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ALGORITHM OF A DEVICE DESIGNED TO SUPPORT DECISION MAKING TO COUNTER THE THREAT OF AN AVIATION ACCIDENT

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Abstract

An algorithm for countering the threat of an aviation accident is proposed. It is realized in a decision-making support device, which is the main element of the aircraft flight safety control system and appears to be a dynamic expert system. A feature of the proposed device is generation of recommendations to a pilot to get out of an aviation accident upon identifying significant variation in time of the input variables affecting the aircraft flight safety based on information about psychophysical state of the pilot, technical conditions of the control object, external influencing factors, as well as forecast of alterations in the flight conditions. A corresponding block diagram is provided to describe the aircraft flight safety control system. An algorithm to support decision making by the crew is constructed making it possible to generate recommendations for the pilot and signals to the control system to increase the aircraft safety level. The set of decision-making support rules is evaluated for completeness and absence of data inconsistency. Numerical simulation of the algorithm operation accompanied by evaluation of the set of decision-making support rules confirmed its operating capability. Results obtained could be introduced in development of the aircraft flight safety control systems

Keywords

Flight safety, expert system, decision-making support

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Introduction. Aircraft industry development ensures significant increase in the operational safety of various types of aircraft. According to statistical data [1], significant number (up to 87 %) of aviation accidents is caused by the so-called human factor. To improve flight safety, different systems to support decision-making process by the flight crew are used taking into account the stages of flight conditions [2–10]. These include intelligent decision-making support systems that are part of the integrated control system. In this case, an expert system is used [2] synthesizing recommendations based on the information received from the operational equipment. Introduction of the expert system ensures identification of the emergency during the aircraft operation, as well as the forecast of its consequences and receipt of recommendations to reduce risks of the situation unfavorable growth. Systems were developed to ensure the required aircraft flight safety level, focused on eliminating accidents on the runway [3–5]. A method is also used envisaging generation of recommendations to the crew under dangerous flight conditions [6]. In this case, the expert system evaluates operability degree of the onboard subsystems, as well as decisions by the pilots. This makes it possible to predict emergency situations, as well as to notify the crew about them.

It should be noted that this method, due to the lack of computer simulation, does not allow evaluating characteristics of a probable catastrophic situation with the required accuracy. Another example of improving the aircraft flight safety conditions is the Automated Highly Intelligent System Ensuring the Aircraft Flight Safety designed and developed at the Gromov Flight Research Institute FSUE [7]. This system neutralizes emergencies in the aircraft control using a forecast of varying conditions and determining the degree of violations in the flight explotation requirements. In this case, an expert system is used to identify the threat of an accident based on a computer model. Disadvantages of the system include the need for significant computer calculation resources based on the aircraft flight mathematical model, as well as the lack of registration for the forecast of variations in characteristics that affect the flight safety level, including assessment of the pilot psychophysiological state.

Construction of a method for predicting the aviation accident danger degree based on control, as well as for predicting variation of characteristics that determine the aircraft flight safety level based on fuzzy algorithms, would make it possible to identify causes of the accident danger, as well as to promptly neutralize it by the crew or by means of automation.

Smart Landing intelligent system to support decision making by pilots is used abroad to prevent collision of an aircraft with the Earth, the system was developed by Honeywell Aerospace [7]. This system notifies pilots about exceeding the aircraft landing speed and about incorrect flight pattern using sound and light signals.

The above systems have certain disadvantages, and the main is impossibility to integrally evaluate the aircraft flight conditions based on a variety of influencing factors, both external and internal. These factors affect the flight safety level, which should be taken into account in the predication. Using the aviation accident predication at earlier stages would make it possible to quickly identify the accident threat and to neutralize it. Thus, a promising option for increasing the aircraft flight safety level is an appropriate system for controlling the flight safety level. Block diagram of such a system is presented in Fig. 1 [10].

