UDC 389:621.317
DOI: 10.15587/1729-4061.2019.160830

COMPUTER SIMULATION METHODS OF REDUNDANT MEASUREMENTS WITH THE NONLINEAR TRANSFORMATION FUNCTION

V. Shcherban'
Doctor of Technical Sciences, Professor, Head of Department*
E-mail: shherban.vy@knutd.com.ua
G. Korogod
PhD, Associate Professor*
E-mail: 5618607@ukr.net
V. Chaban
Doctor of Technical Sciences, Professor
Department of Applied Mechanics and Machines**
E-mail: Chaban.v@knutd.edu.ua
O. Kolysko
PhD, Associate Professor*
E-mail: kolisko.oz@knutd.com.ua
Yu. Shcherban'
Doctor of Technical Sciences, Professor, Head of Department***
E-mail: scherban@i.ua
G. Shchutska
Doctor of Technical Sciences, Associate Professor, Director of Higher State Educational Establishment***
E-mail: polischuka.kklp@gmail.com
*Department of Computer Science and Technology**
**Kyiv National University of Technologies and Design
Nemirovicha-Danchenka str., 2, Kyiv, Ukraine, 01011
***Department of Light Industry Technologies
Higher State Educational Establishment
Kyiv college of light industry
Ivana Kudri str., 29, Kyiv, Ukraine, 01601

Проведеними дослідженнями можливостей методів надлишкових вимірювань встановлено високу ефективність представлених методів щодо підвищення точності вимірювань. Доведено, що рівняння надлишкових вимірювань забезпечує незалежність результату вимірювань від параметрів функції перетворення і їх відхилень від номінальних значень. Також доведена можливість отримання рівняння надлишкових вимірювань параметрів функції перетворення, що дасть можливість здійснення метрологічного самоконтролю. Експериментальними дослідженнями підтверджено, що точність вимірювання підвищується за рахунок обробки результатів проміжних вимірювань за рівнянням надлишкових вимірювань. В запропонованому рівнянні за рахунок операції віднімання виключається адитивная складова похибки, а за рахунок операції ділення виключається мультиплікативна. Це призводить до стійкості результату вимірювання надлишковим методом до змін параметрів функції перетворення. Зокрема встановлено, що зміна параметрів функції перетворення на (1÷10) % не впливає на результат надлишкових вимірювань, тобто відносна похибка в заданому робочому діапазоні становитиме δ_1=(0,04÷0,01) %. Це дозволяє стверджувати про відповідність математичної моделі, що лежить в основі представленого метода, отриманим результатам комп'ютерного моделювання. Останні, зокрема, стосується порівняльного аналізу методів надлишкових і ненадлишкових вимірювань на стійкість до зміни параметрів функції перетворення. Показано, що методи надлишкових вимірювань забезпечують автоматичне виключення систематичної складової похибки, обумовленої зміною параметрів функції перетворення. Це забезпечується завдяки виключенню впливу на результат вимірювання абсолютних значень параметрів нелінійної функції перетворення фотоприймача і їх відхилень від номінальних значень.

Є підстави стверджувати про перспективний розвиток методів надлишкових вимірювань при різних видах функції перетворення сеснора в сфері підвищення точності. Цей результат досягається за рахунок обробки результатів проміжних вимірювань відповідно до рівняння надлишкових вимірювань. Крім того, за необхідності, запропоновані методи дають можливість здійснення метрологічного самоконтролю

Ключові слова: надлишкові методи, рівняння вимірювань, параметри функції, підвищення точності, самоконтроль, фотодіод

1. Introduction

One of the urgent issues for today is the task of increasing the accuracy of measurements while reducing the cost of metrological support. This is due to the fact that, when performing technological processes, for example, in the chemical, light and textile industries, even a small change in the controlled parameter may lead to shortages of products or to a decrease in their quality [1–3].

The measurement result error is largely dependent on measuring instruments and external factors [1, 3]. In high-temperature processes, semiconductor sensors (bolometers, photodiodes, etc.) are most often used. These sensors have features such as the spread of parameters (even within a single lot) and the dependence of parameters on environmental factors (temperature, humidity, ionizing radiation, etc.). According to [4], among the means of measuring equipment supplied for calibration, almost 12 % of them have an error that does not correspond to the normalized. This is due to the fact that the effect of destabilizing factors leads to the accumulation of changes in parameters. As a result, the risk of obtaining inaccurate information increases, which leads to a decrease in measurement accuracy. In addition, when using a sensor with a nonlinear transformation function (for example, a photodiode), it is necessary to carry out its linearization, which adds additional errors or to work in a linear region, which narrows the measurement range.

