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JUSTIFICATION OF THE METHOD FOR DETERMINING THE RELIABILITY OF THE OPERATOR OF A MOBILE FIRE FIGHTING INSTALLATION

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The object of research is the operator of a mobile fire installation; the subject of research is the operator's characteristics, particularly his reliability. The method of determining the reliability of a mobile fire installation operator as a functional element of a dynamic system is substantiated. Operator failure is interpreted as the output of its frequency characteristics beyond permissible limits. Analytical dependences for variations of the operator's frequency characteristics on variations of its parameters – transmission coefficient, delay time, and time constant are constructed. The amplitude and phase reliability of the operator of a mobile fire installation are determined using the Laplace functions, the arguments of which are the permissible values of variations in the frequency characteristics of the operator and variations of its parameters. Determination of variations of operator parameters is carried out by the instrumental method using the operator's activity monitoring system. The test effect on the operator of a mobile fire installation is carried out in the form of a rectangular pulse that formalizes the change in the position of the combustion cell at a priori a given distance over a priori predetermined time. A signal characterizing the operator's response to the test impact is determined using the Laplace integral transform. Measuring the parameters of this signal allows you to determine the variations in operator parameters that are used to determine its reliability. It is shown that for variations of operator parameters, the values of which are 10.0 % with RMS deviations of 3.3 %, with a probability of 0.8715 the amplitude-frequency and phase-frequency characteristics at the time of its control will not differ from their nominal values by more than 5.0 %. The requirements regarding the reliability of the operator's activity control system are determined

Keywords: fire installation operator, operator reliability, parameter variations, dynamic parameters, test impact

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1. Introduction

Mobile fire installations are one of the promising directions for the development of technical means of fire extinguishing. An example of the effective use of such fire extinguishing agents is the use of the mobile installation «Colossus» by Shark Robotics (France) when extinguishing a fire in the Cathedral of Notre Dame (April 2019) [1]. In [2] it is noted that there are new technical solutions for mobile fire institutions, in particular, based on Segways. Such fire extinguishing installations include a human operator, which necessitates the coordination of the characteristics of the installation itself and the operator [3]. To determine the degree of consistency between these components, innovative approaches can be used, for example, human-oriented artificial intelligence (HCAI) methods [4]. The success of the main task of a mobile fire installation – extinguishing a fire is determined by its quality indicators, which have two components – subjective and objective. The subjective component is determined by the quality indicators of the human operator of a mobile fire installation. Such indicators of the quality of a human operator include indicators of his reliability. These indicators are of particular importance for innovative technical solutions for mobile fire installations, in particular, made on the basis of segways. In this regard, there is a need to conduct research aimed at substantiating methods for determining the reliability of operators of mobile fire installations.

