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JUSTIFICATION OF THE METHOD FOR DETERMINING THE DYNAMIC PARAMETERS OF THE MOBILE FIRE FIGHTING INSTALLATION OPERATOR

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The object of this study is the process of functioning of the "man-robot" system. The task to coordinate parameters of the human operator and the robot is investigated. Aligning these parameters is based on the method of determining the dynamic parameters of the human operator using mathematical models that describe two types of relative errors. The first type includes relative errors in determining the dynamic parameters of the operator, which depend on the error in determining the signals characterizing his response to the test impact. The second type of relative errors is the methodical error, which is due to the approximation of partial derivatives.

The formation of a test impact on the operator is carried out using an interactive whiteboard. The method is based on finding the roots of a linear system of algebraic equations, for the construction of which an approximation of partial derivatives from signals characterizing the operator's response to the test effect is used. The parameters of this system of algebraic equations depend on time parameters. Determination of time parameters is carried out using tolerance criteria and using nomograms. When justifying the main parameter of the test impact on the operator – the speed of movement of the fire front on the interactive whiteboard screen, the properties of the angular eye control system of the mobile fire installation operator are used. These properties are formalized as a mathematical model of dynamic error, which occurs in the process of tracking by the operator the image of a fire on the interactive whiteboard screen. To verify the obtained results, a test problem has been solved; it is shown that the error in determining the dynamic parameters of the operator does not exceed 1.0 %.

The results reported here could be used for designing mobile fire installations of a new generation, the structure of which is based on the use of segways

Keywords: fire installation operator, dynamic parameters, test impact, operator response signal

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1. Introduction

Among the means of fire extinguishing, an important place is occupied by mobile fire installations. For example, in 2018, a fire drone produced in Latvia was effectively used. With the help of such a fire drone, fire extinguishing is possible at altitudes up to 300 m [1] without limiting the consumption of a fire extinguishing agent. In 2019, the decisive role in extinguishing a fire in the Cathedral of Notre Dame (France) was played by the mobile fire extinguishing unit “Colossus” by Shark Robotics (France) [2]. Mobile fire installations based on segway [3] can be used in patrol mode or in fire extinguishing mode. The efficiency of this type of mobile fire installations significantly depends on the degree of consistency of the characteristics of the operator and installation [4]. This problem is solved at the stage of development of mobile fire installations. When operating fire installations of this type, it is necessary to monitor and diagnose both the installations themselves and their operators. As regards the mobile fire installations themselves, these tasks are practically worked out, then in relation to the activities of operators of such installations there are a number of problems that are not solved. In particular, this concerns a reasonable choice of methods for controlling the activities of mobile installation operators. In this regard, it is relevant to substantiate the method for determining the dynamic parameters of operators of mobile fire installations, which include segway.

