (or 0.1% of the nominal value);
– the deviation of the parameter S'_{n1} was 0.001 (or 0.05% of the nominal value);
– the deviation of the parameter S'_l was 0,0002 (или 0,01% of the nominal value);
– the deviation of the parameter $\Delta y'$ amounted to small order values.

3. When changing the parameter S_{n2} within ± 10.0%, the parameters S_{n1}, S_l and Δy within ± 1.0%, the following deviations of the parameters are obtained:

– the deviation of the parameter S'_{n2} was 0.01 (or 0.33% of the nominal value);
– the deviation of the parameter S'_{n1} was 0.004 (or 0.2% of the nominal value);
– the deviation of the parameter S'_l was 0.001 (or 0.07% of the nominal value);
– the deviation of the parameter $\Delta y'$ amounted to small order values.

4. When changing the parameters S_{n2} and S_{n1} within ± 10.0%, the parameters S_l and Δy within ± 1.0%, the following deviations of the parameters are obtained:

– the deviation of the parameter S'_{n2} was 0.01 (or 0.33% of the nominal value);
– the deviation of the parameter S'_{n1} was 0.004 (or 0,2% of the nominal value);
– the deviation of the parameter S'_l was 0.02 (or 1.33% of the nominal value);
– the deviation of the parameter $\Delta y'$ was 0.001 (or 1.0% of the nominal value).

5. When changing the parameters S_{n2}, S_{n1} and S_l within ± 10.0%, the parameter Δy within ± 1.0%, the following deviations of the parameters are obtained:

– the deviation of the parameter S'_{n2} was 0.01 (or 0.33% of the nominal value);
– the deviation of the parameter S'_{n1} was 0.004 (or 0.2% of the nominal value);
– the deviation of the parameter S'_l was 0.001 (or 0.07% of the nominal value);
– the deviation of the parameter $\Delta y'$ was 0.001 (or 1.0% of the nominal value).

6. When changing the parameters S_{n1}, S_l and Δy within ± 10.0%, the parameter S_{n2} within ± 1.0%, the following deviations of the parameters are obtained:

– the deviation of the parameter S'_{n2} was 0.01 (or 0.33% of the nominal value);
– the deviation of the parameter S'_{n1} was 0.004 (or 0.2% of the nominal value);
– the deviation of the parameter S'_l was 0.001 (or 0.07% of the nominal value);
– the deviation of the parameter $\Delta y'$ was 0.005 (or 5.0% of the nominal value).

Thus, a computer simulation of the equations of redundant measurements showed that the most significant and, at the same time, the most sensitive parameter for polynomial TF is the parameter S'_{n2}. However, to determine the rate and nature of the change in the TF, it is not enough to determine only the parameter S'_{n2}. Since, as can be seen from cases 1 and 2, the symmetric deviation of the parameter S'_{n2} with other parameters does not lead to a change in the measurement error. In cases 3-6, when an asymmetric deviation of the parameters occurs, the TF shift occurs (the mathematical model becomes inadequate) and the question arises of replacing the sensor.

Therefore, we can conclude that for a polynomial function, to determine the nature of the change in time of its normalized characteristics, it is necessary to control not only the parameter S'_{n2}, but also all other parameters. If the parameter values are outside the permissible limits, then we can conclude that the sensor is replaced.

VI. Conclusion

As a result of the research conducted, it was proved that the methods of redundant measurements are promising in the area of improving measurement accuracy with a nonlinear and unstable sensor transformation function with the ability to determine the values of the parameters of the function itself.

The components of the algorithm of the method of redundant measurements were presented, based on which a mathematical model of the method of redundant measurements was presented with a linear and polynomial transform function of the sensor. The ways of forming redundancy are shown due to the additional introduction of several normalized values using a calibrated source. This made it possible to form a system of equations, the solution of which allowed us to derive the equation of redundant measurements of both the desired physical quantity and the parameters of the transformation function. It is shown that the increase in accuracy is achieved by processing intermediate results by the redundant measurement equation, which excludes the influence of the absolute values of the parameters of the sensor's transformation function and their deviations from nominal values (provided that these parameters remain constant during the measurement cycles). The possibility of determining the values of the parameters of the transformation function by the corresponding equations is shown. Thanks to this self-checking of parameters, it is possible to reduce the material and time costs for calibrating the sensors and carry out its replacement in time.

It was also shown that, in contrast to direct methods, the use of redundant measurement methods for a nonlinear transformation function does not require its direct linearization or operation in a linear segment. This is achieved by processing the results of intermediate measurements according to the equation of redundant measurements, in which the output is the result such as the input.

As a result of a comparative analysis of the errors of the direct method and the method of redundant measurements, it was found that the presented methods provide higher measurement accuracy.