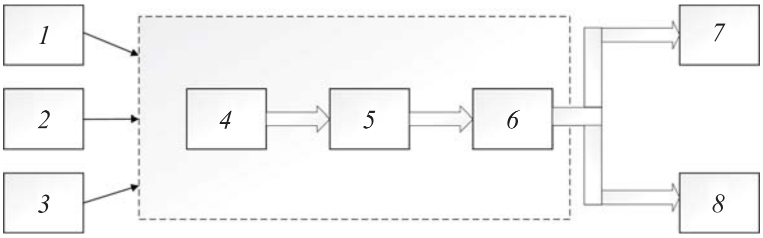

Fig. 1. Block diagram of the aircraft flight safety control system:
1 is state of the pilots; *2* is state of the external influencing factors; *3* is state of the complex onboard equipment; *4* is data preprocessing system; *5* is decision-making support system; *6* is information transmission system; *7* is indication and notification devices; *8* is aircraft control system

As follows from Fig. 1, data preprocessing system, decision-making support system and information transmission system are the central part of the in-flight safety control system. During preliminary data processing, the information and characteristics measurement system receiving data from the aircraft onboard equipment device generates electrical signals indicating the degree of violation of the set values that act on the object under control. On the basis of data on changes in the aircraft flight characteristics, the decision-making support system further synthesizes a conclusion that describes the value of the flight event accident rate, as well as possible ways to neutralize it. This conclusion is transmitted to the information transmission system, which generates the corresponding electrical signals. Then, they pass to the indication and notification device input. If necessary, they are also transmitted to the aircraft control system.

The proposed system to control the aircraft safety is based on the two-level approach identifying variations in its operation conditions. This ensures elimination of a false conclusion on the flight accident, as well as on its possible consequences. Converting devices and program-logic integrated circuits form the system central part. Their type is determined by the system data exchange interface with the complex onboard equipment.

Decision-making support systems are the central part of the proposed class of systems. Main functions of these systems mathematical, algorithmic and software support include generation of recommendations for pilots on observed threats of flight accidents, ways to neutralize them and mutual functioning with the on-board equipment.

Problem statement. Objective of the work is to build a decision-making support algorithm for the crew, which makes it possible to generate recommendations to the pilot and signals to the aircraft flight control system to counter the threat of an aviation accident.

The algorithm should ensure resulting signals to counter the threat of an aviation accident taking into account preliminary processing of both external and internal characteristics that determine the aircraft flight safety, as well as forecast development of the threat of an accident.

To achieve this goal, it is necessary to formalize the algorithm input variables, create a set of decision-making support rules and elaborate the decision-making support algorithm for the crew.

Formalization of input variables. The proposed decision-making support system is a dynamic expert system designed to generate recommendations for pilots to neutralize an aviation accident with varying values of the input coordinates distributed over time. The block diagram is presented in Fig. 2 [10]. Here $X(t)$ is the set of input coordinates obtained as a result of the preprocessing procedures; $X'(t)$ is the aviation accident threat forecast; $Y(t)$ is the set of output coordinates of the decision-making support block describing recommendations to pilots to counter the threat of an aviation accident or signals for automatic countering.

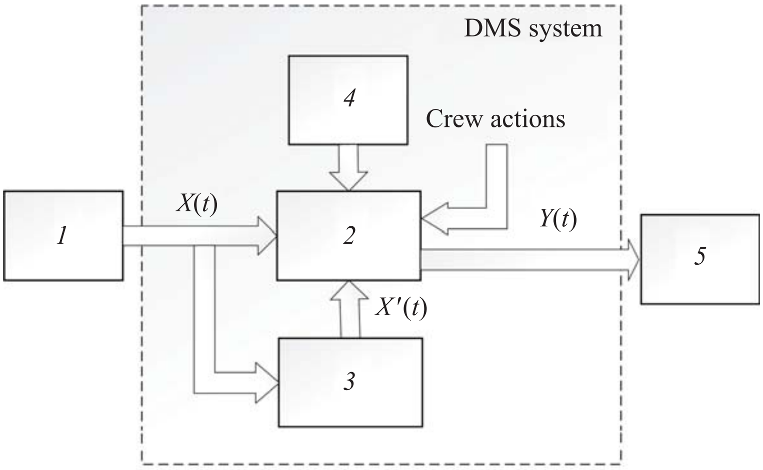

Fig. 2. Block diagram of the decision-making support system:
1 is input data; *2* is decision-making block; *3* is forecasting model; *4* is knowledge base; *5* is data transmission system

Input coordinates include characteristics (external and internal) that determine the aircraft flight safety conditions: psychophysiological state of the crew members, aircraft technical state, as well as weather conditions. In addition, estimates of the predicted controlled coordinates values, as well as flight conditions, are sent to the decision-making support system input.

