Розроблений інтегральний метод моделювання системи вимірювання густини потоків інфрачервоного випромінювання на основі розв'язання зворотної задачі динаміки за допомогою рівняння Вольтери I роду з орієнтацією на вирішення задачі динамічної корекції. Розв'язання задачі структурної корекції динамічних характеристик вимірювальної системи густини потоків полягає в побудові та використанні у перетворюючому каналі або контурі системи деякого блоку. Цей блок завдяки своїм спеціально сформованим динамічним властивостям забезпечує найкращі динамічні характеристики всієї системи.

Апробовано за допомогою експерименту спосіб компенсації динамічної похибки. З цією метою були проведені експерименти з вимірювання густини нестаціонарного потоку інфрачервоного випромінювання із заданим законом зміни, який характерний для практичних умов роботи приймачів. Зміна густини падаючого потоку інфрачервоного випромінювання досягалася за рахунок обертання приймача навколо вісі, що проходить через середину його приймальної поверхні, в полі потоку стаціонарного випромінювача. В результаті експерименту отримана нелінійна апроксимація експериментально отриманої перехідної характеристики у вигляді відгуку приймача на синусоїдальний потік інфрачервоного випромінювання.

Особливо слід зазначити, що результати чисельного моделювання і експерименту показують задовільну збіжність, що дає підставу зробити висновок про те, що вибір моделі є правильним. Розроблені алгоритми здатні забезпечити чисельну реалізацію інтегральних моделей і служити основою при побудові високопродуктивних спеціалізованих мікропроцесорних систем для роботи у режимі реального часу. Це дозволило успішно здійснити динамічну корекцію системи вимірювання потоків інфрачервоного випромінювання і значно підвищити її точність.

Спільне використання розробленого методу при вирішенні математичних задач з використанням комп'ютерних засобів забезпечить можливість підвищення ефективності процесів синтезу і проектування обчислювальних пристроїв корегуючих засобів вимірювань

Ключові слова: інтегральне рівняння Вольтери, інфрачервоне випромінювання, система вимірювання, динамічна корекція

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CONSTRUCTION OF THE INTEGRATED METHOD TO MODEL A SYSTEM FOR MEASURING THE DENSITY OF INFRARED RADIATION FLOWSN

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1. Introduction

Over recent time, given a serious rise in energy cost, more and more thermal equipment manufacturers are seeking ways to effectively use the special features of infrared (IR) radiation when supplying radiant energy [1]. However, wide industrial implementation of the IR equipment faces serious obstacles. On the one hand, these are the difficulties related to growth, and on the other hand, the absence of specialized research and development units that purposefully work in this field. The creation of new modern IR installations requires both analytical and experimental in-depth studies into processes of energy transfer in absorbing environments, as well as the processes of heat exchange via radiation [1, 2]. In this case, an important criterion is the economic and performance characteristics of the designed equipment. In contrast to standard convective systems, strict mathematical modelling of heating, for example in IR-ovens, is a challenging task [3, 4]. Analytical description of the dynamics of heating an object by infrared radiation implies finding relations between the density of IR radiation flows, the maximally permissible temperature and heating rate (a very important characteristic in the processes of polymerization). In this event, the methodological basis of a model could be

a differential equation of energy balance [4]. By using this equation, it is possible to establish the matching rules that bind the interplay within the system "emitter-receiver", however, only for some particular cases and employing the approximations that often reduce the practical value of solutions. Moreover, a significant disadvantage of the approximated methods is the total absence of analytical connection between the functions of temperature, as well as effective flows of IR-radiation and optical properties and settings of the mutual arrangement of elements in the system's design [5]. Under these conditions, it is a relevant task to devise new methods for measuring or application of mathematical methods to process measurement data in order to improve the degree of its reliability.