2. Literature review and problem statement

Industry 4.0 puts human-robot interaction at the center of the production environment [5]. A new generation of robots, cobots, increase the efficiency of the production process through the use of advanced control methods. The authors of the work pay attention to the complex dynamics of human-robot interaction, as well as the presence of a shortage of mathematical models in real time. To determine the model of human interaction and robot, an ensemble of artificial neural networks is used. But such model needs constant updating while performing common tasks. Within Industry 4.0, the authors of [6] consider machine learning as the latest approach to building cognitive models. The analysis of learning algorithms and their features, as well as recognition methods is provided. It should be noted that the authors focus on models that describe the "machine" side of human-robot interaction (HRC), and operator models are not considered. Paper [7] reports the results of the design, development, and evaluation of architecture, which includes task planning, sensors, and control of robots in the industrial environment. This architecture involves the use of AND/OR graphs in models of human interaction and online work. Human models are not explicitly considered. Of the same type is work [8], which declares the need to accurately determine human behavior when it is included in the automated system. This requires objective indicators that follow from the corresponding mathematical models. Such models are not given in the work. The term "reliable human operator models" is used, but reliability indicators of such models are also not given. In work [9], there is a tendency to take into account various factors in the mathematical description of the human operator, in particular, in the event of emergencies. There is no information on models that reflect the behavior of the human operator in such situations. It should be noted that the effectiveness of interaction in such systems is ensured mainly by the machine component. Thus, within the concept of physical interaction between a person and a robot (pHRI), controllers are used [10]. For their construction, methods of optimal design based on Lyapunov's functions, strategies based on a mixed Gauss model and primitive dynamic motion are used. A person is assigned a passive role and his mathematical description is trivial. In [11], to create a controller, a neural network with a radial basis function (RBFNN) is used in conjunction with Lyapunov's barrier functions (BLF). This approach provides universal properties of the controller, but at the same time there is an open question regarding the influence of human characteristics on the efficiency of the man-machine system. One of the ways to take into account the characteristics of a person in such systems is related to obtaining information about human actions in real time. Work [12] reports the results of research within the concept of pHRI using appropriate tests to control the mobile robot E-puck (Switzerland). Control is carried out using appropriate algorithms that use information from primary sensors. But at the same time, formalizations are used in the form of mathematical models of a person, as a result of which there are opportunities to create emergencies. Such abnormal situations are possible due to human actions, they can be both objective and subjective. One of the directions of implementation of the concept of this type is to predict human behavior, for example, using a recursive Bayesian classifier [13] using tracking the position of the head and hands. It should be noted that due to the lack of a data verification procedure for determining the kinematic parameters of a person, abnormal situations may also occur. To prevent the occurrence of such situations, one of the ways is to control the functioning of a person in the "man-machine" system. Work [14] indicates the need for constant monitoring of the state of the human operator, which is due to the maintenance at the required level of efficiency of the functioning of the cyberphysical system. An approach to the formation of a human operator model based on the concept of a hierarchical representation of a virtual model of a complex system is provided. This approach complicates the human-operator model and requires constant adjustment of its parameters. To determine the characteristics of the human operator, one can use simulators "man in the circuit" [15]. But with this approach, the characteristics of the human operator are determined, which reflect its integral properties. In [16], using the virtual reality method, estimates of such operator indicators as the response time to an emergency and the time of the task are obtained. It should be noted that depending on the nature of the emergency and the type of tasks, the values of these indicators will vary. The method used by the authors does not provide identification of such dynamic parameters of the human operator as the time of delay and the constant of time. The process of adaptation of the human operator to perform typical tasks was studied in [17]. The delay time of the human operator, which is included in the control circuit of the automated system, was set a priori. It should be noted that the work does not provide an algorithm for controlling the delay time of the human operator. When adapting a human operator to perform typical tasks, there is a transition period in which the amount of the delay time tends to decrease. This fact is paid attention in work [18]. In the same paper, estimates of the dynamic parameters of the operator of a mobile fire installation based on a segway were obtained. Dynamic parameters of the operator of a mobile fire installation of a new type – the time of delay and the time constant is determined according to the method given in [19]. When determining the dynamic parameters of the operator, there is no justification for choosing the parameters of the method itself. In [20], a method for determining the dynamic parameters of operators of mobile fire installations, which is based on the use of frequency characteristics of operators, is given. Determining these frequency characteristics requires a lot of time and complex equipment. As a result, it is impossible to express determination of the dynamic parameters of operators of mobile fire installations. One of the ways out of this situation is to switch to methods for determining dynamic parameters in the time domain, which requires justification for the choice of test impact parameters on the operator.

Thus, an unsolved problem is the coordination of the parameters of the human operator and the robot. All this gives reason to argue that it is expedient to conduct a study aimed at substantiating the method for determining the dynamic parameters of operators, in particular, the time of delay and the constant of time of operators of mobile fire installations of a new type.

3. The aim and objectives of the study

The aim of this work is to substantiate the method of determining the dynamic parameters of the operator of a mobile fire installation based on segway. This opens up opportunities during the operation of such installations to ensure the control over the activities of their operators using dynamic parameters.