In this regard, studies that aim at developing and refining methods that ensure the independence of the measurement result of the transformation function parameters and their deviations from nominal values should be considered relevant.

2. Literature review and problem statement

As a technological process, we consider a high-temperature process in which the main controlled parameter is temperature. Since temperature can not be measured directly, in this case, another physical quantity related to temperature is used.

In high-temperature measurements, optical-electronic devices are commonly used. But today the tasks of increasing the accuracy, expanding the range of measurement and the possibility of metrological self-control are still relevant. Thus, in [5] the results of the study of the range expansion possibility are presented. It was shown that by using the programmed gain and synchronous detectors, the expansion of the photodiode signal bandwidth was achieved. The investigations of the optimization processes of photodiodes, described in [6], show that due to the introduction of the organic layer, a change in the photoelectric parameters of the photodiode was achieved. However, it should be noted that these works did not address the issue of increasing the accuracy of measurements, which may cause difficulties in obtaining reliable information. One of the reasons for this is the inadequate sensitivity of the photodetector. An option to overcome these difficulties may be to increase the sensitivity of the photodetector, which was considered in the paper [7]. Another option for accuracy improvement, which was presented in [8], is the use of a gauge coefficient. In addition, an increase in the measurement accuracy can be achieved by the statistical processing of multiple measurements, as presented in [9]. But the issues related to the deviation of the transformation function parameters from nominal values under the influence of destabilizing factors remained unresolved in these works. In order to overcome this problem, the algorithm of calculations was presented in [10], which made it possible to improve the output signal of the sensor under different conditions. However, it should be noted that this paper did not consider the possibility of metrological self-control of the sensor. An option to overcome these difficulties was considered in [11]. It is shown that due to the calculation of the frequency characteristic and photocurrent density, it is possible to predict the spectral response. But despite the positive results, the issues associated with obtaining an accurate measurement result with the nonlinear and unstable transformation function of the sensor with the possibility of metrological self-control remain unresolved. The reason for this is that the mentioned works do not give an opportunity to achieve the independence of the result of the deviations of the photodetector parameters. From a practical point of view, this may cause additional errors associated with the deviation of the transformation function parameters from the nominal values. This circumstance is due to the fact that the sensor is influenced by both the environment and material aging. As a result, the readings of the measuring device substantially change and the information becomes unreliable. It should be noted that the problem of the reliability of the result was considered in work [12], where the reliability of the obtained result was increased by introducing redundancy. However, in the presented work, there were no methods of measurement with the nonlinear transformation function. To overcome this problem, the method of redundant measurements was used in [13]. It was shown that due to the use of the redundant measurement equations, an increase in the accuracy of measurement with the cubic transformation function was achieved. Despite the positive results, this work did not indicate the possibility of measurement in a wide range of input characteristics of the sensor, since the photodiode has a logarithmic transformation function.

All this suggests that it is expedient to carry out further studies aimed at increasing the accuracy of measurement with the logarithmic transformation function of the sensor in a wide range of its input characteristics with the possibility of metrological self-control.

3. The aim and objectives of the study

The aim of the work is to increase the accuracy of measurement (radiation flux) on the basis of optoelectronic methods with the use of redundancy by processing the results of intermediate measurements by the equation of redundant measurements.

To achieve this aim, it is necessary to accomplish the following objectives:

– to develop a mathematical model of methods of redundant measurements with the nonlinear transformation function, which allows obtaining the equation of redundant measurements of the desired radiation flux and parameters of the photodetector transformation function;

– to demonstrate the advantages of methods of redundant measurements in relation to known methods in the area of increasing the measurement accuracy due to the independence of the measurement result of the spread of photodetector characteristics.

4. Materials and methods of research of computer simulation of methods of redundant and non-redundant measurements

4. 1. Investigated materials and simulation tools

The research was carried out using an FD307 silicon photodiode with the following parameters: photodiode dark current I_s=0.003 μA, current (monochrome) sensitivity $S_{I\lambda}$=0.27 A/W.

The experimental confirmation of the advantages of the mathematical model of the methods of redundant measurements was carried out using computer simulation in the Mathcad15 environment.

4. 2. Methods of research, the essence and algorithm of the method of redundant measurements

The following methods were used in the study: methods of redundant measurements of physical quantities, analytical methods for analysis of signal transformation processes, methods of mathematical modeling for solving a system of nonlinear equations of values, error theory for determination and estimation of errors.

The essence of the methods of redundant measurement (MRM) is as follows: in addition to the desired physical value, there is a measurement (divided in time) of several normalized values of one physical nature with the desired, resulting in several measurements. Mathematically, these measurements are described by a system of equations of quantities. Moreover, the number of equations in the system depends on the number of parameters of the transformation function of the sensor or one more (depending on the complexity of the nonlinear transformation function). As a result of the solution of the resulting system, the equations of redundant measurements as the desired physical quantity, and, if necessary, the parameters of the transformation function are found.