The development and improvement of methods and measuring tools results in the need for the construction and study of mathematical methods for modelling and analysis of signals as starting experimental data with a focus on computer implementation [5]. Accounting for the increasing requirements to signal processing methods and tools, for the increased volume of calculations, could be achieved by creating the methods of mathematical modeling, as well as numerical algorithms and software that implement mathematical models [6].

2. Literature review and problem statement

Paper [6] reports results of the new method for correction of dynamic characteristics of sensors in measuring systems. The effectiveness of the method is shown in comparison with the classic algorithm of waiting for the end of a transitional response in a measuring circuit. However, the research method is applicable only for measurements at a constant temperature of an object under the influence of the sensor's stage.

Studies [7, 8] present the most important achievements of modern IR-thermography when it is used in technical-scientific, biomedical, and other fields. Authors considered the application of IR thermography methods in two very important areas of scientific research: temperature measurement and non-destructive testing. However, the methods for non-destructive testing and measurements based on the effects of nonlinearity, inertiality, and their physical characteristics, are not considered. Such methods of non-destructive testing, employed based on sending special test signals, include methods that are based on calculating the parameters of dynamic models.

Paper [9] proposed a new approach for modeling heat exchange between receivers and a heat source, taking into consideration losses by convection and radiation. This approach produces the mean values for a flow in terms of a focal volume and time of observation, as well as substantial dynamic errors. However, in some cases, for example when measuring powerful radiation flows at solar furnaces [10], it is also necessary to know the spatial and temporal distribution of density of the infrared radiation fluxes.

Work [11] considered building an integrated information processing algorithm for a micro-electric-mechanical system, which ensures high dynamic precision of the measuring system. A mathematical model of the object being monitored is constructed in the vector-matrix form in order to apply the Kalman filter to deal with disturbances. The result of computer simulation is the derived estimates for effectiveness of the integrated system under conditions of interference. The results obtained prove the efficiency of the implementation of the integrated information processing at a varying intensity of interference, for both the fast and slow measured processes. However, there is a drawback that should be noted: tuning the Kalman filter in this case requires conducting an additional identification of the power of an interference and a signal.

Study [12] proposed an approach that would enable the execution, in the automated system of evaluation of the visibility of objects in the infrared wavelengths, of transition from the combined logic-linguistic models to the generalized models. However, when analyzing a given work, there are certain constraints for instability at dynamic correction and numerical implementation.

As regards the development of new measurement procedures, of particular importance are the methods for structural correction of dynamic errors in measuring transducers, which are discussed in papers [13, 14]. However, despite the advantages of these approaches, there is an unresolved issue about correction of the dynamic characteristics of measuring transducers using the tools of computational equipment.

An analysis of the above papers reveals how significantly the role of modern mathematical apparatus and computational tools has grown in the measuring information processing and in the creation of fundamentally new measurement methods. Of particular interest for measuring equipment are the mathematical methods for correcting the inertiality of the infrared radiation non-stationary flow measurement systems. In this case, the task on improving the accuracy and high-speed performance can be solved by the development of methods and algorithms for solving mathematical problems on signal recovery that come down to solving the Volterra equation of the first kind [15, 16]. This allows us to suggest that the construction of an appropriate method would solve the task on correcting the dynamic characteristics of the IR-radiation flow measurement system by using advanced computer tools.

3. The aim and objectives of the study

The aim of this study is to construct an integrated method for modeling a system to measure the density of infrared radiation fluxes, which would make it possible to implement the dynamic correction of the system and to greatly improve its accuracy.

To accomplish the aim, the following tasks have been set:

– to construct a method and the algorithms to recover a signal at the input of a measuring system by processing the output signal based on solving the Volterra equation of the first kind oriented to solve a task on dynamic correction;

– to verify theoretical results through the numerical implementation of models using a computer.