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

– to build analytical dependences to determine the dynamic parameters of the operator;

– to justify the choice of values of time parameters that determine the measurement conditions for the formation of parameters of analytical dependences;

– to justify the choice of the value of the speed parameter of the test impact on the operator, to verify the method for determining the dynamic parameters of the operator.

4. The study materials and methods

The object of this study is the process of functioning of the "man-robot" system. The main hypothesis of the study is that in order to simplify the mathematical dependences that represent transcendental equations with respect to the dynamic parameters of the operator, it is necessary to use the approximation of partial derivatives from the signals characterizing its reaction to the test effect. This approach provides a transition to a linear system of algebraic equations, the roots of which are the dynamic parameters of the operator. In determining the signal model that characterizes the operator's response to the test effect, the properties of the Laplace integral transformation, in particular, the Borel theorem, are used. To derive analytical dependences regarding the dynamic parameters of the operator, methods of mathematical analysis and linear algebra are used. Justification of the choice of the value of time parameters for determining the measurement conditions is carried out using the theory of measurements, in particular, using models of relative errors. When justifying the choice of the speed parameter of the test impact, the methods of the theory of automatic control were used.

5. The results of research on the justification of the method for determining the dynamic parameters of the operator of a mobile fire installation

5. 1. Construction of analytic dependences for determining the dynamic parameters of the operator

The properties of the operator of a mobile fire installation, in particular on the basis of a segway, are described by its transfer function, which takes the following form [18]:

$$W(p)=K\exp(-p\tau_0)(\tau p+1)^{-1}, \tag{1}$$

where K – transfer coefficient; τ_0, τ – dynamic parameters, respectively, the time of delay and the time constant; p is a complex variable.

To determine the dynamic parameters of the operator τ_0, and τ, an installation is used, the scheme of which is given in [21]. The test effect, which is described by the $x(t)$ function, is set using an interactive whiteboard. On the screen of this interactive whiteboard, an image of a fire is formed, the front of which moves in time at a constant speed a. For the function $x(t)$, the following expression holds:

$$x(t)=at. \tag{2}$$

The operator's reaction to the test impact (2) in accordance with Borel's theorem will be determined by the signal:

$$\begin{aligned}u(t)&=L^{-1}\left[W(p)X(p)\right]=\\&=aK\tau^{-1}\int_0^{t-\tau_0}\exp\left(-\mu\tau^{-1}\right)\left(t-\tau_0-\mu\right)\mathrm{d}\mu 1\left(t-\tau_0\right)=\\&=aK\left[t-\tau_0-\tau\left[1-\exp\left(\left(-t+\tau_0\right)\tau^{-1}\right)\right]\right]1\left(t-\tau_0\right),\end{aligned} \tag{3}$$

where L^{-1} is the operator of the Laplace inverse transform; $X(p)$ – Laplace image from the function $x(t)$; $1(t-\tau_0)$ – Heaviside function.

If we take into account the derivative of function (3):

$$\frac{\partial u}{\partial t}=aK\left[1-\exp\left(\left(-t+\tau_0\right)\tau^{-1}\right)\right]1\left(t-\tau_0\right) \tag{4}$$

and take into account the ratio:

$$\begin{aligned}\frac{\partial u}{\partial t}&=\lim_{\Delta t\to 0}\left[u\left(t+\Delta t\right)-u\left(t\right)\right]\Delta t^{-1}\approx\\&\approx\left[u\left(t+\Delta t\right)-u\left(t\right)\right]\Delta t^{-1}=A\left(t\right),\end{aligned} \tag{5}$$

expression (3) can be rewritten as follows:

$$\tau_0+\tau A\left(t\right)\left(aK\right)^{-1}=t-u\left(t\right)\left(aK\right)^{-1}. \tag{6}$$