Theoretical foundations and application of MRM are given in [14–16].

In the future, it will be proved that the obtained equation of redundant measurements allows obtaining a result independent of the parameters of the nonlinear TF and their deviations from the nominal values.

When applying high-temperature processes as a physical value, we will consider the flux of optical radiation from the investigated object. Consider the mathematical model of the presented method on the example of the optoelectronic method of temperature measurement. According to [17], the connection between temperature T and radiation flux F_x can be established:

$$F_x = A'\sigma T^4, \quad (1)$$

where σ – Stefan-Boltzmann constant (σ=5.668 [W/m^2·K^4]); A' – coefficient of using the radiation flux from the object.

Consequently, for the accurate measurement of temperature, it is necessary to determine the value of the radiation flux as accurately as possible.

It is known [18] that the transformation function (TF) of a semiconductor photodiode operating in a photovoltaic mode (with a load) is described by the following equation of quantities:

$$U_R = \frac{kT}{q}\ln\left[\frac{S_I F_x}{I_s}+1\right] - U_{RM}, \quad (2)$$

where U_R – load voltage; U_{RM} – voltage drop on ohmic elements of the diode; T – photodiode temperature (usually equal to ambient temperature or temperature stabilization unit); q – electron charge (q=1.6·10^{-19} Cl); k – Boltzmann constant (k =1.38·10^{-23} J/K); S_I – current sensitivity of the photodiode; F_x – flux of optical radiation falling on the photodiode; I_s – photodiode dark current.

To simplify the expression, we accept the following replacement: $\frac{1}{F_T}=\frac{S_i}{I_s}$ and also denote the "thermal potential" kT/q through S'_H. In view of this, if we express the value of the radiation flux from equation (2), then we obtain the following expression:

$$F_x = F_T\left(e^{\frac{U_R+U_{RM}}{S'_H}} - 1\right). \quad (3)$$

As can be seen from equation (3), the dependence of the radiation flux on voltage is nonlinear (exponential) and depends on how precise these parameters were given (U_{RM}, S'_H and F_T). Consequently, the deviation of these parameters from nominal values can lead to inaccurate information and, consequently, to a decrease in measurement accuracy.

In contrast to the classical approach, as a result of MRM use, we obtain an equation of redundant measurements of the radiation flux, in which the parameters U_{RM} and S'_H are not included, which makes it possible to increase the accuracy of measurements. It should be noted that the independence of the measurement result of the parameters U_{RM} and S'_H is also important in the case when it is needed to replace the sensor with the same type. The use of MRM, in this case, does not require additional calibration and selection of sensors, which greatly saves time.

To construct a mathematical model of MRM, as already noted, it is necessary to form several normalized (calibrated) radiation fluxes. The formation of calibrated values of the radiation fluxes occurs using a standard source with normalized characteristics.

To determine the number of measurement steps, we determine the number of TF variables. Since the photodiode transformation function described by equation (2) has 4 variables, it is necessary to perform 4 measurement steps, that is, to form 4 radiation fluxes. To do this, using a standard source with normalized characteristics, such additional optical radiation fluxes are created, which will allow redundancy to form. As a result, we form optical radiation fluxes calibrated by the values F_0 and ΔF_0. After the standard source can generate these fluxes, the following 4 radiation fluxes will be sequentially received on the photodetector: $\{F_1\}=\{F_0\}$, $\{F_2\}=\{F_0\}+\{\Delta F_0\}$, $\{F_3\}=\{F_x\}$, $\{F_4\}=\{F_x\}+\{\Delta F_0\}$. As a result of such measurements, at the output of the photodetector (sensor) we obtain the following voltage values:

$$\begin{cases} U'_{R1} = S'_H \ln\left(\left(\Delta F_0/F_T\right)+1\right) - U_{RM}; \\ U'_{R2} = S'_H \ln\left(\left(F_0/F_T\right)+1\right) - U_{RM}; \\ U'_{R3} = S'_H \ln\left(\left(\left(F_0+\Delta F_0\right)/F_T\right)+1\right) - U_{RM}; \\ U'_{R4} = S'_H \ln\left(\left(F_x/F_T\right)+1\right) - U_{RM}; \\ U'_{R5} = S'_H \ln\left(\left(\left(F_x+\Delta F_0\right)/F_T\right)+1\right) - U_{RM}, \end{cases} \quad (4)$$

where U'_{Ri} – voltage in each i-th (i=(1÷5)) measurement cycle; S'_H – transformation steepness.