4. Integrated method for modeling a system to measure the IR radiation flows

The method under consideration implies the calculation of input signal $y(t)$ based on the known output signal $f(t)$ and the assigned pulse transition characteristic $k(t)$. Moreover, the problem is reduced to solving the Volterra equation of the first kind [16]

$$\int_0^t \tilde{k}(t-s)y(s)ds = f(t), \quad (1)$$

where $\tilde{k}$ is the dynamic characteristic of the system; f(t) is the registered signal; y(t) is the restored signal at the input to the system.

In order to synthesize corrective algorithms, it is necessary to have an expression for function *k(t),* which can be derived by differentiating the transition characteristic $P_e(t)$. We derive function $P_e(t)$ as the response of the system to an input signal in the form of a single function, the implementation of which employs a stationary emitter based on a filament lamp and a diaphragm with the shutter controlled by an electromagnet. The approximation of the nonlinear experimentally received transition characteristic, which is one of the most convenient forms of representation [16], takes the form

$$\tilde{P}(t) \cong P_э(t) = \alpha_0 + e^{-\lambda t}\sum_{i=1}^{M}\alpha_i t^{i-1}, \quad i = \overline{1, M}, \tag{2}$$

where α_0, α_i, λ are the constant coefficients that make it possible to find the value for parameters of the approximating expression and to select its order *n* in such a way that the sum of the mean square error in the assigned points of interpolation is minimal. When *n*=7, the pulse transition function of an IR-radiation receiver takes the form

$$\tilde{k}(t) = \left(0{,}562 - 0{,}376t + 0{,}102t^2 - \right.$$
$$-0{,}01198t^3 + 0{,}000657t^4 -$$
$$\left. -0{,}000016t^5 + 0{,}000000144t^6\right)e^{-0{,}178t}. \tag{3}$$

Therefore, the following integral equation should be solved

$$\int_0^t [0{,}562 - 0{,}376(t-s) + 0{,}102(t-s)^2 -$$
$$-0{,}01198(t-s)^3 + 0{,}000657(t-s)^4 -$$
$$-0{,}000016(t-s)^5 + 0{,}000000144(t-s)^6] \times$$
$$\times e^{-0{,}178(t-s)} y(s)ds = f(t). \tag{4}$$

Verification of the considered technique to compensate for a dynamic error should be performed based on any characteristic mode of receiver operation. To this end, we conducted experiments to measure the density of a nonstationary flow of infrared radiation under the assigned law of change characteristic of the practical working conditions of receivers that are used in the measuring equipment. In order to carry out the experiments, we designed a pilot installation for measuring the density of infrared radiation (Fig. 1), whose main elements are a stationary emitter (1) and a measuring system.

The stationary emitter (1) is based on the lamp of IKZK type, whose power is regulated by the thermostat "RIF-101" and a diaphragm with a shutter (made of stainless steel and covered with a ceramic coating), which is operated by an electromagnet.

The infrared radiation measuring system includes a chamber of vacuum installation the type of VUP-5 (2), whose inner surface hosts a screen with a homogeneous absorbing surface (3) (absorption coefficient is not less than 0.98). We used, as a heat flow meter (4), the infrared thermometer MLX90614xAA, which is located on a rotating device (5) with an electric drive of engine the type of DSh-2. A window (6), used to let the IR radiation in, was made of glass for the IR spectrum, the brand TBF512 (OST 3-3442-83 "Optical oxygen-free glass. TU"). Sensor (4) is connected to the microcontroller ATMEGA 328A; data transfer (information about the current temperature of the emitter) is executed via a serial SMBus.

We changed density of the incident flux of infrared radiation by rotating the receiver around an axis running through the middle of its receiving surface in the field of a stationary emitter, as shown in Fig. 1.

