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Methodological Bases of Construction of Intensive Training Flight Simulators of Aircrews

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***Abstract*—The methodical foundations for the construction of aeronautical simulators and organization of intensive training of flight crews for raising their level of training in the management of aviation complexes in emergency situations are offered. The essence of the construction of flight simulators for the organization of intensive training of flight crews is the optimal planning of the number of training tasks with unusual situations and their training on specialized flight simulators, taking into account the current level of training and the functional status of those who are trained, and restrictions on time (cost).**

Keywords—intensive training simulators, flight crew, functional status, optimal planning, training tasks, time and cost

I. Introduction And Problem Statement

Modernization and continuous improvement of modern aviation complex management systems (AC), as well as the necessity to prepare FC for work in emergency situations, raises the increased requirements for the mathematical software of specialized simulators of flight crew training centers (FC). At the same time, in order to enhance the professional skills of FC, there is a need for the development of new methods and the implementation of the latest information technologies for planning, management and control of the level of training and functional state of the FC for controlling AC in emergency situations.

As practice shows, existing training takes place without taking into account the functional states of the FC and the dynamics of the change in their level of training in the implementation of typical training tasks (TTs) regarding the controlling of AC in emergency situations [1]–[3], [9]–[11]. Currently, planning and managing the training process is based on the intuition of an experienced manager of training. Solving the problem of planning intensive training, taking into account the functional states (FS) of specialists, are sharpened in specific, extreme conditions, when physical and psycho-physiological stress of the FC sharply increases. At the same time, the lack of scientifically substantiated intensive methods and mathematical methods for planning and managing the process of training leads to inefficient use of training time and not high enough increase in the level of FC training.

Goal of the paper is the development of methodical bases for the construction of intensive flight training simulators, through which the optimal planning and management of the training process is ensured, taking into account at each stage of the training the FS and the achieved level of training of the FC with the performance of TT in emergencies.

II. Presentation of the Main Research Material

Training should be understood as pilot's (AC) possession of formed skills and the skills of purposeful perception, selection and processing of information during flight, coordinated and timely action on the management of the aircraft and its systems in ordinary and emergency situations, operational thinking, associated with the assessment of the situation, making decisions during flight and adjusting them during the task performance.

In general, training planning is a predicted N-stage dynamic process, which at each (nth) stage is characterized by two types of parameters – control parameters m_n (number of simulated emergency situations in the form of TT) and status parameters $G_n(m_n)$ (the level of training of the FC in the implementation of the TT, taking into account the FS). As a limitation on the planning and management of the intensive training process, the normative FS (K_n), total training time (T) and financial expenses (C) provided for the training of the FC.

The ultimate goal of the training (W_N) is the achievement of the FC's maximum possible level of their training in the implementation of TT with consideration of the FS in emergency situations.

A large number of factors on which the functional state depends, as well as a variety of functions, in which its specificity is manifested, is the main difficulty in solving the tasks of estimating and predicting the FS of AC crews. These tasks can only be solved by using integral methods of determining the FS.

Problems of uncertainty and multifactority arise both in the middle of each component of the FS, and when converting the set of estimates into an integral (more correctly, generalized) indicator of the FS (K_{fs}). For example, the following indicators (in the notation adopted in psychophysiology) can be used to characterize the FS of crews of AC: physiological parameters (heart rate, arterial pressure, latent period of simple sensory-motor reaction, frequency of spontaneous skin-galvanic reflexes); psychological parameters (functional mobility of nerve

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processes, activity motivation, energy indices (maximum oxygen consumption), organizing influence of emotional S-tension).

Intensive preparation of FC is possible on the basis of the use of modern intensive learning technologies. At the same time, intensive technology is defined "as a system of factors that intensify the learning process: the ideal, aimed at increasing the activity of those who are instructed, and material (technical), providing a given (maximum) level of training in the shortest possible time".

The most important for the intensification of training is the activation of the FC activity [4]–[5]. Emerging, as a result of the time deficit, the emotional reactions of the FC to a certain marginal value affect the training of specialists as an organizing factor. At the same time, motivation contributes to increasing the speed of learning the material and reducing the time and financial costs of training. However, after reaching a certain threshold of accelerated learning, emotional tension becomes a disorganizing factor in this process.