When solving the system (4), we deduce the equation of redundant measurements of the desired radiation flux Fx. For this purpose, we the voltage differences U'_{R5} and U'_{R4}, as well as U'_{R3} and U'_{R2} from the system (4). As a result, we obtain the following expressions:

$$U'_{R5} - U'_{R4} = S'_H \ln\frac{\frac{F_x+F_T}{F_T}+\frac{\Delta F_0}{F_T}}{\frac{F_x+F_T}{F_T}} = S'_H \ln\left(\frac{\Delta F_0}{F_x+F_T}+1\right), \quad (5)$$

$$U'_{R3} - U'_{R2} = S'_H \ln\frac{\frac{F_0+F_T}{F_T}+\frac{\Delta F_0}{F_T}}{\frac{F_0+F_T}{F_T}} = S'_H \ln\left(\frac{\Delta F_0}{F_0+F_T}+1\right). \quad (6)$$

For each of the expressions (5) and (6) we define the parameter S'_H, equate them and decide on the desired parameter F_x. As a result, we obtain the following equation of redundant measurements of the radiation flux F_x:

$$F_x = \frac{\Delta F_0}{\left[\left(\left(\Delta F_0/\left(F_0+F_\mathrm{T}\right)\right)+1\right)^{\left(U'_{R5}-U'_{R4}\right)/\left(U'_{R3}-U'_{R2}\right)}\right]-1} - F_\mathrm{T}. \quad (7)$$

To verify the correctness of the resulting expression, we need to put the expressions of the output voltages (U'_{R5}, U'_{R4}, U'_{R3}, U'_{R2}) in equation (7) according to the system (4):

$$F_x = \frac{\Delta \mathrm{F}_0}{\left[\left(\left(\Delta F_0/\left(F_0+F_\mathrm{T}\right)\right)+1\right)^{\left(U'_{R5}-U'_{R4}\right)/\left(U'_{R3}-U'_{R2}\right)}\right]-1} - \mathrm{F}_\mathrm{T} =$$

$$= \frac{\Delta \Phi_0}{\left[\left(\left(\Delta F_0/\left(F_0+F_\mathrm{T}\right)\right)+1\right)^{\frac{\left(S'_\mathrm{H}\ln\left(\left(\left(F_x+\Delta F_0\right)/F_\mathrm{T}\right)+1\right)+U_{RM}-S'_\mathrm{H}\ln\left(\left(\left(F_x\right)/F_\mathrm{T}\right)+1\right)+U_{RM}\right)}{\left(S'_\mathrm{H}\ln\left(\left(\left(F_0+\Delta F_0\right)/F_\mathrm{T}\right)+1\right)+U_{RM}-S'_\mathrm{H}\ln\left(\left(\left(F_0\right)/F_\mathrm{T}\right)+1\right)+U_{RM}\right)}}\right]-1} - F_\mathrm{T} = F_x. \quad (8)$$

As can be seen from equation (8), the parameters of the logarithmic TF (U_{RM} and S'_H) are reduced, which is the proof that the result of redundant measurements of the radiation flux F_x does not depend on TF parameters. It is worth noting that this feature of the MRM is performed provided that the parameters U_{RM} and S'_H remain constant during the measurement.

Another advantage of the proposed methods is that they allow metrological self-control of the sensor. But this process does not happen instantly and requires a predetermined time. A detailed description of the metrological self-control using the MRM is given in [15].

In general, metrological self-control with the help of MRM is carried out thanks to the equation of redundant measurements of TF parameters. To do this, we define the parameters (U_{RM} and S'_H) from the system (4):

$$S'_\mathrm{H} = \frac{U'_{R2}-U'_{R1}}{\ln\left(\dfrac{F_0+F_\mathrm{T}}{\Delta F_0+F_\mathrm{T}}\right)} \quad (9)$$

and

$$U_\mathrm{RM} = S'_\mathrm{H}\ln\left(\frac{\Delta F_0}{F_T}+1\right) - U'_{R1} =$$

$$= \left(U'_{R2}-U'_{R1}\right)\frac{\ln\left(\dfrac{\Delta F_0}{F_T}+1\right)}{\ln\left(\dfrac{F_0+F_T}{\Delta F_0+F_T}\right)} - U'_{R1}. \quad (10)$$

To determine the F_T value, we find the relation of differences for the voltages U'_{R2}, U'_{R1} and U'_{R2}, U'_{R3} of the system (4):

$$\frac{\left(U'_{R2}-U'_{R1}\right)}{\left(U'_{R3}-U'_{R2}\right)}\frac{\ln\left(\dfrac{F_0+F_T}{\Delta F_0+F_\mathrm{T}}\right)}{\ln\left(\dfrac{\Delta F_0}{F_0+F_\mathrm{T}}+1\right)}. \quad (11)$$

From equation (11) it can be seen that the value of the parameter F_T can be obtained by stepwise approximation, that is, using the iteration method.