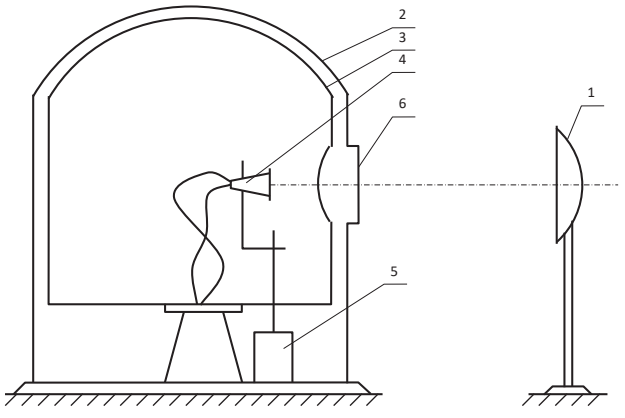

Fig. 1. Pilot installation to measure density of the infrared radiation flows: 1 – emitter; 2 – chamber of a vacuum installation; 3 – internal screen with a homogeneous absorbing surface; 4 – thermal counting device (sensor); 5 – rotating device; 6 – window to let the IR radiation in

Based on the results of preliminary stationary measurements, we established that a change in the radiation flux density at the rotating receiver is described by a sinusoidal dependence with a maximum variation of 2.5 %. The required uniformity of the receiver's rotation during measurements was enabled by the paper feeder mechanism of the recorder N-37. To exclude the influence of convection, the receiver along with a rotating device was put into the chamber of the vacuum installation. A characteristic response of the receiver to the sinusoidal flux of infrared radiation at a period of 28 s is given in Table 1. The derived experimental dependence $f_e(t_i)$ defines the examined regime and represents the right side of equation (1).

Table 1

Results of the experiment to measure the density of a nonstationary flow of infrared radiation

N	ti, s	fэ(ti)	N	ti, s	fe(ti)	N	ti, s	fe(ti)
1	0.00	0.00	11	5.00	10.20	21	10.0	12.44
2	0.50	0.51	12	5.50	10.93	22	10.5	11.78
3	1.00	0.79	13	6.00	11.58	23	11.0	11.35
4	1.50	2.06	14	6.50	12.23	24	11.5	10.87
5	2.00	3.60	15	7.00	12.75	25	12.0	10.22
6	2.50	4.76	15	7.50	13.14	26	12.5	9.48
7	3.00	5.84	17	8.00	13.30	27	13.0	8.60
8	3.50	6.91	18	8.50	13.33	28	13.5	7.59
9	4.00	8.01	19	9.00	13.19	29	14.0	6.11
10	4.50	9.16	20	9.50	12.89	–	–	–

Now we have sufficient information in order to numerically implement integral equation (1), that is, we know the form of the kernel (3) and a value for the right part (Table 1). For computer simulation, we have chosen, as a numerical method to solve equation (1), a quadrature method [16], according to

which an integral is replaced with the resulting amount that leads to a system of algebraic equations

$$\sum_{j=1}^{i} A_j \tilde{k}\left(t_i - t_j\right) y\left(t_j\right) = f\left(t_i\right), \quad i = 1,\ 2, \ldots, \tag{5}$$

where A_j are the coefficients of a quadrature formula, $t_i=(i-1)h$, h is the sampling step.

The application of trapezium formula at constant step $h=const$ to equation (1) makes it possible to obtain a recurrent ratio in the form

$$\left.\begin{aligned} \tilde{y}(0) &= \frac{f_э'(0)}{k(0)} \approx \frac{\left[-3f_э(0)+4f_э(h)-f_э(2h)\right]/2h}{k(0)}, \\ \tilde{y}\left(t_i\right) &= \frac{2}{k(0)}\left[\frac{f_э\left(t_i\right)}{h} - \sum_{j=1}^{i-1} A_j \tilde{k}\left(t_i - t_j\right)\tilde{y}\left(t_j\right)\right]. \end{aligned}\right\} \tag{6}$$

Expression (6) shows that the number of operations performed at each step is continuously increasing with an increase in the numbers of discretization nodes and, accordingly, there is a growth of the required memory for computer implementation. It is therefore advisable to use a modified algorithm of the numerical solution to integral equation (1), based on the kernel separability property. In this case, the kernel of equation (1) is represented in the following form:

$$k(t-s) = \sum_{l=1}^{m} \alpha_l(t)\beta_l(s), \quad l = \overline{1,m}. \tag{7}$$