The basis of the proposed methodological approach to the intensification of training is that the "internal confidence" of operators in the limited time remaining to complete the training task, causes their state of tension. The concept of tension is realized in the aviation simulator by reducing the cycle of reflection of the educational information (the content of the training task) until the tension reaches a given level, at which the deficit of time acts as an organizing factor.

The organizing influence of emotional tension (*S*-tension) is determined by the fact that in the process of training specialists work more accurately, and the probability of correct and timely implementation of elementary training tasks increases.

To solve the classification problem, that is, the assignment of FS of AC crews, characterized by a set of indicators, to one of several states, it is proposed to apply the so-called fuzzy hybrid classifier [6]. Such a classifier is a system that combines the principles of neural network models and the fuzzy logic of data processing in structural and functional terms, respectively.

In general, the task of optimal planning and testing of different types of TT can be as follows. It is necessary to find:

$$\max W_N = \sum_{n=1}^{N} G_n(m_n) \tag{1}$$

if

$$T_N \le T; \quad C_N \le C; \quad K_{fs} \in K_n, \tag{2}$$

where K_{fs}, K_n are current and standard FS of AC crews; TN is the time spent training flight crew; CN is the costs for FC preparation during the N stages of training.

Taking into account the discrete description of the planning process, the objective function of the effectiveness of FC training (W_N) can be given in a following amount:

$$W_N = \sum_{n=1}^{N} G_n(m_n) = \frac{1}{N}\sum_{n=1}^{N} P_n(m_n), \tag{3}$$

where $P_n(m_n)$ is the level of training of FC in the implementation of the *n*th type of TT; m_n is the number of simulated emergencies at the *n*th stage of training; N is the total number of TT types (stages of training).

Thus, it is necessary to find such a number of simulated emergencies for working out typical TT's at each stage (m_n) to maximize the target function (3) under the following restrictions:

$$\left.\begin{aligned} & K_{fs} \in K_n; \\ & m_n = 0, \quad 1, \quad 2, \quad \ldots; \\ & \sum_{n=1}^{N} t_n m_n \le T; \\ & \sum_{n=1}^{N} c_n m_n \le C, \end{aligned}\right\} \tag{4}$$

where K_{fs}, K_n are current and standard FS of aircraft crews; t_n is the time of the TT at the *n*th stage of training; c_n is the cost of the use of training tools in the implementation of the *n*th type of TT.

Problems of uncertainty and multifactority arise both in the middle of each component of the FS, and when converting the set of estimates into an integral (more correctly, generalized) indicator of the FS (K_{fs}).

Thus, for example, for the characteristic of FC FS (FCFS), the following indicators can be used (in the designations adopted in psychophysiology):

a) physiological indicators $\vec{X}^F$:

- heart rate (HR), unit of measurement – bpm, scale of measurement – ratio,
- arterial tension (AT) (systolic ST and diastolic DT), unit of measurement – mmHg, measurement scale – interval,
- latent period of simple sensory-motor reaction (LPSMR), unit of measurement – ms, measurement scale – interval,
- frequency of spontaneous galvanic skin reflexes (GSR), unit of measurement – bpm, measurement scale – ratio.

b) psychological indicators $\vec{Y}^P$:

- functional mobility of nervous processes (FMNP), unit of measurement – ms, measurement scale – interval;
- motivation activity (M), unit of measurement – points, measurement scale – ordinal.

c) energy indicators $\vec{Z}^E$:

- maximum oxygen consumption (MOC), unit of measurement – ml/(min·kg), measurement scale – ratio [6].

Taking into account the specified FCFS indicators, a block diagram of calculation of K_{fs} can be represented in the form depicted in Fig. 1.

In Figure 1 by means of $\vec{\rho}_{HR/AT}$ and $\vec{\rho}_{F/P}$, the expert conclusions about the existence of dependencies between individual indicators of one or several groups of indicators are taken into account.

In order to solve the classification problem, that is, the referring of an FCFS, characterized by a set of indicators, to one of several states, it is proposed to apply the so-called fuzzy hybrid classifier [6]. Such a classifier is a system that combines the principles of neural network models and the fuzzy logic of data processing in structural and functional terms, respectively.

The given task will be solved by means of a 4-layer neuron-fuzzy network, the structural scheme of which is shown in Fig. 2.

The first layer A of the network creates the degree of referring as a measure of compliance of the measured FCFC $\{X, Y, Z\}$ indicators with given requirements.