In general, methods of redundant measurements contribute to improving the accuracy of measurement with linear and nonlinear transformation functions throughout its range with the ability to determine the parameters of the transformation function.

References

[1] R.I. Genkina, Yu.E. Lukashov, Kh.O. Malikova, V.A. Skovorodnikov and I.V. Osoka, “We speak VNIIMS, we mean - legal metrology !”, *Legal and Applied Metrology*, 2010, No. 5, pp. 8-15.

[2] V. Yu. Shcherban’, G. V. Melnyk, M. I. Sholudko and V. Yu. Kalashnyk, “Warp yarn tension during fabric formation”, *Fibres and Textiles*, 2018, Issue 2, pp. 97–104.

[3] V. Chaban “Influence of plastic deformation warp thread on basic physical and mechanical data warp-knitting fabrics”, *Fibres and Textiles*, 2013, Issue 1, pp. 9–13.

[4] V. Yu. Shcherban’, G. V. Melnyk, M. I. Sholudko, O. Z. Kolysko and V. Yu. Kalashnyk, “Yarn tension while knitting textile fabric”, *Fibres and Textiles*, 2018, Issue 3, pp. 74–83.

[5] M. Sengupta, “Accuracy of Photodiode Pyranometers for Photovoltaic Applications”, *Fourth Conference on Weather, Climate, and the New Energy Economy*, 2013. https://ams.confex.com/ams/93Annual/webprogram/Paper222639.html.

[6] I. O. Bragynets, O. G. Kononenko and Yu. O. Masjurenko, “Investigation high sensitive photo detector device based on the avalanche photodiode for optoelectronic measuring systems”, *Tekhnichna elektrodynamika*, 2016, 6, pp. 69–75. http://nbuv.gov.ua/UJRN/TED_2016_6_13.

[7] Wei Liu, Bing Liang, Zhenyuan Jia, Di Feng, Xintong Jiang, Xiao Li and Mengde Zhou, “High-Accuracy Calibration Based on Linearity Adjustment for Eddy Current Displacement Senso”, *Sensors (Basel)*, 2018 Sep; 18(9): 2842. doi: 10.3390/s18092842

[8] Jiabin Wu, Yunshan Chen, Shijie Gao, Yimang Li and Zhiyong Wu, “Improved measurement accuracy of spot position on an InGaAs quadrant detector”, *Applied Optics*, Vol. 54, Issue 27, pp. 8049-8054 (2015). DOI:10.1364/AO.54.008049

[9] Mehdi Rahimi, Yudong Luo, Frederick C. Harris, and Yantao Shen, “Improving measurement accuracy of Position Sensitive Detector (PSD) for a new scanning PSD microscopy system”, *IEEE International Conference on Robotics and Biomimetics (ROBIO 2014)*, Indonesia. DOI: 10.1109/ROBIO.2014.7090577

[10] A.V. Degtyarev, “Correction of the transformation function of the measuring channel using a radial basis neural network [Text]”, *Collection of works of the VI International Scientific and Technical Conference "Metrology, information-measuring technologies and systems"*, Kharkiv, October 24-25, 2017, pp. 42–43.

[11] S.I. Klevtsov and E.V. Hoopoe, “ Management of error of measurements of physical quantity in a microprocessor sensor”, *Izvestiya Southern Federal University. Engineering*, 2015, pp.126-137.

[12] Klevtsov C.I. “Multisegment spatial approximation of the calibration characteristic of a microprocessor sensor”, *Metrology*. 2011. No. 7. pp. 26-36.

[13] V. Shcherban’, G. Korogod, V. Chaban, O. Kolysko, Yu.Shcherban’ and A.Shchutska, “Computer simulation methods of redundant measurements with the nonlinear

transformation function", *Eastern-European Journal of Enterprise Technologies*, 2019, Vol 2, No 5 (98), pp.16-22. DOI: 10.15587/1729-4061.2019.160830.
[14] V. T. Kondratov and A. A. Korogod, "Redundant pyrometry: state and development prospects", *Measuring and computing technology in technological processes*, 2017, No. 2, pp. 37–46.
[15] V. T. Kondratov, "Novaya era razvitiya teorii metrologicheskoy nadezhnosti – funkciya raspredeleniya Kondratova – Veybulla, ee raznovidnosti, svoystva i funkcional'nye vozmozhnosti", *Zakonodatel'naya i prikladnaya metrologiya*, 2009. Issue 2. pp. 21–22.
[16] V.T. Kondratov, "Definitions and basic classification of measuring systems", *Vimiryuvalnaya and obucyuslyuvalnaya technology in technological processes*. 2014, No. 3, pp. 85-100.

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