It should be noted that if measurements do not have a task to determine the TF parameters, then it is possible to carry out not five but four measurement steps, excluding the first cycle in the system (4).

Thus, the algorithm of the MRM will be as follows (Fig. 1).

To confirm the high accuracy of the presented method, the estimation of the influence of TF parameters on the result of radiation flux measurement is carried out on the basis of calculations of measurement errors with the normalized TF parameters and their deviation, as well as their subsequent comparison. As already noted, the determination of the influence of the deviation of TF parameters from their nominal values on the measurement result was carried out on the example of an FD307 silicon photodiode with the parameters: photodiode dark current I_s=0.003 μA, current sensitivity $S_{I\lambda}$=0.27 A/W (at λ=0.55 microns).

The main indicators that were determined during computer simulation were the following: radiation flux value (F_x), relative error of measurement F_x by MRM (δ_1) and relative error of measurement F_x by the non-redundant method (δ_2).

Determination of the values of the relative error of measurement of the studied radiation flux by MRM was determined by the following method: first, the type of TF and the number of its parameters are determined. Since the logarithmic TF, which is described by equation (2), has 4 variables, it is necessary to carry out 4 measurement steps, that is, to form 4 radiation fluxes. As a result, we obtain a system of equations (4), excluding the first cycle (since it is needed in determining the TF parameters for metrological self-control).

For an FD307 silicon photodiode with a logarithmic TF, we determine the operating range of the optical radiation flux F_x, which ranges from 0.07 mW to 1.00 mW. We set normalized optical radiation fluxes F_0 and ΔF_0 such that they are of the same order with the studied flux F_x. We choose F_0=0.05 mW and ΔF_0=0.80 mW. Since the photodiode dark current I_s=0.003 μA and current sensitivity $S_{I\lambda}$=0.27 A/W, in this case, we obtain the following values of the parameters: transformation steepness S'_H=0.025, dark current $F_\mathrm{T}=1.11\cdot10^{-8}$ W.

On the basis of the data obtained by the equation of redundant measurements (7), we determine the value of the studied radiation flux F_x. As a result, we get the value that is given to the input, that is, what value was set at the input, the same is obtained at the output. This is a proof of the correctness of the derived equation. The obtained value will be considered for ideal conditions (without errors). Since in real conditions during any technological process there are errors, then for computer simulation, we set that the error of reproduction of normalized radiation fluxes F_0 and ΔF_0 will be 0.1 μW.

Next, in order to trace the dynamics of the effect of changes in various TF parameters on the result of measurements, calculations were made in two different cases:

1) with a change in the parameter S'_H within ±1.0 % (S'_H= =S_H×(1±0.01)=0.025×(1±0.01)), and the parameter U_{RM} by ±10.0 % (U'_{RM}=(0.01±0.001) V) at constant F_T.

2) with an increase in the parameter F_T to ±10.0 % (with the change in the parameter S'_H within ±1.0 %, U_{RM} ±10.0 %).

In the researches, it was believed that the change of the transformation function parameters is constant during four measurements.

