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DEVELOPING A METHOD FOR DETERMINING THE DYNAMIC PARAMETERS OF THE OPERATOR OF A MOBILE FIRE ENGINE BASED ON A SEGWAY

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A method for determining the dynamic parameters of the operator of a mobile fire engine based on a segway, which fully characterize its dynamic properties – delay time and inertia was developed. The development of the method includes four stages. At the first stage, the problem of obtaining analytical relationships for determining the dynamic parameters of the operator is solved. These relationships include the frequency characteristics of the operator at a fixed frequency and its static parameter. At the second stage, the choice of a fixed frequency is substantiated using a criterion that minimizes errors in determining the dynamic parameters. It is shown that the fixed frequency for the characteristic parameters of the operator does not exceed 0.5 Hz. The third stage includes substantiation of the procedure for determining the frequency characteristics of the operator and its static parameter. The frequency characteristics of the operator at a fixed frequency and its static parameter are determined numerically. This procedure is based on using the data obtained by measuring the values of the operator's transfer function at fixed time intervals. To obtain data, an interactive analog engine is used, which can also perform the functions of a simulator. The time intervals are chosen according to the Kotelnikov-Nyquist-Shannon theorem. At the last stage, the procedure for determining the dynamic parameters of the operator of a segway-based mobile fire engine is described.

It is shown that the error in determining the dynamic parameters of the operator of a mobile fire engine does not exceed 9.0 %, if the error in determining its frequency characteristics at a frequency of 2.5 s^{-1} does not exceed 2.0 %

Keywords: operator of a mobile fire engine, segway, dynamic parameters of the operator, frequency characteristics of the operator

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1. Introduction

Among the means of fire extinguishing, mobile means are given an important place. For example, the Colossus robotic engine developed by Sharks Robotics (France) played a crucial role in extinguishing the fire at Notre Dame Cathedral (April 2019) [1]. One of the promising ways to develop mobile fire extinguishers is to use segways as their base [2]. Such a mobile fire engine is controlled by an operator whose characteristics must be consistent with those of the mobile fire engine. Such coordination of characteristics increases the efficiency of the working process [3], i. e. fire extinguishing. It should be noted that the control of a segway-based mobile fire engine has a number of specific features. One of them is that the position of the stream of extinguishing agent is controlled under the force action on the controls. In addition, it should be noted that segway-based mobile fire engines are at the initial stage of creation. The problem of substantiating the parameters and characteristics of such engines is relevant. Such parameters include dynamic parameters of the human operator, in particular, delay time and inertia. One of the urgent tasks is to determine the parameters of the human operator of a segway-based mobile fire engine.