Generated recommendations to a pilot are the system output information to compensate for a threat of the aviation accident, including the automatic neutralization signals. Aviation accident threats using the automation devices are neutralized in the absence of the pilot response within the observed flight conditions. To formalize a set of the decision-making support system input coordinates, a table form presented is being used (Table) [11].

DMS system input coordinates

Group	Coordinate	Variable	Forecasted variable	Identification method	Linguistic variables
Psycho-physical state of a pilot	Fatigue	x_{11}	x'_{11}	Sensor pupillary response, strain sensor	Low f_1. Medium f_2. High f_3
	…	…	…	…	…
	Stress	x_{14}	x'_{14}	Sensor pupillary response	Missing k_1. Low k_2. Medium k_3. High k_4
Aircraft state	…	…	…	…	…
External coordinates	…	…	…	…	…
Preprocessing	Flight conditions	Z	Z'	Input information processing in the preprocessing and forecast system	Satisfactory k_1. Difficult k_2. Emergency k_3. Catastrophic k_4

It follows from the data in Table that selected groups are described by a complex of input coordinates. These coordinates characterize the variable values, as well as the exposure to the action of aircraft flight conditions. These coordinates are being poorly formalized; therefore, the decision-making support system input coordinates are described in the form of fuzzy (linguistic) variables.

Each fuzzy variable is determined in the area of linguistic values of a space-time set. Similar approach in representing the input coordinates of a decision-making support system in the form of fuzzy variables provides an opportunity to develop and implement fuzzy information processing procedures, which is successfully used in these systems and in the aircraft control systems [12–14].

Creating a set of rules to support the decision-making process. According to the block diagram (see Fig. 2), the flight safety control system main elements include the decision-making block and the knowledge base. The algorithm software implementation to counter the aviation accident threat is in the decision-making block based on the input information and a set of the system knowledge base rules. The structure of the decision-making support rules to counter the aviation accident threat is as follows:

$$Rule < * >: if \quad Z = \{k_i\} \,\&\, X_{1j} = \{f_i,\, k_i\} \,\&\, X_{2j} = \{f_i,\, k_i\} \,\&\, X_{3j} = \{f_i,\, k_i\} \,\&$$

$$\& \, Z' = \{k_i\} \,\&\, X'_{1j} = \{f_i,\, k_i\} \,\&\, X'_{2j} = \{f_i,\, k_i\} \,\&\, X'_{3j} = \{f_i,\, k_i\} \;\; then \;\; Y = \{g_i\}. \qquad (1)$$

Here $Z, X_{1j}, X_{2j}, X_{3j}, Z', X'_{1j}, X'_{2j}, X'_{3j}, Y$ are the input coordinates of the decision-making block; f_i, k_i are the input values (see Table); Y is the output coordinate of the decision-making block, i.e., the control impact value to neutralize the aviation accident threat; g_i is the output coordinate.

It follows from expression (1) that the decision-making support rule has a rather complicated structure, which implementation could lead to high computational expenses. Therefore, it is expedient to structure the set of decision-making support rules by groups of the aircraft flight conditions. The set of rules output coordinate value describes control action of the crew members, its information signals, as well as automatic modification of the aircraft control system. In this case, the content of a set of rules is determined by the controlled object, the corresponding on-board equipment, as well as by the required functionality. This is being elaborated within the construction period of an aircraft flight safety control system.