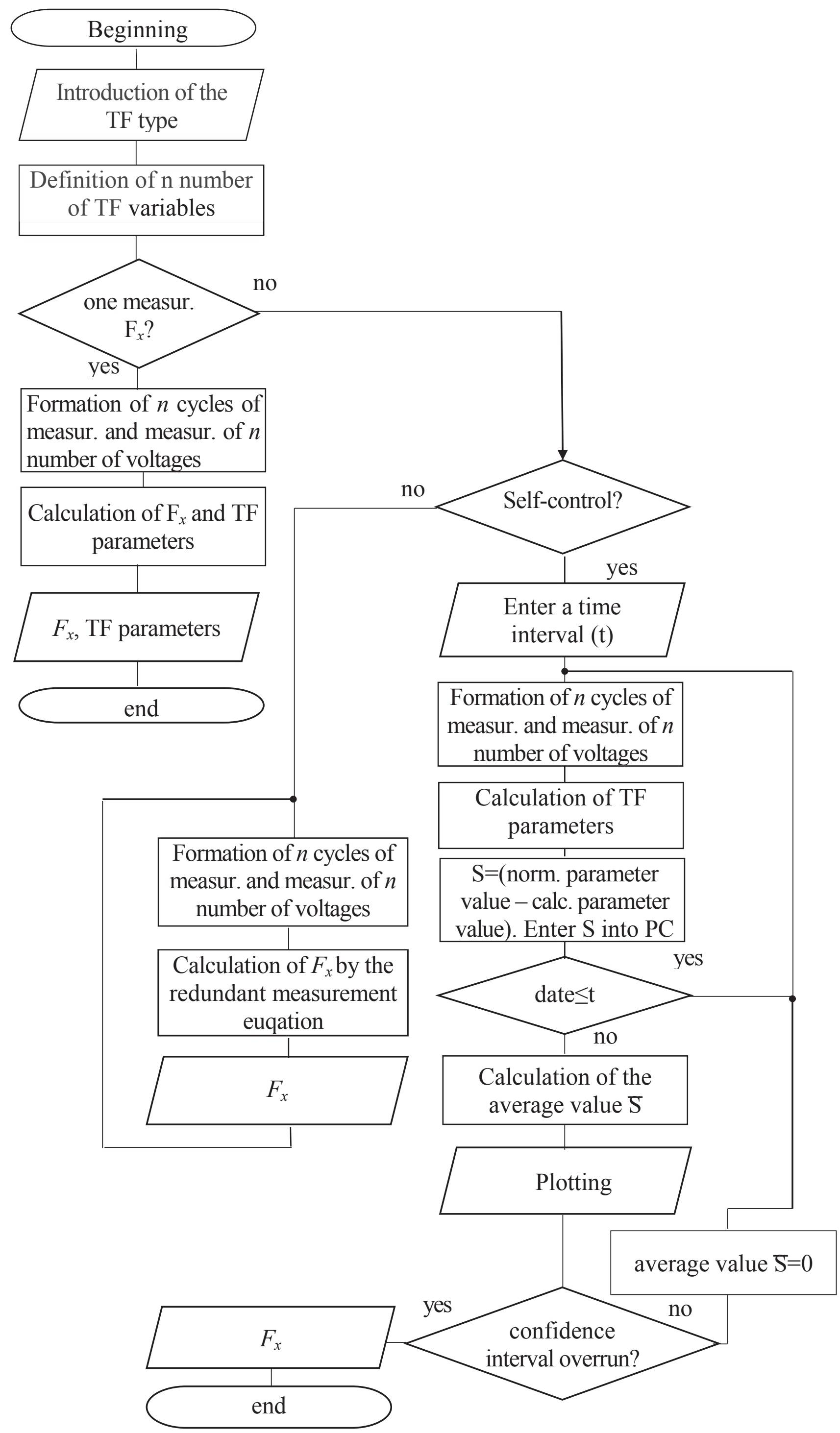

Fig. 1. Algorithm of MRM

For each of these two cases, the required radiation flux F_x was calculated for the equation of redundant measurements (7), and also the relative error of measurement was determined.

In order to present the existing advantages of the results obtained with the help of MRM, a comparative analysis with the results of the non- redundant method under the same conditions was carried out. That is, the calculations were carried out with the same specified changes in the parameters as for the MRM: with the change of the parameter S'_H within ±1.0 % and the parameter U_{RM} by ±10.0 %.

5. Results of the study of non-redundant and redundant methods for the stability to changes in the parameters of the transformation function

The results of the computer simulation and comparative analysis of the MRM and non-redundant method for the stability to changes in the TF parameters are given below. The calculations were carried out on the condition that changes in the TF parameters remain constant in all measurement steps.

1. Computer simulation of methods of redundant measurements in the working range of the photodiode in the of Mathcad15 environment yielded the following results:

– with the change in the parameter S'_H within ±1.0 % ($S'_H=S_H\times(1\pm0.01)=0.025\times(1\pm0.01)$), and the parameter U_{RM} by ±10.0 % ($U'_{RM}=(0.01\pm0.001)$ V) at a constant value of the parameter F_T, the relative error δ_1 of flux determination will be $\delta_1=(0.04\div0.01)$ %.

It was also found that an increase in the parameter S'_H to ±10.0 % (with the same values of parameters U_{RM} and F_T) does not lead to a change in the result.

– with an increase in the parameter F_T to ±10.0 % (with a change in the parameter S'_H within ±1.0 %, U_{RM} by ±10.0 %), the error value will be $\delta_1=(0.04\div0.01)$ %.

2. Since the nonlinear transformation function of the sensor when using non-redundant methods requires linearization or operation on a linear region, then in the computer simulation the linear region of the input characteristic of the photodiode was chosen. This region ranges from 0.66 mW to 0.88 mW. The calculations showed the following results:

– when changing only the parameter S'_H within ±1.0 %, the relative error δ_2 of flux determination F_x will be δ_2=1.0 %;

– when changing only the parameter U_{RM} by ±10.0 %, the relative error δ_2 of flux determination F_x will already be $\delta_2=(0.5\div0.4)$ %;

– with the change of the parameter S'_H within ±1.0 % and the parameter U_{RM} by ±10.0 %, the relative error δ_2 of flux determination F_x will already be $\delta_2=(1.5\div1.4)$ %.