2. Literature review and problem statement

In [4], based on the analysis of models of «human-robot» systems, the problem of inaccuracy in determining the behavior of a human as a part of automated systems was formulated. Such uncertainty complicates the prediction of human and system performance needed to design automated control systems. Conceptual approaches to solving this problem were proposed, but no specific technical solutions were given. The human operator plays a central role in industrial production [5], especially in emergencies. The paper defines how the technical characteristics of the system create the basis for the operator's work, paying attention to his qualifications and training. Special attention is paid to dealing with emergencies and related problems for the operator. But models reflecting his behavior in such situations were not given. In [6], it is noted that most of the developed human operator models do not take into account such factors as experience, workload, etc. It is shown that in some situations, the influence of these factors can be decisive. At the same time, the question remains how to take into account the characteristics of a particular person in the model parameters [7] states that humans and robots can perform common tasks that involve physical interaction. The concept of physical human-robot interaction (pHRI) involves the development of new methods to achieve a compromise between reliable stability and high efficiency of interaction. But recommendations for implementing such a concept were not considered. For the technical implementation of such methods, controllers have been developed [8], which allow reducing human effort when performing relevant tasks. However, the dynamic parameters of the system (delay time, etc.) are not taken into account. [9] shows the results of research on HRI (human-robot interaction) using gestures. But the dynamic parameters of the operator were also not considered. In [10], a method is discussed that allows controlling a mobile wheeled robot using human operator gestures. Gestures are measured by inertial sensors and processed according to the developed algorithms. The method was tested on the E-puck mobile robot (Switzerland). This paper does not use the mathematical model of the human operator, which does not allow us to generalize the results. The work [11] notes that the efficiency of a cyberphysical system depends on the adequacy of the model description, in particular, of the human operator. As a result, the authors point to the need for constant monitoring of the human operator's condition. An approach to constructing an adequate human operator model based on the concept of hierarchical representation of a virtual model of a complex system and a synergetic method of basic functions is given. Based on the test results, the parameters of the upper-level digital twin model were evaluated. The disadvantage of this approach is the complexity of the human operator model and the constant adjustment of its parameters. In [12], parameters that allow determining the readiness of the operator to perform certain tasks as part of the «human-robot» system were defined. However, the issue of building a mathematical model of the system is left out of consideration. [13] uses process simulators or «human-in-the-loop» simulators to determine the parameters and characteristics of the human operator. The disadvantage of this approach is the impossibility to generalize the results to other processes. In [14], using the «moon mission simulator» virtual reality (VR) method, estimates of the operator's performance parameters were obtained. It is shown that the time parameters (emergency response time and task execution time) tend to deteriorate under simulation conditions. At the same time, the moon-specific conditions caused by lower gravity were reproduced, which does not make it possible to use the results in terrestrial conditions. The work [15] studied the adaptation of the human operator to performing the main tasks of a manually controlled system. It should be noted that the operator's delay time was set a priori during research. However, the paper does not indicate under what conditions the value of this parameter was chosen. In addition, this parameter was not monitored during the implementation of the control algorithm. The identification procedure is based on a batch and recursive autoregressive exogenous (ARX) model to capture operator adaptation in tracking tasks. In particular, the introduction of Industry 4.0 technologies opens up new opportunities for human-machine interaction [16]. In this context, understanding and modeling the human role are an important factor in developing systems of the future. The architecture for studying both hierarchical and heterarchical decision-making processes is presented. But this approach needs to be differentiated to be implemented at the lower level of the architecture. All this gives grounds to claim that new technical solutions for building automated systems require the creation of new models or correction of existing models of the human operator. In particular, this concerns the emergence of a new class of mobile fire engines based on a segway [17]. Today there are no segway-based mobile fire engines including a human operator. Only one piece of a segway-based mobile fire engine was created [2], which does not involve a human operator during operation. The main disadvantage of such a mobile fire engine is limited tactical capabilities due to the need to connect to stationary mains with the extinguishing agent.

Autonomous segway-based fire engines are free from this drawback. Their effective use requires coordination of the technical characteristics with those of the operator. As a result, one of the problems for the effective use of such fire engines is the coordination of the characteristics of the human operator and the mobile fire engine of the new type.

3. The aim and objectives of the study

The aim of the study is to develop a method for determining the dynamic parameters of the operator of a segway-based mobile fire engine. This will make it possible to coordinate the parameters and characteristics of the human operator with those of the mobile fire engine.

To achieve the aim, the following objectives were set:

– to obtain analytical relationships for determining the dynamic parameters of the operator;

– to justify the choice of the frequency for determining the frequency characteristics of the operator;

– to formalize the procedures for determining the amplitude-frequency and phase-frequency characteristics of the operator;

– to form a sequence of procedures for implementing the method of determining the dynamic parameters of the operator.

4. Materials and methods

In determining analytical relationships between the dynamic parameters of the mobile fire engine operator and its dynamic properties, the methods of complex variable theory are used. Substantiation of the choice of frequency for determining the dynamic parameters is carried out using the methods of sensitivity theory of automated control systems and methods of mathematical analysis. Graphical interpretation of the research results is carried out using the Maple package (Canada). When obtaining the frequency characteristics of the operator, the methods of complex variable theory are used in combination with the Kotelnikov-Nyquist-Shannon theorem. The frequency characteristics of the operator are obtained using a physical analog engine.

5. Results of research to determine the dynamic parameters of the operator

5. 1. Analytical relationships for the dynamic parameters

The actions of the operator of the mobile fire engine are described by a complex transfer function as follows:

$$W(j\omega)=K\exp(-j\omega\tau_0)(1+j\omega\tau_1)^{-1}, \quad (1)$$

where K, τ_0, τ_1 are the parameters, ω is the angular frequency; j is the imaginary unit.