2. Literature review and problem statement

In [5], using a non-traditional indicator – total equipment efficiency (OEE), the impact of human reliability on workstation performance in the short and long term is shown. For this, a simulation model is used. But the algorithm for determining indicators of human reliability remains out of consideration. The simulation model is also used in [6] to study the human factor of the Industry 4.0 system. The application of the anthropocentric approach, when a human operator makes decisions with the support of cyber-physical systems, is considered. Such an organization of management decision-making is complicated by the activities of the operator and may make an additional mistake due to the need to interact with the cyber-physical system. [7] provides data on bibliometric analysis and review of human reliability analysis (HRA) literature over two decades. 271 publications taken from the Web of Science on the collaboration network, the co-citation network, and the keyword-sharing network were analyzed. It is noted that new research trends are defined as «decision making», «data on human performance», «dependence assessment» and «ratio estimation». Analysis of the keyword-sharing network shows that «quantification» and «performance» are most common, but there are no «reliability model», «reliability determination method», or «structural reliability». In [8], it is noted that human reliability analysis (HRA) is a method of assessing human error and providing human error probabilities (HEP) for use in safety probabilistic assessment (PSA). There is no any universally accepted HRA method for obtaining HEP estimation, due to the scarcity of data for HEP prediction, as well as significant differences in HRA in the results of different experts (even when applying the same method). In [9] it is noted that the assessment of the dependence of human actions has an important role in analyzing its reliability. A new approach to the evidence network is considered, which is expanded by the rules of beliefs and measures of uncertainty. On this basis, a structure is provided for assessing dependence. But this approach does not completely include various uncertainties in the judgments of analysts and the knowledge of experts in assessing human reliability. In [10], the dependence of human reliability on external factors over time is investigated. For this, the Bayesian approach is used. A similar approach is used in [11], where human errors are assessed using the fault tree analysis (FTA) structure and using the cognitive reliability error analysis (CREAM) method in combination with a fuzzy Bayes network. Unlike [10], [11] does not lose information that is used by experts in the formation and decision-making. In [12] it is noted that modeling the interdependence between factors that influence human error in the CREAM method stimulates the use of Bayesian networks (BN) in human reliability analysis (HRA). However, identifying subjective probability for BN is often a difficult task, requiring a high level of knowledge and engineering training from experts. This paper presents a hybrid approach to combining the evidence-based argumentation approach. The essence of this approach is to develop the worst and best possible conditional probabilities for BNs, which are used in determining the probability of human error (HEP). It should be noted that this approach significantly limits the possibilities for predicting indicators of human reliability. In [13], the Success Probability Index (SLIM) method is used to predict human error by including interval types of 2 fuzzy sets (IT2ES). SLIM is used to obtain HEP evaluation, and IT2ES is responsible for the subjectivity of the process of using expert assessments. In [14] it is noted that models for analyzing human reliability, in particular, such as THERP, SPAR-H, and ASEP do not have a cognitive architecture capable of coping with human information processing. The development of ATHEANA, INTEROPS, OMAR, and PROCRU (USA), CREAM, COSIMO, MERMOS (Europe), as well as SEAMAID and SYBORG (Japan) techniques improved this situation, in particular, due to the complexity of models. But for the most part, these techniques are designed to improve the human-machine interface than to analyze human errors. In first-generation methods, such as THERP, a person is considered as a mechanical or electrical component [15]. In second-generation methods, such as CREAM, operator cognition is considered a major contributing factor to HEP. It should be noted that both generations of development have limitations: high subjectivity, lack of a causal mechanism for linking performance factors (PSF) with operator performance and incompatibility with safety assessment models. In [15] it is noted that the SLIM model is one of the widely used methods for assessing human reliability, especially when data is scarce. However, this method suffers from epistemic uncertainty, due to relying on expert judgment to determine the parameters of the model. In addition, if there are multiple tasks, then SLIM calculates the probability of human error (HEP) without taking into account dependences between tasks. One of the ways to eliminate these shortcomings is the use of the Bayesian network (BN) – the use of BN-SLIM techniques. The probabilistic structure BN allows one to consider uncertainty using previous probability distributions. It also helps reduce uncertainty when updated probabilities are replaced by previous probabilities as more information becomes available, resulting in a priori subjective estimates tending to a posteriori more objective results. But it should be noted that the use of the BN-SLIM technique only mitigates the effect of epistemic uncertainty in the calculation of HEP. In [16], attention is drawn to the need to create more systematized structures for the integration of various sources of information related to HRA (cognitive model, empirical data, and expert assessments). It also notes the need to study algorithms in order to avoid detecting many relationships through expert judgment. HRA methods need to be developed, in particular by expanding the scope (to various types of errors and other industries), due to their applicability to improve human-machine interfaces. In addition, a structured and detailed analysis of the factors influencing failure is necessary. It is noted that the Bayesian Persuasion Network (BBN) is receiving increasing attention. BBNs are models that represent and quantify probabilistic relationships between factors. It should be noted that given the limited availability of empirical data for comprehensive model validation, the phase of model development itself is of particular importance. Typically, the main source of information for developing BBN models is expert judgment. Paper [17] presents a hybrid algorithm for developing HRA methods using data from modeling causal models and cognitive science. The main elements of the algorithm include a complete set of causal factors, team tasks, human and machine events, BN causal models, and methods for updating Bayes parameters. It should be noted that the need for science-based models is a major problem in the field of HRA. To this end, there are two areas of research – the development of HRA databases and the improvement and development of methods for reliability analysis. But there is very little research on how to use new data from multiple sources to quantify HRAs based on cognitive function.

The analysis shows that determining the reliability of a human operator as an element of an automated control system requires the availability of an array of statistical data in conjunction with the use of the method of expert assessments.

In particular, the BN-SLIM technique is aimed at this. But when solving such a problem in relation to new models of technology, problems arise with the formation of arrays of statistical data and the formation of expert judgments.

All this gives reason to assert that it is expedient to conduct research aimed at creating a method for determining the reliability of a human operator of a mobile fire installation. This method should exclude the subjective factor and be focused on taking into account the dynamic properties of the operator.

3. The aim and objectives of the study

The aim of the work is to substantiate the method for determining the reliability of the operator of a mobile fire installation, which eliminates the need to use expert judgments. In practice, this opens up opportunities for obtaining express assessments in the process of selecting operators of such installations, as well as in monitoring their activities in normal operation.