If we represent the kernel in equation (3) in the form (7), equation (4) takes the form

$$\begin{aligned} &\left[B_1R_1 + B_2\left(tR_1 - R_2\right) + B_3\left(t^2R_1 - 2tR_2 + R_3\right) + \right. \\ &+B_4\left(t^3R_1 - 3t^2R_2 + 3tR_3 - R_4\right) + \\ &+B_5\left(t^4R_1 - 4t^3R_2 + 6t^2R_3 - 4tR_4 + R_5\right) + \\ &+B_6\left(t^5R_1 - 5t^4R_2 + 10t^3R_3 - 10t^2R_4 + 5tR_5 - R_6\right) + \\ &\left.+B_7\left(\begin{matrix} t^6R_1 - 6t^5R_2 + 15t^4R_3 - \\ -20t^3R_4 + 15t^2R_5 - 6tR_6 + R_7 \end{matrix}\right)\right]e^{-0,178t} = f(t), \end{aligned} \tag{8}$$

where

$B_1=0.562$; $B_2=-0.376$; $B_3=0.102$;

$B_4=-0.01198$; $B_5=0.000657$;

$B_6=-0.000016$; $B_7=0.000000144$;

$$R_k = \int_0^t e^{0,178s} s^{k-1} y(s)\,ds, \quad k = \overline{1,7}.$$

Calculation expression (6) then takes the following form

$$\left.\begin{aligned} \tilde{y}(0) &= \frac{f_э'(0)}{h\sum_{l=1}^{m}\alpha_l(0)\beta_l(0)}, \\ \tilde{y}\left(t_i\right) &= \frac{2}{\theta}\left(\frac{f_э\left(t_i\right)}{h} - \sum_{l=1}^{m}\alpha_l\left(t_i\right)\sum_{j=1}^{i-1} A_j\beta_l\left(t_j\right)\tilde{y}\left(t_j\right)\right), \end{aligned}\right\} \tag{9}$$

where

$$\theta = \sum_{l=1}^{m}\alpha_l\left(t_i\right)\beta_l\left(t_i\right) = \tilde{k}\left(t_i - t_i\right) = \tilde{k}(0).$$

Thus, in expression (9) the number of computational operations does not depend on the number of the sampling nodes, since components $\sum_{j=1}^{i-1} A_j\beta_l\left(t_j\right)y\left(t_j\right)$ depend only on a single free variable t_j. Results of solving the equation (8) are given in Table 2.

Table 2

Solving results at various steps of quadrature

t_i	y_h= =0,5(t_i)	y_h=1(t_i)	y_h=1,5(t_i)	t_i	y_h= =0,5(t_i)	y_h=1(t_i)	y_h=1,5(t_i)
0.0	2.224	0.392	1.424	7.5	18.837	–	17.525
0.5	2.189	–	–	8.0	17.484	17.343	–
1.0	1.870	2.973	–	8.5	16.938	–	–
1.5	9.858	–	4.518	9.0	15.248	15.356	14.946
2.0	9.805	10.426	–	9.5	13.972	–	–
2.5	11.114	–	–	10.0	12.141	12.270	–
3.0	12.694	11.244	11.397	10.5	9.940	–	10.614
3.5	14.321	–	–	11.0	10.672	9.567	–
4.0	16.078	15.347	–	11.5	8.187	–	–
4.5	17.858	–	14.991	12.0	6.969	7.385	7.661
5.0	18.498	17.887	–	12.5	5.198	–	–
5.5	18.067	–	–	13.0	3.332	3.717	–
6.0	19.067	17.814	17.126	13.5	1.361	–	2.578
6.5	19.378	–	–	14.0	3.189	1.299	–
7.0	19.120	18.913	–	–	–	–	

It should be noted that the quadrature method is matched with the regularizing algorithm, in which the regularization parameter is a step in the quadrature.