For moments in time t_1 and t_2 ($t_2>t_1$), from (6), there is a system of linear algebraic equations with respect to the dynamic parameters τ_0 and τ:

$$\begin{aligned}&\tau_0+\tau A_1\left(aK\right)^{-1}=B_1;\\&\tau_0+\tau A_2\left(aK\right)^{-1}=B_2,\end{aligned} \tag{7}$$

where the notation is taken into account:

$$\begin{aligned}&A_1=A\left(t_1\right);\;\; A_2=A\left(t_2\right);\\&B_1=t_1-u\left(t_1\right)\left(aK\right)^{-1};\;\; B_2=t_2-u\left(t_2\right)\left(aK\right)^{-1}.\end{aligned} \tag{8}$$

Defining the roots of a system of algebraic equations (7), for example, using the Kramer method leads to the following expressions for the dynamic parameters of the operator:

$$\tau_0=\left(B_1A_2-B_2A_1\right)\left(A_2-A_1\right)^{-1}; \tag{9}$$

$$\tau=\left(B_2-B_1\right)\left(A_2-A_1\right)^{-1}aK. \tag{10}$$

The implementation of the method for determining the dynamic parameters of the operator of a mobile fire installation is reduced to the formation of a test signal in the form of (3), measurement at time t_1, $t_1+\Delta t$, t_2 and $t_2+\Delta t$ of signals characterizing its reaction to this test effect, determining the parameters according to (5) and (8), and determining the values of τ_0 and τ according to (9) and (10). But at the same time, it is necessary to determine the choice of the value for such parameters as t_1, t_2, Δt and a.

5. 2. Justification of the choice of values of time parameters

To select time parameters t_1 and t_2, we use expressions for the relative errors $\delta\tau_0$ and $\delta\tau$ to determine the dynamic parameters of the operator. These expressions are of the form:

$$\delta\tau_0=u\left(t\right)\left(\tau_0 abs\frac{\partial u}{\partial\tau_0}\right)^{-1}\delta u; \tag{11}$$

$$\delta\tau=u\left(t\right)\left(\tau abs\frac{\partial u}{\partial\tau}\right)^{-1}\delta u, \tag{12}$$

where δu is the relative error in determining the signal u(t).

Due to the fact that for partial derivatives there is:

$$abs\frac{\partial u}{\partial\tau_0}=aK\left[1-\exp\left(\left(-t+\tau_0\right)\tau^{-1}\right)\right]1\left(t-t_0\right); \tag{13}$$

$$abs\frac{\partial u}{\partial \tau}=aK\begin{bmatrix}1-(t+\tau-\tau_0)\tau^{-1}\times\\ \times\exp\left((-t+\tau_0)\tau^{-1}\right)\end{bmatrix}1(t-t_0), \tag{14}$$

then expressions (11) and (12) finally take the form:

$$\delta\tau_0=\left[t-\tau_0--\tau\left[1-\exp\left((-t+\tau_0)\tau^{-1}\right)\right]\right]\times$$
$$\times\left[\tau_0\left[1-\exp\left((-t+\tau_0)\tau^{-1}\right)\right]\right]^{-1}\delta u; \tag{15}$$

$$\delta\tau=\left[t-\tau_0-\tau\left[1-\exp\left((-t+\tau_0)\tau^{-1}\right)\right]\right]\times$$
$$\times\left[\tau\left[1-(t+\tau-\tau_0)\tau^{-1}\exp\left((-t+\tau_0)\tau^{-1}\right)\right]\right]^{-1}\delta u. \tag{16}$$

In these expressions, their nominal values are used as values of parameters τ_0 and τ. Thus, according to [18], $\tau_0=0.2$ s and $\tau=0.3$ s can be taken as such values. Fig. 1, 2 show the graphical dependences $\delta\tau_0=f(t)$ and $\delta\tau=f(t)$ at δu=const, $\tau_0=0.2$ s, $\tau=0.3$ s.