The expression can be rewritten as follows:

$$W(j\omega)=K\left[1+(\omega\tau_1)^2\right]^{-0.5}\exp\left[-j(\omega\tau_0+\operatorname{arctg}\omega\tau_1)\right]. \quad (2)$$

From (2), the amplitude-frequency $A(\omega)$ and phase-frequency $\varphi(\omega)$ characteristics of the operator have the following form:

$$A(\omega)=K\left[1+(\omega\tau_1)^2\right]^{-0.5}; \quad (3)$$

$$\varphi(\omega)=-\omega\tau_0-\operatorname{arctg}\omega\tau_1. \quad (4)$$

According to (3), the expression for the parameter τ_1 can written as follows:

$$\tau_1=\omega^{-1}\left[\left[K\left[A(\omega)\right]^{-1}\right]^2-1\right]^{0.5}, \quad (5)$$

and according to (4) and (5), the expression for the parameter τ_0 will be as follows:

$$\tau_0=-\omega^{-1}\left[\varphi(\omega)+\operatorname{arctg}\left[\left[K\left[A(\omega)\right]^{-1}\right]^2-1\right]^{0.5}\right]. \quad (6)$$

These expressions are the basis for developing a method of determining the dynamic parameters τ_0 and τ_1 of the mobile fire engine operator. The use of expressions (5), (6) implies that the parameter K – the transfer coefficient of the operator, as well as the amplitude-frequency $A(\omega)$ and phase-frequency $\varphi(\omega)$ characteristics of the operator, at the a priori frequency ω are known.

5. 2. Justification of the choice of frequency

To determine the a priori frequency ω, we take into account the relationship of errors in determining the amplitude-frequency and phase-frequency characteristics of the operator – ΔA and $\Delta\varphi$ depending on the errors $\Delta\tau_1$ and $\Delta\tau_0$ of the dynamic parameters of the operator.

This relationship has the following form:

$$\Delta A=\frac{\partial A(\omega)}{\partial\tau_1}\Delta\tau_1; \quad (7)$$

$$\Delta\varphi=\frac{\partial\varphi(\omega)}{\partial\tau_0}\Delta\tau_0+\frac{\partial\varphi(\omega)}{\partial\tau_1}\Delta\tau_1. \quad (8)$$

Given the relationship:

$$a(\omega)=K^{-1}A(\omega),$$

expression (7) is transformed to the following form:

$$\Delta a=\frac{\partial a(\omega)}{\partial\tau_1}\Delta\tau_1. \quad (10)$$

The partial derivatives in expressions (7)–(10) are the sensitivity functions of the operator's frequency characteristics according to the corresponding dynamic parameters.

Given that:

$$\left|\frac{\partial a(\omega)}{\partial\tau_1}\right|=\omega\tau_1\left[1+(\omega\tau_1)^2\right]^{-1.5}; \quad (11)$$

$$\left|\frac{\partial\varphi(\omega)}{\partial\tau_1}\right|=\omega\left[1+(\omega\tau_1)^2\right]^{-1}; \quad (12)$$

$$\left|\frac{\partial\varphi(\omega)}{\partial\tau_0}\right|=\omega, \quad (13)$$

expressions for the errors $\Delta\tau_1$ and $\Delta\tau_0$ are as follows:

$$\Delta\tau_1=(\omega\tau_1)^{-1}\left[1+(\omega\tau_1)^2\right]^{1.5}\Delta a; \quad (14)$$

$$\Delta\tau_0=\omega^{-1}\left[\Delta\varphi-\tau_1\left[1+(\omega\tau_1)^2\right]^{0.5}\Delta a\right]. \quad (15)$$

The errors $\Delta\tau_1$ and $\Delta\tau_0$, as follows from (14), (15), depend on the frequency ω. If the values of Δa and $\Delta\varphi$ are restricted, the minimum of the error $\Delta\tau_1$ will be reached at the frequency that is the solution of the equation:

$$\frac{\partial\Delta\tau_1}{\partial\omega}=\left[1+(\omega\tau_1)^2\right]^{0.5}\times$$
$$\times\left[3\tau_1-\omega^2\tau_1\left[1+(\omega\tau_1)^2\right]\right]\Delta a=0 \quad (16)$$

and the minimum of the error $\Delta\tau_0$ will be reached at the frequency that is the solution of the equation:

$$\frac{\partial\Delta\tau_0}{\partial\omega}=-\omega^2\left[\Delta\varphi-\tau_1^{-1}\left[1+(\omega\tau_1)^2\right]^{0.5}\Delta a\right]-$$
$$-\tau_1\left[1+(\omega\tau_1)^2\right]^{-0.5}\Delta a=0. \quad (17)$$

The solution of equation (16) is:

$$\omega_1=0.5\sqrt{2}\tau_1^{-1}, \quad (18)$$

and the solution of equation (17) is:

$$\omega_0=\tau_1^{-1}\left[\left[\Delta a(\tau_1\Delta\varphi)^{-1}\right]^2-1\right]^{0.5}. \quad (19)$$

It should be noted that the frequencies ω_0, ω_1 depend on the dynamic parameter τ_1 and are indifferent to the dynamic parameter τ_0. In [18], it was experimentally determined that the value of the dynamic parameter τ_1 of the mobile fire engine operator is (0.28 ± 0.02) s. Fig. 1 shows a graphical interpretation of expression (19) at $\tau_1=0.3$ s.