The process of creating a set of rules for a decision-making support system presumes that validation thereof is quite important, which consists in evaluating completeness and consistency of conclusions generated by the system. Thus, the output data completeness characterizes the share of coverage of the output coordinate within the total range of its alterations. As a rule, completeness of the expert system set of rules is evaluated using the completeness index (CI) [15]:

$$\text{CI} = \int_u z5(u) \cup z1(u) du \,/ \int_u 1(u)\, du, \qquad (2)$$

where $1(u)$ is the output coordinate value corresponding to the full coverage of its variation range; $z5(u)$, $z1(u)$ are the output coordinate values under various conditions for the input coordinates.

Missing inconsistency in the set of rules is characterized by the same values of output data with the same values of the input data and is evaluated by the inconsistency index (II) [15] presented in our case by the following formula:

$$\mathrm{II} = 1 - \int_u z5(u) \cup z1(u)\, du \,/\, \min\left(\int_u z5(u) du; \quad \int_u 1(u)\, du \right). \tag{3}$$

Taking into account the aircraft flight conditions division into classes and applying the precedent matrix provided in [15], the following set of decision-making support rules is obtained:

1. *Accident-free flight conditions*: $Z = k_1$.

$$\textit{Rule} <1.1>:\ X_{1j} = \{f_1, k_1\} \,\&\, X_{2j} = \{f_1, k_1\} \,\&\, X_{3j} = \{f_1, k_1\},$$
$$\textit{then } Y = \{g_1\}. \tag{4}$$

Here g_1 means that the aviation accident threat is missing, countermeasures are not required.

2. *Severe flight conditions*: $Z = k_2$.

$$\begin{gathered} \textit{Rule} <2.1>: \textit{if } X_{1j} = \{f_3, k_3\} \,\&\, X_{2j} = \{f_1, k_1\} \,\&\, X_{3j} = \{f_1, k_2\}, \\ \textit{then } Y = \{g_2\}; \\ \textit{Rule} <2.2>: \textit{if } X_{1j} = \{f_3, k_4\} \,\&\, X_{2j} = \{f_1, k_1\} \,\&\, X_{3j} = \{f_1, k_2\}, \\ \textit{then } Y = \{g_2\}; \\ \textit{Rule} <2.3>: \textit{if } X_{1j} = \{f_2, k_2\} \,\&\, X_{2j} = \{f_1, k_1\} \,\&\, X_{3j} = \{f_1, k_2\}, \\ \textit{then } Y = \{g_2\}. \end{gathered} \tag{5}$$

Here g_2 is the threat of an aviation accident countered by means of automation, the aircraft controllability is increased by signals from the automatic control systems, and stability and controllability are improved.

3. *Emergency flight conditions*: $Z = k_3$.

$$\begin{gathered} \textit{Rule} <3.1>: \textit{if } X_{1j} = \{f_1, k_3\} \,\&\, X_{2j} = \{f_3, k_4\} \,\&\, X_{3j} = \{f_2, k_1\}, \\ \textit{then } Y = \{g_3\}; \\ \textit{Rule} <3.2>: \textit{if } X_{1j} = \{f_1, k_1\} \,\&\, X_{2j} = \{f_2, k_4\} \,\&\, X_{3j} = \{f_3, k_1\}, \\ \textit{then } Y = \{g_3\}; \end{gathered} \tag{6}$$

$$\begin{gathered}
Rule < 3.3 >: if\ X_{1j} = \{f_3, k_4\} \& X_{2j} = \{f_2, k_3\} \& X_{3j} = \{f_1, k_1\}, \\
then\ Y = \{g_4\}; \\
Rule < 3.4 >: if\ X_{1j} = \{f_2, k_2\} \& X_{2j} = \{f_1, k_1\} \& X_{3j} = \{f_3, k_2\}, \\
then\ Y = \{g_4\}.
\end{gathered} \tag{6}$$

Here g_3 is the crew notification about failures on board the aircraft, threat of an aviation accident with its subsequent countering by the pilot on recommendation of the voice translator; g_4 is the crew notification about failures on board the aircraft, threat followed by its countering with reconfiguration of the aircraft control system and landing at the nearest suitable site.