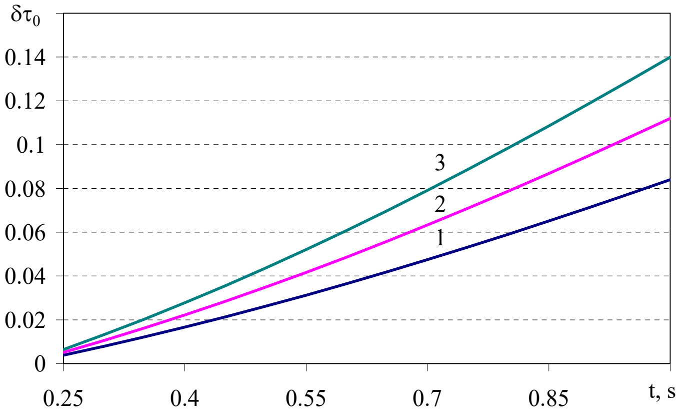

Fig. 1. Dependence $\delta\tau_0=f(t)$ at δu=const: 1 – $\delta u=0.03$; 2 – $\delta u=0.04$; 3 – $\delta u=0.05$

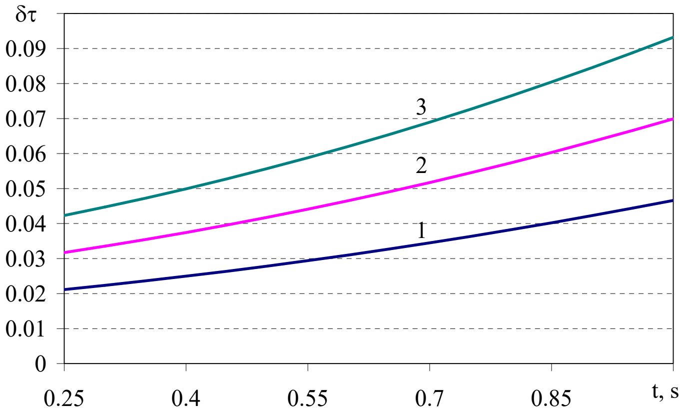

Fig. 2. Dependence $\delta\tau=f(t)$ at δu=const: 1 – $\delta u=0.02$; 2 – $\delta u=0.03$; 3 – $\delta u=0.04$

The choice of the value of the time parameters t1 and t2 is carried out using criteria:

$$\delta\tau_0(t_i)\le\delta\tau_{0\,adm},\quad \delta\tau(t_i)\le\delta\tau_{adm},\quad i=1,2. \tag{17}$$

For example, for $\delta\tau_{0\text{ adm}}=\delta\tau_{\text{adm}}=5{,}0$ % and $\delta u=3{,}0$ %, according to Fig. 1, 2, it can be assumed that $t_1=0.5$ s, and $t_2=0.6$ s.

To determine the value of the time parameter Δt, we use the expression for the relative methodical error δ, which is described by the expression:

$$\delta=A(t)\left(\frac{\partial u}{\partial t}\right)^{-1}-1=\begin{bmatrix}\Delta t-\tau\exp\left((-t+\tau_0)\tau^{-1}\right)\times\\ \times\left[1-\exp\left(-\Delta t\tau^{-1}\right)\right]\end{bmatrix}\times$$
$$\times\left[\Delta t\left[1-\exp\left((-t+\tau_0)\tau^{-1}\right)\right]\right]^{-1}-1. \tag{18}$$

Fig. 3 shows the dependence $\delta=f(t,\Delta t)$ at $\tau_0=0.2$ s and $\tau=0.3$ s.