Based on the results obtained, we can state that the MRM provide the invariance of the measurement results to the changes in the TF parameters (provided that the changes of these parameters are unaltered during measurements). At the same time, the error value of the determination of the desired radiation flux will remain practically unchanged (changes occur only in the third sign at the beginning of the operating range only if the F_T parameter is changed by 10 %). In the case of using the non-redundant method, with the same parameter changes, the error increases by an order of magnitude compared with the MRM than demonstrates its dependence on the stability of the TF parameters. In addition, the use of non-redundant methods with the nonlinear transformation function of the sensor requires its linearization or operation in the linear region, which leads to a narrowing of the operating range.

It should be noted that, despite all the benefits of MRM, they also have a methodological error due to the error of reproduction of the normalized values of radiation fluxes. Thus, the requirements for the source of radiation are put forward, that is, the more accurately the normalized flux is reproduced, the less the methodological error will be.

6. Discussion of the results of computer simulation of the mathematical model of methods of redundant measurements

In determining the measurement error of the studied (desired) radiation flux, as follows from the results of the study, it is logical that the proposed MRM provides an increase in measurement accuracy compared with the use of non-redundant methods. This is due to the peculiarity of the equation of measurements, in which, due to differences in certain voltages, the additive component of the systematic error is excluded, and the multiplicative component is excluded due to the operation of division of the specified voltages.

It should be noted that MRM are directly used with the nonlinear transformation function of the sensor of any kind without the need for its linearization.

The obtained data on the influence of deviations of the parameters of the nonlinear transformation function of the photodetector from the nominal values on the measurement result allows asserting the following:

– MRM are directly used with the nonlinear transformation function of the sensor without additional linearization, which improves the accuracy and expands the range of measurements;

– these methods are independent of changes in the photodetector parameters (provided that such changes of parameters remain constant during measurement). This also provides an opportunity to increase measurement accuracy and reduce the time to replace the photodetectors, since no further calibration is required.

Such conclusions can be considered expedient from a practical point of view, because MRM as a whole can improve the accuracy, expand the range of measurements and allow reducing the time to replace the photodetectors. From the theoretical point of view, they allow us to assert that the MRM can be used both with linear and nonlinear transformation functions, which is one of their advantages. However, it is impossible not to note that the results obtained are such that the reproduction error of the normalized radiation fluxes will be sufficiently small. This imposes certain limitations on the study of the results, which can be interpreted as a drawback. However, it should be noted that these fluxes are formed using a calibrated source with normalized characteristics, so this error will be several times less than the error of the measurement itself.

7. Conclusions

The researches revealed the features of methods of redundant measurements, which consist in their application with the nonlinear and unstable transformation function of the photodetector.

This can be argued for an increase in the accuracy of the measured parameter, since this significantly influences the quality of measurements. To this end, the method of redundant measurements was proposed.

As a result of computer simulation of the methods of redundant measurements, the following was discovered:

1. The ways of redundancy formation, which involves the additional input of several fluxes of optical radiation, are presented. This creates a system of value equations in order to obtain an equation of redundant measurements. The resulting equation of redundant measurements (7) provides for the elimination of the influence of changes in the parameters of the nonlinear transformation function of the photodetector (provided that these changes remain constant during measurements). In addition, the solution of the system also gives the possibility to obtain the equation (9)–(11) of redundant measurements of the TF parameters and, subsequently, to conduct metrological self-control on their basis.

2. As a result of the comparative analysis of the errors of the non-redundant method and the MRM, it was found

that the methods of redundant measurements provide a high accuracy of radiation flux measurement, which will be at the given parameters (0.04÷0.01) %. These values are obtained by processing the results according to the equation of redundant measurements (7). In this equation, due to subtraction of voltages, the additive component of the systematic error is eliminated, and the multiplicative component is excluded due to the operation of division of voltage differences.

In general, it can be argued about the effectiveness of the methods of redundant measurements in improving the accuracy of measurement and ensuring metrological reliability.