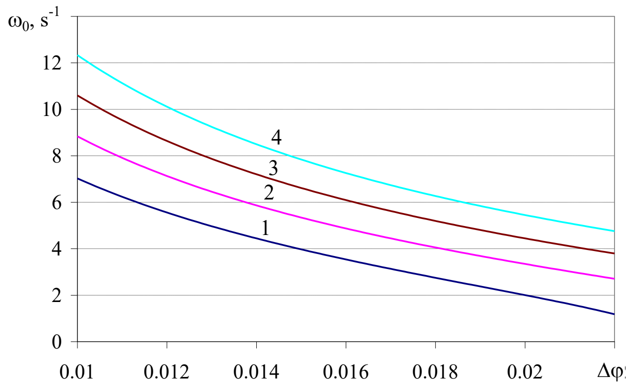

Fig. 1. Relationship between the frequency ω_0 and the error $\Delta\varphi$: 1 – Δa=0.007; 2 – Δa=0.085; 3 – Δa=0.01; 4 – Δa=0.0115

Fig. 2 shows the relationship $\Delta\tau_1=f(\omega)$ for Δa=const, and Fig. 3 – the relationship $\Delta\tau_0=f(\omega)$ for Δa=0.01 and $\Delta\varphi$=const. The relationships are given for τ_1=0.3 s.

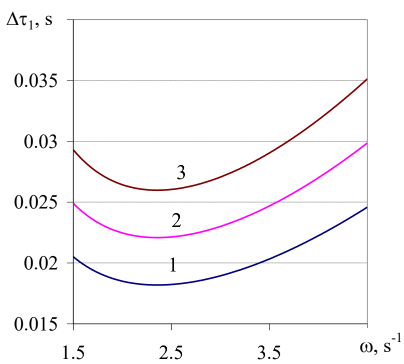

Fig. 2. Relationship between the error $\Delta\tau_1$ 1 and the frequency ω: 1 – Δa=0.007; 2 – Δa=0.085; 3 – Δa=0.01; 4 – Δa=0.0115

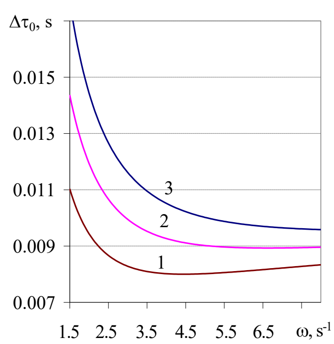

Fig. 3. Relationship between the error $\Delta\tau_0$ and the frequency ω: 1 – $\Delta\varphi$=0.01; 2 – $\Delta\varphi$=0.015; 3 – $\Delta\varphi$=0.02

Analysis of these relationships shows that:

– the extremums of the errors $\Delta\tau_1$ and $\Delta\tau_0$ are at different frequencies;

– in the frequency range of (1.5÷3.0) s^{-1}, corresponding to the minimum error $\Delta\tau_1$, the error $\Delta\tau_0$ is less than the error $\Delta\tau_1$.

Due to these features of the frequency-error relationships, it is advisable to choose the frequency when determining the dynamic parameters of the mobile fire engine operator by a criterion that minimizes the error $\Delta\tau_1$.

5. 3. Formalization of the procedure for determining the frequency characteristics of the operator

To determine the values of $A(\omega)$ and $\varphi(\omega)$, an analog engine is used, the scheme of which is shown in Fig. 4 [19]. The operator 1 is placed on the platform 4 and controls the angular position of the nozzle 3. The springs 5 provide a horizontal position of the platform 4, and the force response of the stream of extinguishing agent to the steering rack 2 is simulated using the electric drive 7 and the cable 8. The spring 6 compensates for this force action. The screen of the interactive whiteboard 9 provides test information in determining the operator's characteristics. The LED emitter is arranged on the nozzle 3.