4. *Catastrophic flight conditions*: $Z = k_4$.

$$\begin{gathered}
Rule < 4.1 >: if\ X_{1j} = \{f_2, k_3\} \& X_{2j} = \{f_3, k_4\} \& X_{3j} = \{f_2, k_1\}, \\
then\ Y = \{g_5\}; \\
Rule < 4.2 >: if\ X_{1j} = \{f_2, k_4\} \& X_{2j} = \{f_3, k_4\} \& X_{3j} = \{f_3, k_4\}, \\
then\ Y = \{g_5\}.
\end{gathered} \tag{7}$$

Here g_5 is the crew notification about failures on board the aircraft and about the threat of an aviation accident with requirement to leave the aircraft.

The above set of rules demonstrates that, if failures in the aircraft control systems are detected, as well as if the flight weather conditions are deteriorating, an aviation accident is possible, which could further be neutralized by the crew. If deterioration in the psychophysiological state of pilots is registered in flight, as well as in the observed weather conditions, under satisfactory technical state of the aircraft, then an emergency situation is neutralized by the system controlling the aircraft flight safety. It should be noted that structure of the set of rules depending on the predicted values of alterations in the device input variables is similar to the one presented by relations (4)–(7) regarding the flight condition.

Thus, the set of rules for the decision-making support algorithm consists of two main groups: according to the current and to the forecasted flight conditions. Each of them is subdivided into four types according to the type of an accident threat.

Design and development of the crew decision-making support algorithm. An algorithm for countering the threat of an aviation accident is proposed on the basis of the obtained set of rules and of the input information for the decision-making block. The algorithm output data in the process of its software realization is light and voice information about alterations in flight conditions and threat of an aviation accident. Moreover, voice information on countering the aviation accident threat, as well as control signals, are provided through the aircraft onboard equipment systems. Fig. 3 presents the proposed block diagram of the decision support algorithm for countering the aviation accident threat.