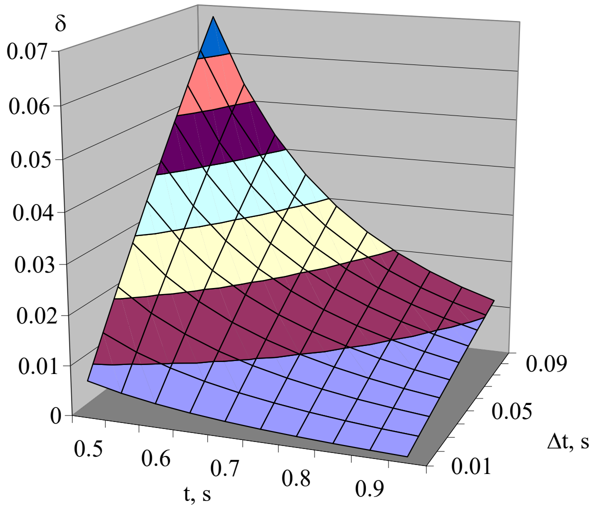

Fig. 3. Dependence $\delta=f(t,\Delta t)$

The selection of the value of the time parameter Δt is carried out using the criterion:

$$\delta(t_1,\Delta t)\le\delta_{adm}. \tag{19}$$

For example, according to the data shown in Fig. 3, at $\delta_{\text{adm}}=3.0$ %, the value of Δt can be chosen as equal to 0.03 s.

5. 3. Justification of the choice of the value of the speed parameter

To determine the value of parameter a, consider the angular control system of the operator's eyes. The functioning of such a system is described by the model:

$$\beta(p)=\alpha(p)\prod_{i=1}^{3}W_i(p), \tag{20}$$

where $\alpha(p)$ – Laplace image from the angular position of the combustion site on the interactive whiteboard screen; $\beta(p)$ – Laplace image of the angular position of the optical axis of the operator's eye; $W_i(p)$ is the i-th component of the transfer function of the operator's angular eye control system.

The transfer function $W_1(p)$ describes the operation of photoreceptors – cones of the operator's mesh of the eye and takes the following form:

$$W_1(p)=\sum_{k=1}^{n}K_k, \tag{21}$$

where K_k is the gain of the k-th cone.

When $K_k=K_0=\text{const}$, the expression for $W_1(p)$ is transformed to the form:

$$W_1(p)=nK_0. \tag{22}$$

The transfer function $W_2(p)$ describes the operation of the nerve communication channel, which is created by affective and effective nerve fibers over the delay time of τ_1. This transfer function takes the following form:

$$W_2(p)=\exp(-p\tau_1)\left[1+\exp(-2p\tau_1)\right]^{-1}. \tag{23}$$

Due to the fact that $\tau_1 \leq 0.05$ s, as well as taking into account the ratios:

$$\exp(-p\tau_1)=1-p\tau_1;$$

$$\exp(-2p\tau_1)=1-2p\tau_1, \tag{24}$$

the expression for the transfer function is transformed as follows:

$$W_2(p)=0.5. \tag{25}$$

The transfer function $W_3(p)$ describes the operation of the subsystem that moves the eyes of the operator. This transfer function takes the following form:

$$W_3(p)=K_1p^{-1}\left[1+K_1K_2p^{-1}\right]^{-1}=\left[K_2(Tp+1)\right]^{-1}, \tag{26}$$

where $T=(K_1K_2)^{-1}$ is the time constant; K_1 – transfer coefficient of the direct link of the subsystem; K_2 – the coefficient of the feedback link of the subsystem.

Therefore, combining expressions (20), (22), (25), and (26) transforms expression (20) to the form:

$$\beta(p)=0.5nK_0\left[K_2(Tp+1)\right]^{-1}\alpha(p), \tag{27}$$

which describes the operation of the angular eye control system of the operator.

The process of tracking by the operator of the mobile fire installation of the angular position of the combustion site on the interactive whiteboard screen has a dynamic error of $\varepsilon(t)$. The expression for this dynamic error in operator form is:

$$\varepsilon(p)=0.5nK_0K_2^{-1}\left[1-(Tp+1)^{-1}\right]\alpha(p)=$$

$$=0.5nK_0K_2^{-1}Tp(Tp+1)^{-1}\alpha(p), \tag{28}$$

where $\varepsilon(p)$ is the Laplace image from the function $\varepsilon(t)$.