References

1. Warp yarn tension during fabric formation / Shcherban' V. Yu., Melnyk G. V., Sholudko M. I., Kalashnyk V. Yu. // Fibres and Textiles. 2018. Issue 2. P. 97–104. URL: http://vat.ft.tul.cz/2018/2/VaT_2018_2_16.pdf.
2. Chaban V. Influence of plastic deformation warp thread on basic physical and mechanical data warp-knitting fabrics // Fibres and Textiles. 2013. Issue 1. P. 9–13. URL: http://vat.ft.tul.cz/Archive/VaT_2013_1.pdf.
3. Yarn tension while knitting textile fabric / Shcherban' V. Yu., Melnyk G. V., Sholudko M. I., Kolysko O. Z., Kalashnyk V. Yu. // Fibres and Textiles. 2018. Issue 3. P. 74–83. URL: http://vat.ft.tul.cz/2018/3/VaT_2018_3_12.pdf.
4. Govorim VNIIMS, podrazumevaem – zakonodatel'naya metrologiya! / Genkina R. I., Lukashov Yu. E., Malikova H. O., Skovorodnikov V. A., Osoka I. V. // Zakonodatel'naya i prikladnaya metrologiya. 2010. Issue 5. P. 8–15.
5. Orozco L. Optimizing Precision Photodiode Sensor Circuit Design // Analog devices. 2011. URL: https://www.analog.com/en/technical-articles/optimizing-precision-photodiode-sensor-circuit-design.html
6. Imer A. G., Tombak A., Korkut A. Electrical and photoelectrical characteristic investigation of a new generation photodiode based on bromothymol blue dye // Journal of Physics: Conference Series. 2016. Vol. 707. P. 012012. doi: https://doi.org/10.1088/1742-6596/707/1/012012
7. Photodiodes as Optical Radiation Measurement Standards / Munoz Zurita A. L., Campos J., Ferrero A., Pons A. // Photodiodes – From Fundamentals to Applications. 2012. doi: https://doi.org/10.5772/51462
8. Sengupta M. Accuracy of Photodiode Pyranometers for Photovoltaic Applications // Fourth Conference on Weather, Climate, and the New Energy Economy. 2013. URL: https://ams.confex.com/ams/93Annual/webprogram/Paper222639.html
9. Bragynets I. O., Kononenko O. G., Masjurenko Yu. O. Investigation high sensitive photo detector device based on the avalanche photodiode for optoelectronic measuring systems // Tekhnichna elektrodynamika. 2016. Issue 6. P. 69–75. URL: http://nbuv.gov.ua/UJRN/TED_2016_6_13
10. Su Z., Liang X. Computation and analysis on the Volt-Ampere characteristics of photodiode sensor under the certain conditions // 2011 4th International Congress on Image and Signal Processing. 2011. doi: https://doi.org/10.1109/cisp.2011.6100750
11. Deyasi A., Ganguly A., Rakshit P. C. Calculating frequency response and photocurrent density of p-i-n photodiode // Proceedings of National conference on frontline research in computer, communication and device. 2015. P. 119–123. URL: https://books.google.com.ua/books?id=Pw19CwAAQBAJ&pg=PA123&lpg=PA123&dq=conference+characteristics+of+photodiode+sensor&source=bl&ots=iqTXP8NJL8&sig=ACfU3U1a1-P4MxMB_WmXDjrJ8jMNQk7ppg&hl=uk&sa=X&ved
12. Pronin A. N., Sapozhnikova K. V., Taimanov R. E. Reliability of measurement information in control systems. Problems and solutions // T-Comm: Telecommunications and transport. 2015. Vol. 9, Issue 3. P. 32–37.
13. Kondratov V. T., Riabov O. P. Pyrometer for measuring temperature by spectral ratio: Pat. No. 73426 UA. No. 20031212097; declareted: 12.23.2003; published: 15.07.2005, Bul. No. 7. 5 p. URL: http://uapatents.com/5-73426-pirometr-spektralnogo-vidnoshennya.html
14. Kondratov V. T., Korogod A. A. Redundant pyrometry: the condition and development prospects // Vymiriuvalna ta obchysliuvalna tekhnika v tekhnolohichnykh protsesakh. 2017. Issue 2. P. 37–46. URL: http://fetronics.ho.com.ua/pdf/pdf_full/2017/vottp-2017-2.pdf
15. Kondratov V. T. 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. P. 21–22.
16. Kondratov V. T., Zarnitsyna H. O. Digital pyrometer for measuring temperature by spectral ratio: Pat. No. 77840 UA. No. a200501402; declareted: 15.02.2005; published: 15.01.2007, Bul. No. 1. 11 p.
17. Kanarchuk V. E., Derkach O. B., Chigrinec A. D. Termometricheskaya diagnostika mashin. Kyiv: «Vyshcha shkola», 1985. 168 p.
18. Soboleva N. A., Melamid A. E. Fotoelektronnye pribory: ucheb. pos. Moscow: «Vysshaya shkola», 1974. 376 p.