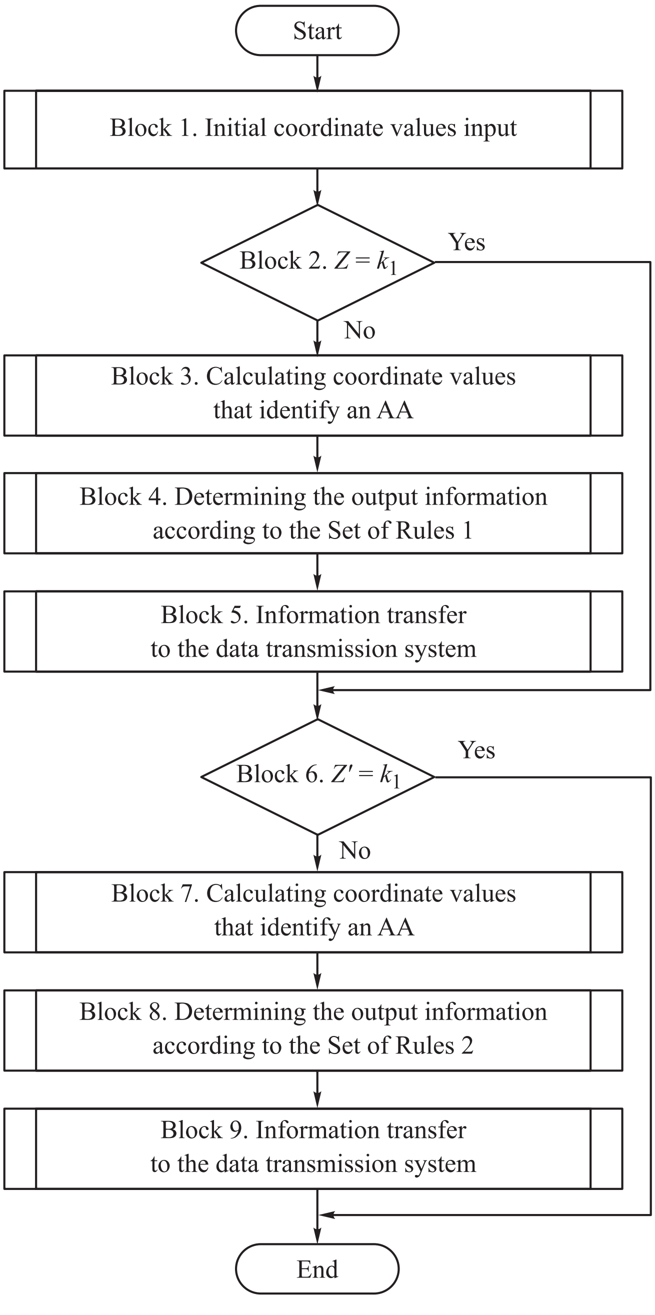

Fig. 3. Block diagram of the decision-making support algorithm for countering the aviation accident threat

According to the block diagram presented, the decision-making support algorithm to counter an aviation accident threat operate as follows.

Block 1. Initialization of the input variables characterizing the aircraft flight condition state on the basis of preprocessing the influencing characteristics (external and internal).

Block 2. Establishing the absence of an aviation accident threat. If such a threat is missing, then transition to analysis of the forecast results in the controlled variables and the aircraft flight condition alteration is performed.

Block 3. If condition according to Block 2 is not satisfied, then transition is made to the procedure setting the coordinate values affecting the aviation accident based on comparing the values thereof with the reference values, as well as with the coordinate of the aircraft flight condition.

Block 4. A method of neutralizing the aviation accident threat is determined according to the set of rules for threat identification (Set of Rules 1) followed by further advice and control decisions by the decision-making support system.

Block 5. Information is transmitted by the type of the aviation accident threat neutralization due to the observed coordinates affecting the flight safety conditions, which is presented in the form of a control command input into the aircraft onboard equipment control and notification system.

Block 6. Determination of the absence of the aviation accident forecasted threat. If this condition is met, transfer to the program end is performed.

Block 7. If the condition is not met, then the procedure for determining the variables affecting the aviation accident threat based on the results of forecasting is implemented.

Block 8. A method is being created to counter a potential threat of an aviation accident.

Block 9. Information is transmitted by the type of aviation accident threat neutralization taking into account the predicted values of coordinates affecting the flight safety conditions. This information in the form of a control decision arrives to the input of the aircraft onboard equipment control and notification systems.

Computing experiment. Using the proposed decision-making support algorithm, a set of rules (2)–(5) and the values of the aircraft flight safety control system input variables, threat of an aviation accident was simulated followed by providing recommendations to the crew to counter it. Accident threat simulation results are shown in Fig. 4–6.

Within the process of numerical simulation, the following states of the aircraft flight conditions were obtained:

– fuzzy variables, which values are equal to one. Flight conditions evaluation is also equal to one, which is identified as the accident-free flight mode, i.e., a threat of an aviation accident is missing and there is no need to neutralize the threat at the $Y = 0.8$ value (see Fig. 4);

– fuzzy input variables, which are equal to –1. Flight conditions evaluation is –1, which is identified as the catastrophic flight mode. Thus, a threat of a catastrophic accident arises influenced by a complex of characteristics; therefore, it is necessary to evacuate the crew at the $Y = -0.8$ value (see Fig. 5);

– fuzzy input variables corresponding to difficult flight conditions (low level of the aircraft controllability and increased crew fatigue from monotonic load). It is required to improve flight conditions by means of automation, which corresponds to $Y = 0.5$ (see Fig. 6).

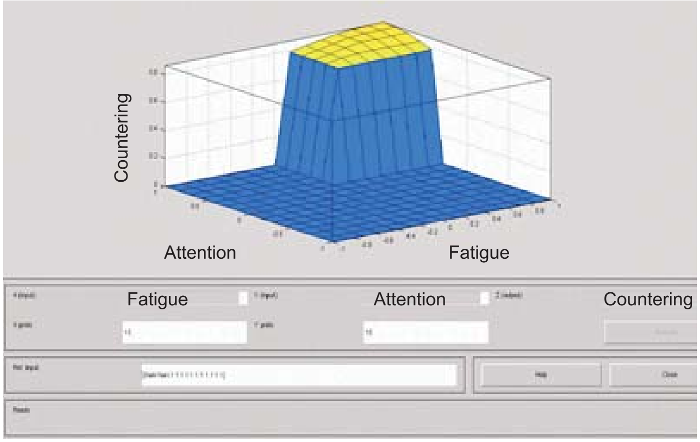

Fig. 4. Results of the aircraft flight conditions numerical simulation in the accident-free situation