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

– to build models for determining the reliability of the operator of a mobile fire installation, which are based on taking into account its dynamic properties through amplitude-frequency and phase-frequency characteristics;

– to substantiate the determination of variations of its parameters using the control system of the operator of a mobile fire installation, which are used as initial data in obtaining reliability assessments.

4. The study materials and methods

The object of research is the operator of a mobile fire installation, and the subject of research is the characteristics of the operator, in particular, the characteristics of his reliability. The main hypothesis of the study is that to determine the reliability of the operator of a mobile fire installation, an indicator of his reliability is used – the probability of trouble-free operation. This indicator is defined in terms of parametric reliability and physically means that the frequency characteristics of the operator do not go beyond the permissible limits.

To determine the reliability indicators of a mobile fire installation operator, methods of probability theory are used, in particular, Lyapunov's theorem and the Laplace function. The definition of arguments to Laplace functions is carried out using methods of mathematical analysis and using the Laplace integral transform. This approach ensures the implementation of an instrumental method for determining variations in the parameters of a mobile fire installation operator both with the help of simulators and directly using mobile fire installations. The scheme of the simulator of a mobile fire installation based on Segway is given in [18], and the scheme of construction of such mobile fire installations is presented in [19].

The main assumptions are:

– variations of the amplitude-frequency and phase-frequency characteristics of the operator of a mobile fire installation in accordance with the Lyapunov rule comply with the normal distribution law;

– test impact on the operator of a mobile fire installation is carried out by the system of monitoring its activities (when determining the parameters of the operator).

The research used methods of probability theory, methods of mathematical analysis, and the integral Laplace transform.

5. Results of justification of the method for determining the reliability of a mobile fire installation operator

5. 1. Building models to determine the reliability of a mobile fire installation operator

Mobile fire installation based on Segway refers to automated control systems, due to the inclusion of a human operator in its control loop. The probability of trouble-free operation of such a mobile fire installation in the time interval t, $t+\Delta t$ is determined by two multiplicative components – the probability of trouble-free operation of the technical part of the installation $P_T(t, \Delta t)$ and the probability of trouble-free operation of the operator $P_0(\Delta t)$:

$$P_1(t,\Delta t)=P_T(t,\Delta t)P_0(\Delta t). \qquad (1)$$

The presence of an operator in the composition of a mobile fire installation helps to increase its reliability. This is due to the possibility of compensating for failures of the technical part of a mobile fire installation due to the actions of its operator. If the operator reproduces the technical part of the installation after its failure during the time t_V with probability $PV(t_V)$, then the probability of trouble-free operation of a mobile fire installation is determined by the expression:

$$P_2(t,\Delta t)=P_0(\Delta t)\left[P_T(t,\Delta t)+\left[1-P_T(t,t_0)\right]P_V(t_V)\right], \qquad (2)$$

where t_0 is the time at which the technical part of the mobile fire extinguisher fails.

It follows from (1) and (2) that during the recovery actions of the operator, an increase in the probability of trouble-free operation of the mobile firefighting system is ensured via the quantity $\Delta P(\Delta t)$:

$$\Delta P(\Delta t)=P_0(\Delta t)\left[1-P_T(t,t_0)\right]P_V(t_V). \qquad (3)$$

The properties of the operator as an element of a dynamical system depend on his parameters and are also determined by the input and external influences. The characteristics of the operator of a mobile fire system, his parameters, and the conditions in which its operation is carried out are interconnected by functional dependencies. This gives reason to interpret the probability of trouble-free operation of the operator as the probability of non-exit of its characteristics beyond the permissible limits for some time. The output of operator characteristics beyond the permissible limits by analogy with [20] is an operator error. In general, the definition of such a probability is associated with the use of multidimensional probability density of operator characteristics. Simplification of this approach is carried out by approximating the multidimensional probability density of the operator's characteristics. The main disadvantage of this method of determining the reliability of a mobile fire installation operator is the lack of statistical data. The solution to this problem is greatly simplified if we determine the probability of compliance of the operator not with all its characteristics, but only with a generalized characteristic – functionality. For the operator of a mobile fire installation, as an element of a dynamic system, as such functional, it is logical to use its transfer function or its mathematical equivalent – amplitude-phase frequency response. This frequency characteristic has two components – amplitude-frequency $A(\omega)$ and phase-frequency $\varphi(\omega)$ characteristics, expressions for which are defined as follows [18]:

$$A(\omega) = K\left[1 + (\omega\tau_1)^2\right]^{-0.5}; \quad (4)$$

$$\varphi(\omega) = -\omega\tau_0 - \mathrm{arctg}\,\omega\tau_1, \quad (5)$$

where K, τ_0, τ_1 are the transmission coefficient, delay time, and time constant of the operator, respectively; ω is the circular frequency.