The proposed version of the network is calculated on the 3rd level of unclear rating: "below the norm" (bn or <), "norm" (n or ≈), "above the norm" (an or >). A typical example of distribution functions for these linguistic evaluations is shown in Fig. 3.

If necessary, the resolution of such a classifier may be increased, which entails an increase in the number of neurons in the layer A, but will not affect the other layers of the network and the algorithm of its operation.

The second layer B is an aggregate for each specific indicator $x_i(y_j, z_k)$ and it is necessary in order to take into account the possibility of falling of i sign simultaneously into two classification groups (usually with different degrees of referring). For example (Fig. 3):

$$B_{11} = \tilde{\phi}_1(x) = \left\{A_{11}^F \middle| \mu_{11}(x_1),\quad A_{12}^F \middle| \mu_{12}(x_1)\right\},$$

where μ_{11} is the measure of compliance with the measurement of heart rate with the requirement "below the norm"; μ_{12} is the measure of compliance with the measurement of heart rate with the requirement of "norm".

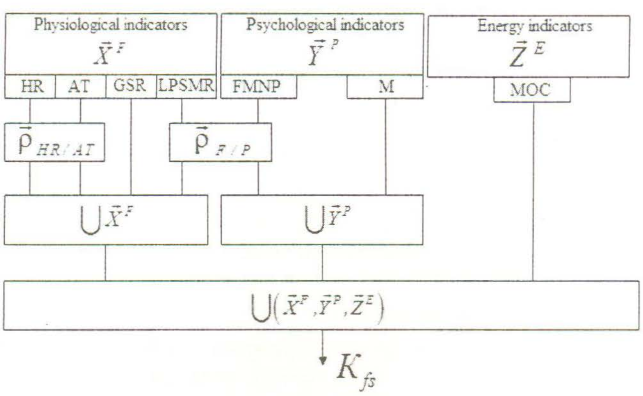

Fig. 1. Block diagram of calculation of the generalized index of the FS

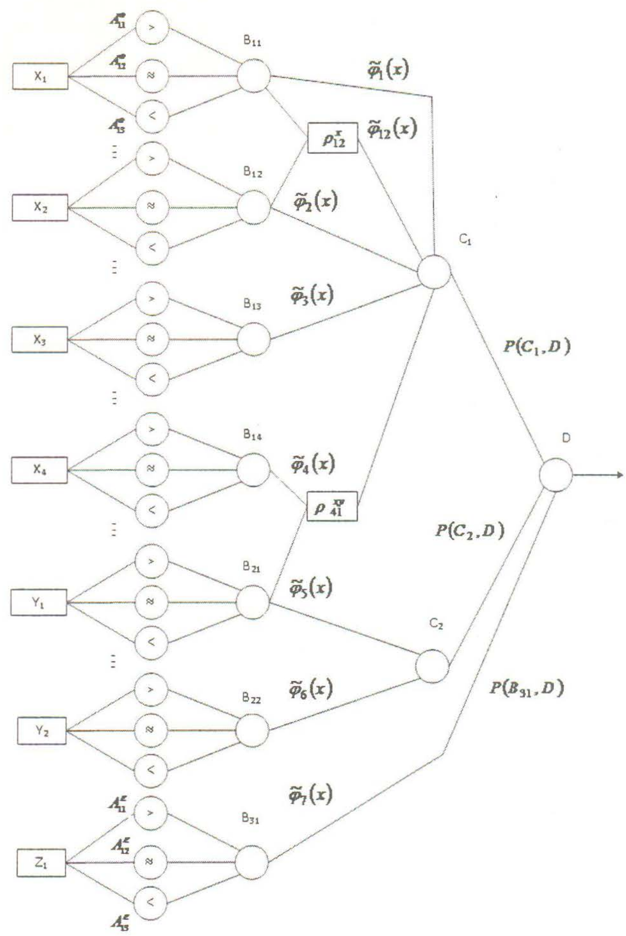

Fig. 2. Structural diagram of the interlayer neuro-fuzzy network.