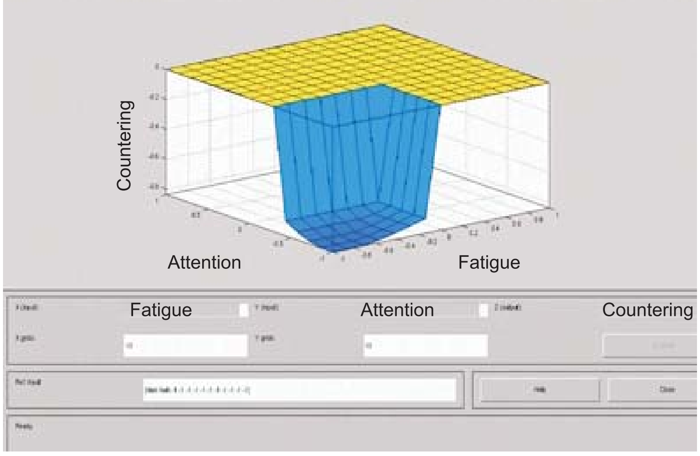

Fig. 5. Results of the aircraft flight conditions numerical simulation in the catastrophic situation

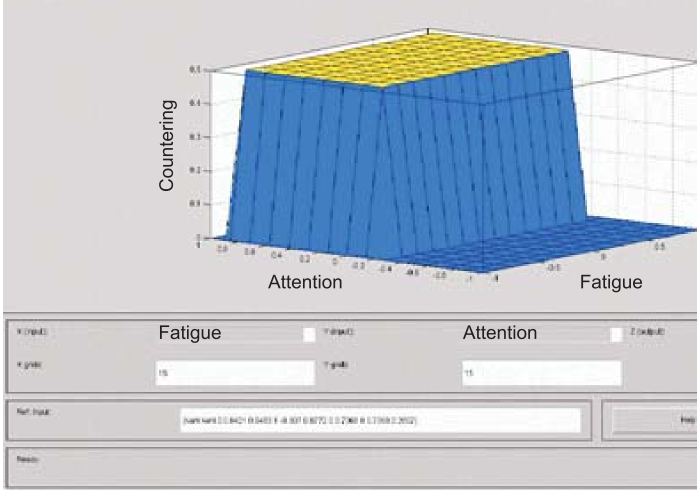

Fig. 6. Results of the aircraft flight conditions numerical simulation in the difficult flight conditions

Analysis of the results of computer simulation shows that it is possible to identify compliance of the set of decision-making support rules with the corresponding criteria, i.e., missing inconsistency and completeness. In particular, situation corresponding to the CI = 1 condition is similar to accounting for different values of the input coordinates, if the flight conditions are changing. On the other hand, when the II ≤ 0.4 condition is satisfied, characteristic of the missing inconsistency between the output coordinates of the decision-making support rules set for identical values of the input coordinates appears.

The proposed algorithm makes it possible to formulate recommendations to the crew and control signals to neutralize the aviation accident threat taking into account the predicted alteration in various characteristics, both external and internal, which determine the aircraft flight conditions.

Conclusion. Input and output coordinates of the decision-making support system were analyzed, a set of production rules for the knowledge base was formulated, and the algorithm for countering an aviation accident threat was proposed. Its characteristic feature is to support countering both current and forecasted aviation accident threats. With the operational flight safety conditions control system, the aircraft control signal is automatically calculated, if any positive response from the crew to neutralize the threat is missing.

The prospects for continuation of work in the selected subject area of constructing the aircraft flight safety conditions control systems are focused on mathematical, software and hardware realization followed by subsequent full-scale testing, as well as by corresponding experiments using the flying laboratories.

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