The use of expressions (4) and (5) makes it possible to reformulate the problem of determining the probability of failure-free operation of the operator of a mobile fire extinguisher as a problem of determining the probability of the frequency characteristics $A(\omega)$ and $\varphi(\omega)$ not exceeding the permissible limits. If δA and $\delta\varphi$ are variations of the frequency characteristics of the operator, then the problem is reduced to finding the probabilities:

$$P_A = P\left(\delta A < \delta A_{dop}\right); \quad (6)$$

$$P_\varphi = P\left(\delta\varphi < \delta\varphi_{dop}\right), \quad (7)$$

where δA_{dop}, $\delta\varphi_{dop}$ are the permissible values of variations in the frequency characteristics $A(\omega)$ and $\varphi(\omega)$ of the operator, respectively.

In accordance with (4) and (5), the following expressions apply to the variations δA and $\delta\varphi$:

$$\delta A = A^{-1}(\omega)\left[\frac{\partial A}{\partial K} K\delta K + \frac{\partial A}{\partial \tau_1}\tau_1\delta t_1\right] = \\ = \delta K - (\omega\tau_1)^2\left[1 + (\omega\tau_1)^2\right]^{-1}\delta\tau_1; \quad (8)$$

$$\delta\varphi = \varphi^{-1}(\omega)\left[\frac{\partial\varphi}{\partial\tau_0}\tau_0\delta\tau_0 + \frac{\partial\varphi}{\partial\tau_1}\tau_1\delta\tau_1\right] = \\ = \left[\omega\tau_0\delta\tau_0 + \omega\tau_1\left[1 + (\omega\tau_1)^2\right]^{-1}\delta\tau_1\right]\times \\ \times\left[\omega\tau_0 + \mathrm{arctg}\,\omega\tau_1\right]^{-1}, \quad (9)$$

where δK, $\delta\tau_0$, $\delta\tau_1$ are variations of parameters K, τ_0, and τ_1, respectively.

In accordance with Lyapunov's rule, the distributions of variations δA and $\delta\varphi$ can be considered to correspond to the normal law. As a result of the symmetry, which is determined by the signs of the variations of the operator parameters, the following occurs:

$$m_A = m_\varphi = 0;\ \sigma_A = \delta A_m/3;\ \sigma_\varphi = \delta\varphi_m/3, \quad (10)$$

where m_A, m_φ are mathematical expectations of variations δA and $\delta\varphi$, respectively; σ_A, σ_φ – root mean square deviations of variations δA and $\delta\varphi$, respectively; δA_m and $\delta\varphi_m$ are the absolute values of the largest values of δA and $\delta\varphi$, respectively.

The probabilities P_A and P_φ are determined using the expressions:

$$P_A = \Phi\left(\delta A_{dop}\sigma_A^{-1}\right); \quad (11)$$

$$P_\varphi = \Phi\left(\delta\varphi_{dop}\sigma_\varphi^{-1}\right), \quad (12)$$

where $\vartheta(\cdot)$ is the Laplace function.

Fig. 1, 2 show graphic dependences constructed according to expressions (8) and (9) at τ_0=0.2 s; τ_1=0.3 s; δK=$\delta\tau_0$=$\delta\tau_0$=δ.δ.

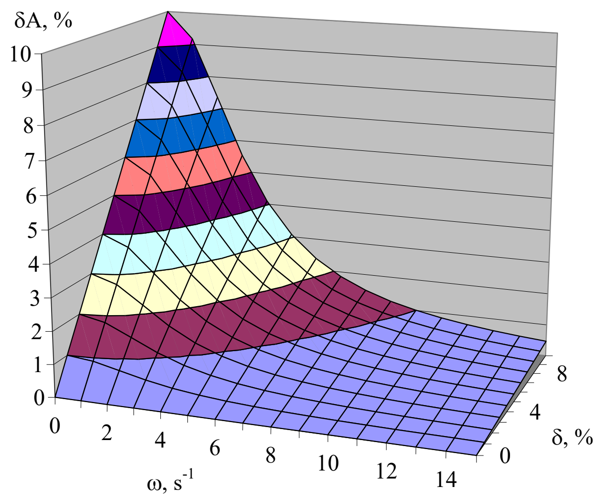

Fig. 1. The dependence of variations of the amplitude-frequency characteristic of the operator on the frequency and on the variations of its parameters at τ_0=0.2 s; τ_1=0.3 s