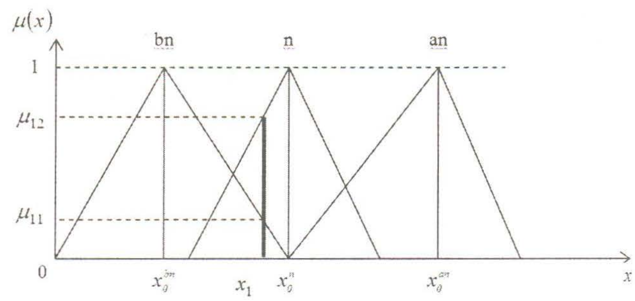

Fig. 3. An example of the functions of distributing linguistic evaluations

The third layer is intended to combine fuzzy marks within each group of indicators: physiological $\vec{X}^F$, psychological $\vec{Y}^P$ and energetic $\vec{Z}^E$. The peculiarity of the connections between the 3rd and 4th layers is the presence within the group ρ_{ij}^x and intergroup ρ_{ij}^{xy} of auxiliary functional elements that reflect the fact of the functional dependence of the corresponding (i, j) indicators. The introduction of auxiliary functional elements allows to increase the flexibility and reliability of the classifier in conditions of possible incompleteness of measurements due to time or technical problems in the regular and nonregular operation of the AC.

Thus, for example, heart rate and arterial tension are linked through the coefficient of blood flow following the empirical ratio [6]:

$$2600 = (AT\max - AT\min)\cdot HH. \quad (5)$$

Therefore, in the absence of, for example, data on blood pressure (x_2) to the input of the neuron C_1, rating of AT is provided ($\tilde{\varphi}_{12}(x)$)

$$\tilde{\varphi}_{12}(x) = \rho_{12}^{x}\left[\tilde{\varphi}_1(x)\right]$$

where ρ_{12}^{x} is the conversion operator.

Neurons layer C – standard neurons, the outputs of which are formed using activation functions of the sigmoidal type and are treated as the degree of referring (compliance measures) of the physiological (psychological, energetic) state of the FC to the specified requirements.

The fourth layer D is represented by a single neuron, the inputs of which are weighted values of compliance measures of FCFS for each group of indicators, and the output is a measure of compliance of the FCFS in general with the given requirements.

Weight balances $P(C_i, D)$ between the third and fourth layers are determined by experts in advance, depending on the specific kind of professional activity, and characterize the importance of a group of indicators for the effective functioning of FC of the AC.

The proposed neuro-fuzzy network can be classified as a synchronous multi-layer heterogeneous network with local bonds, but without feedback. The latter allows us to remove the question of the dynamic balance of the neural network, which is an important advantage of the given structure.

To find optimal values (m_n), we will use the method of dynamic programming [7] – [8].

Since there are two types of resources in the task (T and C), two parameters ξ_T and ξ_C must be entered.

Let us denote

$$\max_{m_1,\dots,m_k} \sum_{n=1}^{k} G_n(m_n)$$

on condition

$$\sum_{n=1}^{k} t_n m_n \le \xi_T; \quad \sum_{n=1}^{k} c_n m_n \le \xi_C; \; m_n \ge 0, \; n = 1,\dots,k.$$

through $\Lambda_k(\xi_T; \xi_C)$.

After simple transformations, we come to the next major recurring ratio of dynamic programming:

$$\Lambda_k(\xi_T, \xi_C) = \max_{0\le m_k \le \delta_k}\left[G_k(m_k) + \Lambda_{k-1}(\xi_T - t_k m_k; \xi_C - c_k m_k)\right]$$

where

$$\delta_k = \min\left\{\left[\frac{\xi_T}{t_k}\right]; \left[\frac{\xi_C}{c_k}\right]\right\}.$$

Simultaneously with $\Lambda_k(\xi_T; \xi_C)$ we find the optimal solution $m_k^o(\xi_T; \xi_C)$. At the Nth stage we define $\Lambda_N(T; C)$ and at the same time – $m_N^o(T; C)$.

The most significant obstacle in solving this problem is its large dimension. Therefore, in order to reduce the dimension of the problem (1), we proceed to the problem with one restriction

$$\max W_1 = \max_{\{m_n\}} \sum_{n=1}^{N} G_n(m_n) - \lambda \sum_{n=1}^{N} c_n m_n \quad (6)$$

on condition

$$\sum_{n=1}^{N} t_n m_n = T; \; m_n \ge 0,$$

where λ is the Lagrange multiplier.

Using the Lagrange method reduces the dimension and therefore the problem (6) is incomparably simpler than the initial one.