For the steady mode, according to the finite value theorem at:

$$\alpha(t)=bt, \tag{29}$$

where $b=\text{const}$ is the angular velocity of movement of the combustion site on the interactive whiteboard screen, we have:

$$\varepsilon_{st}=\lim_{t\to\infty}\varepsilon(t)=\lim_{p\to 0}p\,\varepsilon(p)=0.5nK_0bTK_2^{-1}. \tag{30}$$

The maximum value b_m of the angular velocity is determined under the condition that the image of the object goes beyond the area of central vision. The formalization of this condition is the condition:

$$\varepsilon_{st}\geq 2rR^{-1}, \tag{31}$$

where r is the radius of the central vision area; R – focal length of the optical system of the eye.

Combining expressions (30) and (31) yields:

$$b_m=4rK_2\left(nK_0TR\right)^{-1}. \tag{32}$$

For example, at $r=0.7$ mm; $R=18.0$ mm; $T=0.16$ s, and at $nK_0=2K_2$, the value of b_m is 0.49 s^{-1} or 28.1 deg/s.

Let's establish a relationship between the parameters a and b. To do this, we write:

$$\frac{d\alpha}{dt}=\frac{d\alpha}{dt}\frac{dx}{dx}=\frac{dx}{dt}\left(\frac{dx}{d\alpha}\right)^{-1}=a\left(\frac{dx}{d\alpha}\right)^{-1}=b \tag{33}$$

or

$$a=b\frac{dx}{d\alpha}. \tag{31}$$

The linear size x of the combustion site on the interactive whiteboard screen at a distance ℓ from the operator is determined by the expression:

$$x=\ell\,\mathrm{tg}\,\alpha. \tag{35}$$

Due to the fact that:

$$\frac{dx}{d\alpha}=\ell\left(\cos^2\alpha\right)^{-1};$$

$$\cos^2\alpha=\ell^2\left(\ell^2+x^2\right)^{-1}, \tag{36}$$

then, after merging (34) to (36), we have:

$$a=b\left(\ell^2+x^2\right)\ell^{-1}. \tag{37}$$

The value of parameter a is selected by criterion:

$$a<b_m\left(\ell^2+x^2\right)\ell^{-1}. \tag{38}$$

At $x=\ell=1.0$ m $a<0.98$ ms^{-1}.

To verify the method for determining the dynamic parameters τ_0 and the operator of the mobile fire installation, we solve the test problem. At the given $\delta\tau_{0\,adm}=\delta\tau_{adm}=5.0$ %, $\delta u=3.0$ %, $\delta_{adm}=3.0$ % and for nominal values $\tau_0=0.2$ s, $\tau=0.3$ s, we choose $t_1=0.5$ s, $t_2=0,6$ s, $\Delta t=0.03$ s. For these values of time parameters, there is:

$A_1=0.32$ Vs^{-1}, $A_2=0.37$ Vs^{-1},

$B_1=0.39$ s, $B_2=0.42$ s.

We accept that $a=0.5$ ms^{-1}; $K=1{,}0$ Vm^{-1}.

According to expressions (9) and (10), there is $\tau_0=0.198$ s; $\tau=0.3$ s, that is, the error in determining these parameters does not exceed 1.0 %.

6. Discussion of results of research on the justification of the method for determining the dynamic parameters of the operator of a mobile fire installation