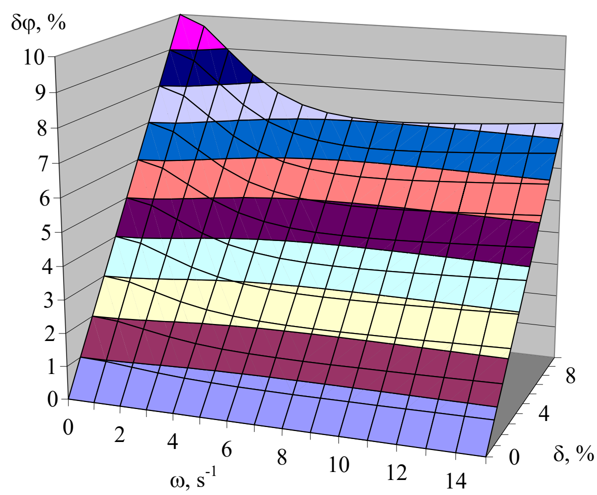

Fig. 2. The dependence of variations of the phase-frequency characteristic of the operator on the frequency and on the variations of its parameters at τ_0=0.2 s; τ_1=0.3 s

For the above dependences, δA_{m}=$\delta\varphi_{m}$=10.0 %, as a result of which σ_A=σ_φ=3.3 %. If δA_{dop}=$\delta\varphi_{dop}$=5.0 %, then P_A=P_φ=0.8715. This means that at the moment of time Δt, with a probability of 0.8715, the amplitude-frequency and phase-frequency characteristics of the operator of the mobile fire installation will not differ from their nominal values by more than 5.0 %. From Fig. 1, 2 it follows that the largest values of variations δA_m and $\delta\varphi_m$ are at $\omega\to 0$. If expressions (8) and (9) are taken into account, then for the variations δA_m and $\delta\varphi_m$ the following will occur:

$$\delta A_m = \lim_{\omega\to 0}\delta A = \delta K; \quad (13)$$

$$\delta\varphi_m = \lim_{\omega\to 0}\delta\varphi = (\tau_0\delta\tau_0 + \tau_1\delta\tau_1)(\tau_0 + \tau_1)^{-1}. \quad (14)$$

Due to the fact that the values of τ_0 and τ_1 are approximately the same [21], we can adopt $\delta\tau_0$=$\delta\tau_1$=$\delta\tau$ and expression (32) will be transformed into the form:

$$\delta\varphi_m = \lim_{\omega\to 0}\delta\varphi = \delta\tau. \quad (15)$$

When (13) and (15) are taken into account, the expressions for probabilities (11) and (12) will be:

$$P_A = \Phi\left(3\delta A_{dop}\delta K^{-1}\right); \quad (16)$$

$$P_\varphi = \Phi\left(3\delta\varphi_{dop}\delta\tau^{-1}\right). \quad (17)$$

Fig. 3 shows a graphical relationship for probability (16). Graphical dependence (17) will be identical to graphical dependence (16).

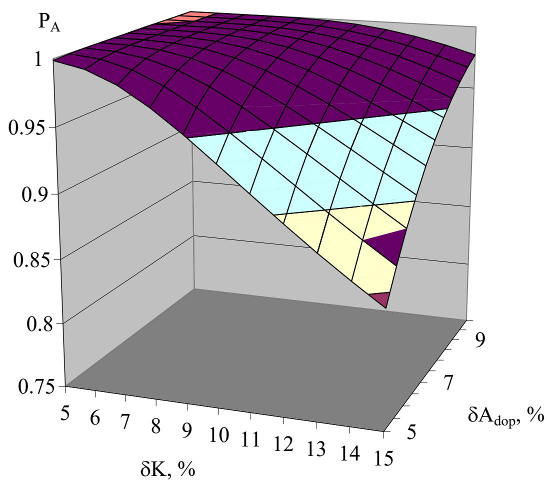

Fig. 3. Dependence of the probability of non-output of the amplitude-frequency characteristic of the operator on the permissible values of its variations and on the variations of the operator's transmission coefficient

It should be noted that tightening the requirements for variations in the amplitude-frequency characteristics of the operator of a mobile fire installation leads to a decrease in his reliability.