A priori value λ unknown, and therefore the problem (6) has to be solved with several arbitrary values of λ. The optimal solution of problem (6) will depend on λ:

$$m_{n\,\mathrm{opt}} = m_n^o(\lambda) \quad (n = 1, \dots, N).$$

If the found solution of $m_n^o(\lambda)$ corresponds to the restriction (4), then it is a sought-after solution to the problem (1). Otherwise value of λ needs to be corrected. In particular, if it turns out that $\sum_{n=1}^{N} c_n m_n^o(\lambda) \rangle C$, then you need to increase λ.

For quick finding of λ, the method of successive approximations can be applied [7] – [8]. If optimal solutions of $m_1^o(\lambda_1)$, $m_2^o(\lambda_2)$ for values λ_1, λ_2 were found, then in the next step we get λ_3 from the following formula

$$\lambda_3 = \frac{\lambda_2 - \lambda_1}{h_2 - h_1}(C - h_1) + \lambda_1,$$

where

$$h_2 = \sum_{n=1}^{N} c_n m_n^o(\lambda_2); \quad h_1 = \sum_{n=1}^{N} c_n m_n^o(\lambda_1).$$

Since one problem (C) is considered in task (6), therefore, one state parameter ξ_C must be entered.

Let us denote

$$\max_{m_1,\dots,m_k} \sum_{n=1}^{k} G_n(m_n)$$

on condition

$$\sum_{n=1}^{k} t_n m_n \le \xi_T; \quad m_n \ge 0,\ n = 1,\dots,k.$$

through $\Lambda_k\ (\xi_C)$.

Then the main recurring ratio of dynamic programming is as follows

$$\Lambda_k\left(\xi_C\right) = \max_{m_k}\left[G_k\left(m_k\right) - \lambda c_k m_k + \Lambda_{k-1}\left(\xi_C - c_k m_k\right)\right].$$

It should be noted that the method of dynamic programming is a directed sequential overview of options, which necessarily leads to a global maximum and optimal solution of the problem (1) [8].

In the process of planning the training using the above method for each stage of training, optimal values (m_n^o) are determined, that is, there is an optimal number of simulated emergency situations necessary to achieve the ultimate goal (W_N).

The solution of this task is carried out with the help of a special automated workplace instructor (AWI). Thanks to the developed mathematical apparatus and AWI software, in addition to determining the optimal amount of working out of different types of TTs, the content processing of the process of testing different types of TTs is also carried out in a defined time sequence. At the same time, in the database of aeronautical simulators, emergency situations on the AC, scenarios and episodes that have taken place over the past 50 years, are accumulated and saved.

In the process of training, until the goal is achieved, the following sequence of actions is carried out:

- in accordance with the optimal plan, the necessary number of emergency situations is restored for the stage-by-stage development of such a set of typical TTs, in which the achievement of the required (maximum) level of training of the FC ($\Lambda_n(\xi_n)$) is performed;
- on the basis of comparison of the current level of training of the FC in the implementation of the TT with the necessary decision on the further course of training. If the current level is not lower than the required one – the training continues. In other cases, depending on the level of training of FC at the n-th stage, there is a need for an adaptive change (re-optimization) of the plan for working out various types of training tasks. For this purpose, with the help of the above-mentioned method, for each stage (starting from the nth), the training process ensures the formation of an optimal set of working out TT taking into account the current level of FC training, their FS and restrictions on the cost and time allocated for training.

Preparation and development of intensive training courses (modules) is carried out according to the only optimal plan of intensive training, which involves a combined solution of the following two main tasks [4] and [5]:

- accelerated training of specialists to the required level for the implementation of training tasks at a minimal time (the first phase of intensive training).
- preparation of specialists for the tasks to be performed to the maximum possible level of professional training at given time (cost) constraints in the course of scheduled training (second phase of intensive training).

In general, the system of intensive training can be represented (Fig. 4) in the form of two main parts: the control object (those who are trained) and the control device (AW instructor).