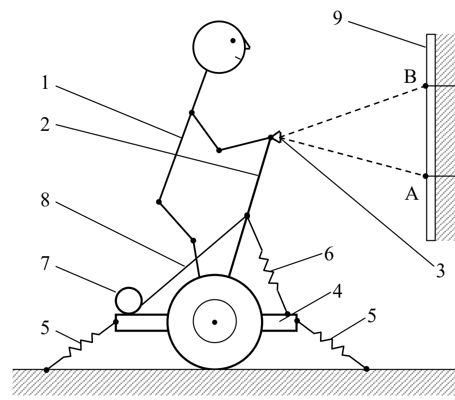

Fig. 4. Scheme of the analog engine for determining the characteristics of the mobile fire engine operator: 1 – operator; 2 – steering rack; 3 – nozzle; 4 – platform; 5, 6 – springs; 7 – electric drive; 8 – cable; 9 – interactive whiteboard

The frequency characteristics of the operator of the mobile fire engine are determined as follows. The operator 1 uses controls to change the angular position of the nozzle 3 so that the light signal from the LED emitter was at point A. After that, the position of the combustion source changes abruptly – its center moves to point B, i. e. by the distance Q relative to point A. The operator 1 monitors this change in the combustion source position, which is formalized as a signal u(t).

The test signal set on the screen of the interactive whiteboard 9 is described as follows:

$$x(t)=Q\cdot 1(t), \qquad (20)$$

where $1(t)$ is the Heaviside function.

At each of the time points separated by the value Δt, the gain Δu_k of the signal $u(t)$ is measured [20]:

$$\Delta u_k=u_{k+1}-u_k,\ \ k=\overline{0,n}. \qquad (21)$$

The value of the interval Δt is chosen according to the Kotelnikov-Nyquist-Shannon theorem:

$$\Delta t=0.5 f_m, \qquad (22)$$

where f_m is the maximum spectrum frequency of the function $x(t)$. The expression for the function $u(t)$ can be written as follows:

$$u(t)=\sum_{k=0}^{n}\Delta u_k 1\left[t-(k+0.5)\Delta t\right], \qquad (23)$$

as a result, taking into account (20), the complex transfer function of the operator will have the following form:

$$W(j\omega)=Q^{-1}\sum_{k=0}^{n}\Delta u_k\begin{bmatrix}\cos\left[\omega(k+0.5)\Delta t\right]-\\-j\sin\left[\omega(k+0.5)\Delta t\right]\end{bmatrix}. \qquad (24)$$

Such a complex transfer function corresponds to the expressions for the amplitude-frequency $A(\omega)$ and phase-frequency $\varphi(\omega)$ characteristics of the operator:

$$A(\omega)=Q^{-1}\begin{bmatrix}\left(\sum_{k=0}^{n}\Delta u_k\cos\left[\omega(k+0.5)\Delta t\right]\right)^2+\\+\left(\sum_{k=0}^{n}\Delta u_k\sin\left[\omega(k+0.5)\Delta t\right]\right)^2\end{bmatrix}^{0.5}; \qquad (25)$$

$$\varphi(\omega)=-\mathrm{arctg}\begin{bmatrix}\left(\sum_{k=0}^{n}\Delta u_k\sin\left[\omega(k+0.5)\Delta t\right]\right)\times\\\times\left(\sum_{k=0}^{n}\Delta u_k\cos\left[\omega(k+0.5)\Delta t\right]\right)^{-1}\end{bmatrix}. \qquad (26)$$

From (25) follows the expression for the static parameter of the operator – the transfer coefficient K, which has the following form:

$$K=A(0)=Q^{-1}\sum_{k=0}^{n}\Delta u_k. \qquad (27)$$

Note that no additional measurements are required to determine the static parameter. This parameter is determined numerically using information about the operator's response to the test signal (20).

5. 4. Method for determining the dynamic parameters of the operator

The method for determining the dynamic parameters of the operator of a segway-based mobile fire engine is based on the use of expressions (5), (6). This method consists in sequential implementation of the following procedures:

– the operator is placed on the analog engine (Fig. 4);

– using an interactive whiteboard, a test signal is formed in the form of (20);

– at each of the time points separated by the value Δt, determined by expression (22), the gains Δu_k, $k=0..n$ of the output signal (operator's response to the test signal) $u(t)$ are measured;

– the a priori frequency ω is selected from the frequency range of $(1.5\div3.0)$ s^{-1};

– for the a priori frequency ω, the values of $A(\omega)$ and $\varphi(\omega)$ are determined using expressions (25) and (26);