5. 2. Determination of variations in operator's parameters with the help of the mobile fire installation operator control system

Determination of variations in the parameters of the operator of a mobile fire installation is carried out when controlling his activities. To do this, we use the test effect on the operator, the expression of which is:

$$z(t) = B_0\left[1(t) - 1(t - T)\right], \quad (18)$$

where B_0, T – amplitude and duration of a rectangular pulse; $1(\cdot)$ – the Heaviside function.

The reaction of the operator to the test effect (18) is described by the expression:

$$x(t) = L^{-1}\left[W(p)Z(p)\right], \quad (19)$$

where L^{-1} is the inverse Laplace transform operator; $W(p)$ is the transfer function of the operator; $Z(p)$ is the Laplace image of the function $z(t)$; p is a complex variable.

Due to the fact that the transfer function $W(p)$ takes the form [22]:

$$W(p) = K\exp(-p\tau_0)(\tau_1 p + 1)^{-1}, \quad (20)$$

the expression for $x(t)$ is described as follows:

$$x(t) = KB_0\left[\begin{array}{l}\left[1 - \exp(-\dfrac{t - \tau_0}{\tau_1}\right]1(t - \tau_0) - \\ -\left[1 - \exp\left(-\dfrac{t - \tau_0 - T}{\tau_1}\right)\right]1(t - \tau_0 - T)\end{array}\right].$$

When measuring signals $x(t_i)$, the moments of time t_i, $i=1, 2, 3$ are specified a priori [23]:

$$t_1; t_2 = nt_1; t_3 = t_1 + T,$$

where $1.0 < n < 1.0 + Tt_1^{-1}$, the following holds:

$$B_1 = KB_0\left[1 - \exp\left(-\frac{t_1 - \tau_0}{\tau_1}\right)\right]; \quad (21)$$

$$B_2 = KB_0\left[1 - \exp\left(-\frac{nt_1 - \tau_0}{\tau_1}\right)\right]; \quad (22)$$

$$B_3 = KB_0\exp\left(-\frac{t_1 - \tau_0}{\tau_1}\right). \quad (23)$$

It follows from (21) and (23) that:

$$K = (B_1 + B_3)B_0^{-1}. \quad (24)$$

As a result, in accordance with (22)÷(24), it is possible to write:

$$\tau_0 - nt_1 = \tau_1\ln\left[(B_1 + B_3 - B_2)(B_1 + B_3)^{-1}\right]; \quad (25)$$

$$\tau_0 - t_1 = \tau_1\ln\left[B_3(B_1 + B_3)^{-1}\right]. \quad (26)$$

After combining (25) and (26), we have an expression for the parameter τ_1:

$$\tau_1 = (n-1)t_1\left[\ln\left[B_3(B_1 + B_3 - B_2)^{-1}\right]\right]^{-1}. \quad (27)$$

Combining (26) and (27) results in an expression for τ_0:

$$\tau_0 = t_1\ln\left[\begin{array}{l}\left[(B_1 + B_3)(B_1 + B_3 - B_2)^{-1}\right]\times \\ \times\left[B_3(B_1 + B_3)^{-1}\right]^n\end{array}\right]\times$$

$$\times\left[\ln\left[(B_1 + B_3 - B_2)B_3^{-1}\right]\right]^{-1}. \quad (28)$$

The expressions (24), (27), and (28) are used to determine variations of the corresponding operator parameters:

$$\delta K = (K - K_0)K_0^{-1}; \; \delta\tau_1 = (\tau_1 - \tau_{10})\tau_{10}^{-1};$$

$$\delta\tau_0 = (\tau_0 - \tau_{00})\tau_{00}^{-1}, \quad (29)$$

where K_0, τ_{10}, τ_{00} – nominal values of parameters K, τ_1 and τ_0, respectively.

Monitoring the activities of the operator of a mobile fire installation is carried out using a control system, the probability of trouble-free operation of which is $P_k(t_k)$.

The probability that the actions of the operator of a mobile fire installation will be recognized as correct by the result of control is described by the expression:

$$P_{21}(t,t_2) = P_0(t,t_2)P_k(t_k), \quad (30)$$

where t_k is the control time.

The probability of incorrect actions of the operator of a mobile fire installation has the expression:

$$P_{22}(t,t_k)=\left[1-P_0(t,t_k)\right]P_k(t_k)\beta P_G, \quad (31)$$

where β, P_G – completeness of control and the probability that characterizes the non-ideality of the control method.