Fig. 2 shows the restored input signal at different values for the step. One can see that an increase in step increases the stability of the obtained solution that reflects the significant influence of step h on solving the equation (1).

In order to derive a more stable solution, we shall apply, when implementing the model, the method of Lavrentyev regularization [17], according to which we solve, instead of equation (1), the following equation

$$\alpha y + \int_0^t K(t-s)y(s)\,ds = f(t). \tag{10}$$

To determine the regularization parameter α, we shall use a method of model examples, applying it to the Volterra equation of the first kind [15].

According to the above experiment, we determined a reaction of the system on a sinusoidal infrared flux (Fig. 3, curve 1). The period and amplitude of the input sinusoidal signal are given the values, respectively, 28 s and 18.01 mV. Therefore, according to the technique of model examples, considering $y_Q(t)=18.01\sin(2\pi/28)t$, ($t \in [0, T]$), we compute the integral

$$f_Q(t)=\int_0^t \tilde{K}(t-s)y_Q(s)ds, \qquad (11)$$

by the quadrature method.

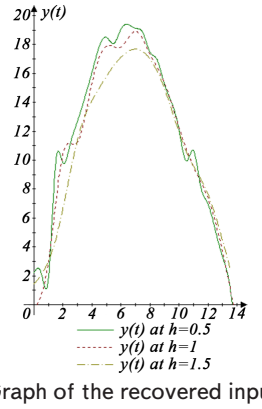

Fig. 2. Graph of the recovered input signal

$f_Q(t)$ (Fig. 3, curve 2), derived in this case, is disturbed by a certain error ξ, such that condition $f^*(t)=f_Q(t)+\xi f_Q(t)$ is satisfied. By applying the regularization method by Lavrentyev [17], we obtain

$$\alpha y_{Q_\alpha}(t)+\int_0^t \tilde{K}(t-s)y_{Q\alpha}(s)ds=f^*(t), \qquad (12)$$

where $f^*(t)$ is the function $f_Q(t)$, disturbed with a certain error.

To determine α_{optQ}, equation (12) was solved repeatedly by a computer applying the quadrature method. A minimum of the functional

$$\sum_{i=1}^{m}\left|y_{Q_\alpha}(t_i)-y_Q(t_i)\right|^2,$$

which matches α_{optQ}, is the only one. The resulting value for α_{optQ} was employed to solve equation (10). Fig. 4 shows several variants of the recovered input signal, obtained when solving integral equation (10) (at $\alpha=\alpha_{optQ}$) at different values for the disturbance of the right side of a model example:

– at ξ=2 % ⇒ α_{optQ}=0.0049;
– at ξ=3 % ⇒ α_{optQ}=0.0124;
– at ξ=5 % ⇒ α_{optQ}=0.0207.

One can see that the application of regularization provides for a more stable solution.

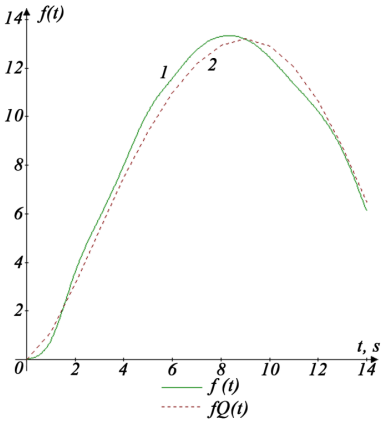

Fig. 3. Graph of curves f(t) and fQ(t)

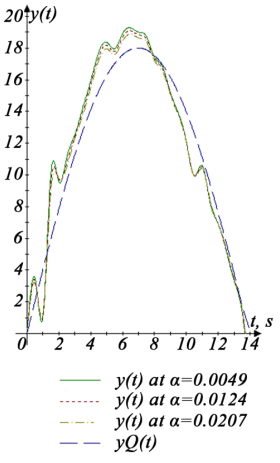

Fig. 4. Graph of the input signal recovered by the Lavrentiev regularization method

5. Discussion of results of modelling the system to measure the density of infrared radiation flows

The obtained results of numerical modelling of the system to measure the density of infrared radiation fluxes (Fig. 2–4) based on solving the inverse problem of dynamics applying the Volterra equation of the first kind (1) demonstrated the feasibility of constructing correcting computational devices.