The mathematical description of the system of intensive training can be presented in the following form:

$$\begin{aligned}&\phi_i[z_i(t),\ \dot{z}_i(t),\dots,z_i^{(n_K)};\ u_1(t),\dot{u}_1(t),\dots,u_1^{(k_1)}(t);\\ &u_2(t),\dot{u}_2(t),\dots,u_2^{(k_2)}(t);\ \ u_m(t),\dot{u}_m(t),\dots,u_m^{(k_k)}(t);\\ &f_1(t),\dot{f}_1(t),\dots,f_1^{(k_1)}(t);\ f_2(t),\dot{f}_2(t),\dots,f_2^{(k_2)}(t);\\ &f_m(t),\dot{f}_m(t),\dots,f_m^{(k_k)}(t)],\ i=1,2,\dots,K,\end{aligned} \qquad (7)$$

where K is the number of trainees; $z_i(t),\ \dot{z}_i(t),\dots,z_i^{(n_K)}$ are output parameters of trainee; $u_m(t),\dot{u}_m(t),\dots,u_m^{(k_k)}(t)$ is the controlling the effects of intensive training in the form of an adaptive change in the speed of performing of training tasks; $f_m(t),\dot{f}_m(t),\dots,f_m^{(k_k)}(t)$ are external influences.

When $K = 1$, the object is one-dimensional. If $K \neq 1$, then the differential equations (7), in the absence of external influence and taking into account the variables of trainees, can be represented in the normal form of Cauchy:

$$\dot{p}_i(t) = \psi(p_1(t),\ p_2(t),\ \dots,\ p_n(t);\ u_1(t),\ u_2(t),\ \dots,u_k(t)), \quad i = 1,2,\dots n. \qquad (8)$$

The outcomes (parameters) of trainees are expressed by the following form of ratios:

$$\dot{z}_i(t) = \Theta(p_1(t),\ p_2(t),\ \dots,\ p_n(t);\ u_1(t),\ u_2(t),\ \dots,\ u_k(t)), \quad i = 1,2,\dots,K. \qquad (9)$$

In the general case one can present the equation of the state of trainees, in the following form:

$$P(t) = \psi\left[P(t),\ U(t),\ t\right];\ Z(t) = \theta\left[P(t),\ U(t),\ t\right]. \qquad (10)$$

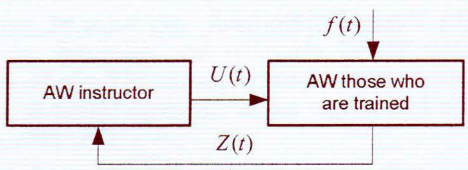

Fig. 4. Structure of the intensive training system.

Assume that at some time $t_0 = 0$, which is taken as the start of the time frame, the state vector is equal to $P(t_0)$. Assume that the moment t_0 corresponds to the beginning of the control of the process of intensive training, that is, starting from this moment on the object of training is given control $U(t)$. The set of constraints forms the area of possible values of the effects that govern. Denote this area by a symbol $\Omega(U)$. Managing influences of intensive training courses that are actually submitted to the entrance of the control object must belong to the domain of acceptable controls:

$$U(t) \in \Omega(U). \quad (11)$$

The SIP model assumes the implementation of the following two phases of the intensification of the training process:

Phase 1: accelerated training of specialists to the required level of training $P_n(t)$ at minimum time T and cost C with $K_{fs} \in K_n$. In this case, you need to find such management $U(t) \in \Omega(U)$, at which the trainees will move from state $P(t_0 = 0)$ to the required state $P_n(t)$ at minimum C and T, i.e.

$$\left[\min_{U(t)\in\Omega(U)}\right] C, T. \quad (12)$$

Phase 2: after the required level of training, the support of the acquired skills (knowledge, skills) and their further improvement at $T_N \leq T$; $C_N \leq C$; $K_{fs} \in K_n$, in this case, the initial state of specialists $P(t_0)$, the domain of admissible managements $\Omega(U)$ and the criterion of optimality are given:

$$\left[\max_{U(t)\in\Omega(U)}\right] P(t). \quad (13)$$

As can be seen from the table, applying the first version of the system provides a reduction in costs by 1.5–2 times, and the average level of training is increased by more than 15%.

III. Conclusion

Thus, on the basis of the developed methodological foundations of the construction of aeronautical simulators of intensive training of flight crews, the optimal planning and management of the training process is ensured, taking into account at each stage of the training of the FS and the achieved level of training of the FC from the performance of TT with emergency situations. Creation of intensive training systems and organization of their functioning in the form of a two-phase model of intensive training provides the professional training of specialists (FC) to the necessary (maximum possible) level of training with certain financial and time costs.

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