The probability of errors of the first kind $P_{23}(t, t_k)$ and of the second kind $P_{24}(t, t_k)$ are described as follows:

$$P_{23}(t,t_k)=\left[1-P_0(t,t_k)\right]\left[1-\beta P_G P_k(t_k)\right]; \quad (32)$$

$$P_{24}(t,t_k)=P_0(t,t_k)\left[1-P_k(t_k)\right]. \quad (33)$$

The expressions (30)÷(33) allow you to formalize the degree of trust in the operator of a mobile fire installation in the form of:

$$P_{dov}(t,t_k)=\sum_{i=1}^{2}P_{2i}(t,t_k)=1-\sum_{i=3}^{4}P_{2i}(t,t_k)=$$
$$=\left[P_0(t,t_k)+\left[1-P_0(t,t_k)\right]\beta P_G\right]P_k(t_k). \quad (34)$$

The presence of a system for monitoring the activities of the operator of a mobile fire installation provides an increase in reliability in relation to his results by an amount determined by the condition:

$$P_{dov}(t,t_k)-P_0(t,t_k)>0. \quad (35)$$

When this condition is met for the control system of the operator of the mobile fire installation, the probability of its fault-free operation is determined by the inequality:

$$P_k(t_k)>\left[1+\left[1-P_0(t,t_k)\right]P_0^{-1}(t,t_k)\beta P_G\right]^{-1}. \quad (36)$$

It should be noted that for parameters β and P_G:

$$0<\beta P_G<1.0. \quad (37)$$

If we denote the right-hand side of (36) by $\alpha(P_0, \beta P_G)$, then at the end of monitoring the activity of the operator of the mobile fire installation, its graphical dependence will take the form shown in Fig. 4.

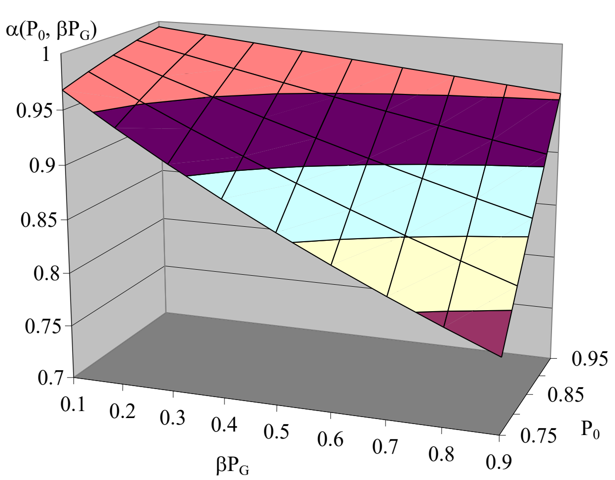

Fig. 4. Dependence of the lower limit of the probability of trouble-free operation of the operator control system on the probability of its uptime and on the completeness (β) and non-ideality of control (P_G)

To meet condition (35), the probability of trouble-free operation of the mobile fire installation operator monitoring system must be above the surface $\alpha(P_0, \beta P_G)$.

The obtained results determine the following edition of the method for determining the reliability of a mobile fire installation operator:

– with the help of the control system, a test effect is carried out on the operator in the form of a rectangular pulse with parameters B_0 and T;

– with the use of the operator's activity control system, at a priori given moments of time t_i, $i=1, 2, 3$ (t_1, $t_2=nt_1$, $t_3=t_1+T$, where $1.0<n<1.0+t_1^{-1}$) we measure the signals characterizing the operator's reaction to the test impact (18) – B_i, $i=1, 2, 3$;

– according to expressions (24), (27), and (28), the values of parameters K, τ_0 and τ_1 are determined;

– with the help of expressions (29), the variations of the parameters of the operator δK, $\delta\tau_0$ and $\delta\tau_1$ are determined;

– according to the a priori set permissible values of variations in the frequency characteristics of the operator δA_{dop} and $\delta\varphi_{dop}$ using expressions (16) and (17), we determine the indicators of the amplitude and phase reliability of the operator of the mobile fire installation. If the value of the variations of parameters $\delta\tau_0$ and $\delta\tau_1$ differ from each other, then expression (17) uses the largest of these values.