Determination of the dynamic parameters of the operator of a mobile fire installation is based on the use of information contained in his reaction to the corresponding test impact. A feature of this approach is that the test impact is formed on the interactive whiteboard screen in the form of fire spreading at a constant speed. The operator's reaction model to such a test effect is determined using the Laplace integral transform using the Borel theorem. The direct use of such a model to determine the dynamic parameters of an operator leads to the need to solve algebraic equations of a transcendental type. The elimination of such a need is ensured by using the differentiation operation in relation to the signal (3), which characterizes the operator's response to the test impact. A feature of this approach is that an approximate value of the derivative of such a signal is used. This makes it possible to ensure uniformity of measurements in the formation of initial data to determine the dynamic parameters of the operator. The consequence of this methodical approach is the construction of a linear system of algebraic equations (7), the roots of which (9) and (10) are the dynamic parameters of the operator. The parameters of such a system of algebraic equations are the time moments t_1 and t_2, the time interval Δt, and the magnitude of speed a. To justify the choice of the values of time parameters t_1 and t_2 and Δt, metrological characteristics are used, in particular relative errors as a function of time. Obtained analytical dependences for relative errors in determination of dynamic parameters of the operator (15) and (16) provide ease of choice of values of time parameters t_1 and t_2. This choice is carried out under conditions (17) using graphic dependences $\delta\tau_0=f(t)$ and $\delta\tau=f(t)$ with a priori specified values of relative error δu of signal definition $u(t)$. The choice of the value of the time parameter Δt is carried out using the criterion (19). For this purpose, a graphical interpretation of the relative methodological error (18) is used, which is due to the approximation of the derivative according to expression (5). To select the value of parameter a, mathematical models are used that describe the functioning of the operator's angular eye control system. One of the features of the functioning of such a system is that it is characterized by a dynamic error $\varepsilon(t)$ when the operator tracks the angular position of the combustion sites on the interactive whiteboard screen. The magnitude of this dynamic error depends on the angular position of the combustion site on the interactive whiteboard screen and on the parameters of the operator's angular eye control system – expression (28) or expression (30). The maximum value of the angular velocity of movement of the combustion site is determined under the condition that the image of the object goes beyond the central vision area of the operator. This value is at (25÷30) deg/s and is related to the value of parameter a via condition (38). Condition (38) is used to select the value of parameter a.

Verification of the developed method using the solution of the test problem confirms the high reliability in determining the dynamic parameters of the operator of the mobile fire installation.

A feature of the method is the simplicity of its implementation, which is ensured by the use of trivial ratios (5), (8) to (10).

Thus, our research shows the validity of the method for determining the dynamic parameters of operators on the example of operators of a new type of mobile fire installations.

The advantage of our method over existing ones is that the operator of a mobile fire installation is tested in more comfortable conditions. This is ensured by the choice of test effects on the operator in the form that is formalized by expression (2). In addition, a reasonable choice of the speed of movement of the front of the combustion site on the interactive whiteboard screen was made during the formation of the test impact. It should be noted that when choosing the values of time parameters t_1, t_2 and Δt, as well as when choosing the value of the parameter a for a test impact, the tolerance criteria (17), (19), and (38) are used.

The method for determining the dynamic parameters of the mobile fire installation operator is limited by the maximum angular speed of movement of the virtual combustion site.

The disadvantage of the proposed method is the ambiguity of the choice of the value of these parameters.

Further research should be directed to the justification of the choice of optimal values of the parameters of the developed method.

7. Conclusions

1. Analytical dependences have been built to determine the dynamic parameters of the operator of a mobile fire installation, the structure of which is based on the use of approximate values of partial derivatives from signals that characterize his response to the test impact, in time. The values of these dynamic parameters are the roots of a linear system of second-order algebraic equations.

2. To determine the parameters of analytical dependences that belong to the time domain, the choice of values of these parameters is justified, which regulates the measurement conditions and includes the construction of two types of mathematical models of errors – errors that are caused by signal measurement errors characterizing the operator's response to the test impact, and methodological errors that are caused by the approximation of partial derivatives over time.

3. It is shown that the value of the speed parameter of the test impact on the operator is limited by the value of the angular velocity of movement of the combustion site on the interactive whiteboard screen, which does not exceed 30 deg/s, and the geometric parameters of the simulator device. To verify the method for determining the dynamic parameters of the operator of a mobile fire installation, a test problem was solved, and it was shown that the errors in their determination do not exceed 1.0 %.

Conflicts of interest

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

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Data availability

The data will be provided upon reasonable request.

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