– the static parameter K of the operator is determined using expression (27);

– the values of ω, K, $A(\omega)$ and $\varphi(\omega)$ are used to determine the dynamic parameters τ_1, τ_0 using expressions (5) and (6);

– the dynamic parameter τ_1 determined by expression (5) is used to form a new value of the a priori frequency ω_1 using expression (18);

– the amplitude-frequency $A(\omega_1)$ and phase-frequency $\varphi(\omega_1)$ characteristics of the operator are determined using expressions (25) and (26);

– the values of ω_1, K, $A(\omega_1)$ and $\varphi(\omega_1)$ are used to determine the final values of the dynamic parameters τ_1, τ_0 of the mobile engine operator using expressions (5), (6).

It should be noted that the implementation of this method of determining the dynamic parameters τ_1 and τ_0 of the mobile fire engine operator provides a minimum error $\Delta\tau_1$, and the error τ_0 is less than the error τ_1. It is shown that at the frequency $\omega=2.5$ s^{-1}, the errors in determining the dynamic parameters τ_1, τ_0 do not exceed 9.0 %.

6. Discussion of the results of developing a method for determining the dynamic parameters of the mobile fire engine operator

The difference between the developed method and the known ones is the use of the dynamic characteristics of the mobile engine operator. Such characteristics are determined by transforming data from the time domain to the frequency domain. Such a transformation is carried out numerically.

The dynamic parameters τ_0 and τ_1 fully characterize the dynamic properties of the operator of a segway-based mobile fire engine. The parameter τ_0 characterizes the delay time, and the parameter τ_1 – the inertial properties of the operator. These parameters are related to the frequency characteristics of the operator through analytical expressions (5), (6). As a consequence, these analytical expressions can be used in the development of a method for determining the dynamic parameters of the operator. Using these expressions requires information about the values of the amplitude-frequency $A(\omega)$ and phase-frequency $\varphi(\omega)$ characteristics at a fixed frequency. Due to the fact that the error in determining the dynamic parameters depends on the frequency – expressions (14) and (15), it is advisable to choose this frequency provided that these errors are minimum. It follows from the studies that the error in determining the dynamic parameter τ_0 is less than the error in determining the parameter τ_1. In addition, for the error in determining the parameter τ_1, there is a frequency at which the minimum error is reached. This minimum is reached at a frequency for which the expression is (18). It should be noted that for the characteristic parameters of the operator of a segway-based mobile fire engine, this frequency does not exceed 0.5 Hz. Determination of the operator's frequency characteristics at this frequency by measuring them is characterized by very low metrological indicators. A feature of determining the frequency characteristics at the a priori frequency is that it is carried out numerically using data on the time characteristic of the operator. This time characteristic of the operator is its response to the signal in the form of Heaviside function. Another feature of this approach in determining the frequency characteristics of the operator is that the static parameter of the operator is determined in parallel. This parameter is included in the expression that determines the parameters τ_0 and τ_1 of the operator.

Another feature is that an interactive analog engine is used to obtain data on the time characteristics of the operator. It should be noted that this engine can also be used as a simulator for training mobile fire engine operators.

The advantage of the developed method of determining the dynamic parameters of the operator of a segway-based mobile fire engine is that the method can be implemented simultaneously with the development of practical skills on a simulator.

The method of determining the dynamic parameters of the human operator of a mobile fire engine is focused on the representation of the human operator as a linear dynamic system. Further development of this research may be associated with the nonlinear properties of the human operator.

7. Conclusions

1. Analytical relationships for determining the dynamic parameters of the operator of a segway-based mobile fire engine, including its amplitude-frequency and phase-frequency characteristics at the a priori frequency were obtained.

2. Using the sensitivity theory of automated control systems, the choice of a priori frequency for determining the frequency characteristics of the operator was substantiated. It is shown that the minimum error in determining the operator time constant is provided at a frequency within $(1.5 \div 3.0)\ s^{-1}$, and the error in determining the delay time of the operator is less than the time constant error.

3. A formalized procedure for determining the amplitude-frequency and phase-frequency characteristics of the operator using an analog engine applying a numerical method for transforming the time domain into the frequency domain was developed.

4. The sequence of procedures for implementing the method of determining the dynamic parameters of the operator of a segway-based mobile fire engine with the minimum errors of these parameters, which do not exceed 9 %, is presented. This result is achieved through parameter optimization when choosing a priori frequency, which determines the amplitude-frequency characteristic and the transfer coefficient of the operator.

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