6. Discussion of the results of justification of the method for determining the reliability of the operator of a mobile fire installation

One of the factors that significantly affects the success of extinguishing a fire with a mobile fire installation is the trouble-free operation of the operator of this installation. The operator of a mobile fire installation is a functional element of a dynamic system, as a result of which its dynamic properties depend on its parameters, as well as are determined by input and external influences. These dynamic properties of the operator are determined by its characteristics, which gives grounds to interpret the probability of trouble-free activity of the operator as the probability of finding these characteristics within acceptable limits. The lack of statistical data makes it impossible to use the traditional approach, which is associated with the use of multidimensional probability density of operator characteristics. The use of methods of the theory of expert assessments introduces an essential component of subjective error. One of the ways out of this situation is an approach based on determining the probability of the operator not meeting all its characteristics, but only a generalized functional characteristic. As such functionality, an amplitude-phase frequency characteristic is used, which has two components – amplitude-frequency and phase-frequency characteristics. This allows you to reformulate the problem, which is reduced to determining the probabilities of non-exit of variations in the frequency characteristics of the operator beyond the permissible limits. Variations in the frequency characteristics of the operator according to (8) and (9) depend on the variations of its parameters – transmission coefficient, delay time and time constant, and also depend on the frequency. Under the normal law of distribution of these random variables, which takes place in accordance with the Lyapunov rule, the probabilities of non-exit of variations of frequency responses beyond permissible limits are determined through Laplace functions. This approach makes it possible to obtain estimates of the amplitude and phase reliability of the operator of a mobile fire installation at a fixed point in time. The operating frequency range of the mobile fire installation operator lies in the infrafrequency region (does not exceed (10.0–12.0) s^{-1}). This allows determining the amplitude and phase reliability of the operator through the permissible values of variations of its frequency characteristics and through the corresponding variations in the transmission coefficient and variations of time parameters – expressions (16) and (17). When determining the variations of operator parameters by instrumental methods, the influence is completely excluded expert judgments on the results of assessing the reliability of the operator. The instrumental method for determining variations in operator parameters is implemented using a system for monitoring his activities. Such a system forms a test effect on the operator in the form of a rectangular pulse that formalizes the movement of the source of fire at a priori specified distance for a priori specified time. Using the Laplace integral transform, the operator's reaction to such a test effect is determined, which allows obtaining expressions for variations of operator parameters. The degree of confidence in the results obtained through the operator's activity monitoring system is determined by the reliability of its functioning (34). If condition (36) is met, the reliability of the results obtained is increased. The method for determining the reliability of a mobile fire installation operator is presented in a verbal interpretation, it does not require the use of an array of statistical data and is free in relation to the subjective factor. This method is focused on obtaining express assessments of the reliability of operators of mobile fire installations during their training, as well as monitoring their activities in normal operation.

The peculiarity of the method for determining the reliability of a mobile fire installation operator is that, unlike the approaches provided, for example, in [11] and [16], it is not focused on the use of BN or BBN. This, in turn, excludes the subjective factor, which is due to expert judgment.

The positive properties of the method for determining the reliability of the operator of a mobile fire installation include the possibility of obtaining reliability assessments in the absence of statistical data, which is especially important for new samples of fire installations. Another advantage is the absence of dependence on expert judgments.

The limitations of the method for determining the reliability of a mobile fire installation operator are related to the type of components of its amplitude-phase frequency response.

The disadvantage of the developed method can be attributed to the complexity of the formation of test exposure to the operator during his regular work.

Further development of this direction of research may be associated with the development of methods for the formation of test effects on the operator during his regular work, as well as with conducting experimental studies aimed at obtaining estimates of its reliability indicators.

7. Conclusions

1. To determine the reliability of the operator of a mobile fire installation – amplitude and phase, models are constructed, which are based on the dependence of variations of his amplitude-frequency and phase-frequency characteristics on variations of operator parameters. As operator parameters, the transmission ratio, delay time, and time constant are used. The amplitude and phase reliability of the operator is determined using Laplace functions, the arguments of which are the permissible values of variations in the frequency characteristics of the operator and variations of its parameters. It is shown that for variations of operator parameters, the values of which are 10.0 % with RMS deviation of 3.3 %, at the time of control with probability 0.8715 the amplitude-frequency and phase-frequency characteristics will not differ with respect to their nominal values by more than 5.0 %.

2. To determine the variations in the parameters of the operator of the mobile fire installation, a system of monitoring his activity is used. With the help of the control system, the test effect on the operator is formed, and the variations of the operator parameters are determined based on the signal that characterizes his reaction to this test effect. The test-effect on the operator formalizes the movement of the combustion sites at an a priori specified value at an a priori specified time interval. A verbal interpretation of the method of determining the reliability of the operator of a mobile fire installation is provided, the implementation of which does not require the use of an array of statistical data and is free from expert judgments.

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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