Fig. 2 shows the restored input signal at different values for a step. One can see that an increase in step improves stability of the derived solution, which demonstrates a significant impact of step h on solving the equation (1). Application of the Lavrentiev regularization method [16] provides a possibility to derive a more stable solution when implementing the model (1).

Based on the experiment that we conducted to measure the density of a nonstationary flow of infrared radiation under the assigned law of change, characteristic of the practical working conditions of receivers, we determined a reaction of the system to the sinusoidal infrared flux (Fig. 3, curve 1). The dependence $f_Q(t)$ (Fig. 3, curve 2), derived in this case, is disturbed by a certain error ξ, such that $f^*(t)=f_Q(t)+\xi f_Q(t)$ is satisfied.

Fig. 4 shows several variants of the recovered input signal, received when solving integral equation (10) (at $\alpha=\alpha_{optQ}$) for different values of disturbance in the right part of a model example. The figure shows that the application of regularization provides for a more stable solution.

The results of modelling the system for measuring the density of infrared radiation flows, as well as the experiment, demonstrate a satisfactory agreement, which allows us to argue about the correct choice of the model's structure. The proposed algorithms could enable the numerical implementation of integrated models and form the basis for building high-performance, specialized microprocessor systems in real time in order to successfully implement the dynamic correction of a measurement system.

Despite a certain specificity of the model (1) that describes the task on restoring a signal without feedback, at present there is a rather wide choice of methods to solve them [16]. In this case, capabilites of analytical and operational methods are quite limited, and the choice of a specific numerical method depends on the character and purpose of the problem that is being addressed. When solving tasks on modeling or designing the systems of measurement, there are no strict

requirements for time costs, which is why it is possible to employ both the high-precision computational schemes and the iterative procedures. When designing algorithms for solving tasks on recovery of the input signal from a measurement system and the dynamic correction in the systems of operational measurements, management, and control, it is necessary to take into consideration a real-time mode.

6. Conclusions

1. The constructed integrated method for modeling a system to measure density of the infrared radiation fluxes based on solving the inverse problem of dynamics using the Volterra equation of the first kind has demonstrated the feasibility of construction of correcting computational devices. The developed algorithms are capable of enabling the numerical realization of integrated models and could form the basis for building high-performance specialized microprocessor systems under a real-time mode.

It should be noted that solving a problem on the structural correction of the dynamic characteristics of the infrared radiation flow density measuring system implied the construction and application of a certain unit in the transforming channel or in the system's circuit. Owing to its specially created dynamic properties, this unit ensured the best dynamic characteristics of the entire system. That makes it possible to successfully implement dynamic correction of the system to measure the infrared radiation fluxes and to greatly improve its accuracy.

2. The technique for the dynamic error compensation has been verified experimentally. To this end, we conducted experiments to measure the density of a nonstationary flow of infrared radiation under the assigned law of change, characteristic of the practical operating conditions of receivers. A change in the density of the incident flux of infrared radiation was achieved through the receiver's rotation around an axis, running through the middle of its receiving surface, in the field of a stationary emitter's flow. The result of the experiment is the derived approximation of the nonlinear experimentally obtained transitional characteristic in the form of the receiver's response to the sinusoidal flux of infrared radiation. The results of numerical simulation of the infrared radiation flow density measuring system using a computer reveal a satisfactory agreement with the experimentally acquired data. This suggests that the constructed method could be used as a tool for computer simulation in tasks on studying the systems to measure the density of infrared radiation flows.

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