

Assessment of the Degree of Danger Posed by In-flight Contingencies When Exposed to Adverse Factors Affecting the Aircraft

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Abstract – Abnormal situations in flight arise when an aircraft in normal flight mode is exposed to one or more unfavourable factors. Therefore, such situations have a pronounced random nature. To assess the degree of danger of contingencies, it is convenient to use the Airworthiness Standards governing the list of situations and probability of their occurrence in flight. The degree of danger can be determined from the assumption that during the life of the aircraft each of the four contingencies will give the same level of risk. By combining all contingency situations with their normalized indicators and using this assumption, we can quantitatively determine their degree of danger (risk level) in the form of probabilistic indicators.

Keywords – Aircraft, faulty condition, flight delay, flight safety.

I. INTRODUCTION

Adverse Events (AE) in air transport result from exposure of aircraft (A/C) to adverse factors (AF) in flight. All adverse events (AE) are divided into the four following categories [1]–[3], [10]:

- aviation accidents (AA) with human casualties (disaster (D));
- accidents without casualties (accident (A));
- serious aviation incidents (SI) (there was a real safety risk);
- aviation incidents (I) (there was a potential safety hazard).

During a flight, the aircraft is affected by a large number of adverse factors. The development of an adverse event in flight is usually associated with a combination of several different factors that exponentially complicate the situation. The factors that eventually lead to an accident are related to crew activities (human factor – HF), functional efficiency of the aircraft (technical factor – TF) and environmental conditions (environmental factors – EF). Thus, an AE for the most part is a complex event serving as the last element in a chain of sequential events with cause-effect relationships. Tracing the sequence of adverse event development, we can distinguish the following categories of causes: MAIN, IMMEDIATE and CONCOMITANT. The MAIN one creates a potential opportunity for the emergence of AE in a certain situation. IMMEDIATE and CONCOMITANT causes create real conditions for turning such an opportunity into reality. Thus, the immediate cause is the one that entails AE. Usually it is a consequence of the main cause [4], [5].

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II. IN-FLIGHT CONTINGENCIES

Abnormal situations in flight arise when an aircraft in normal flight mode is exposed to one or more unfavourable factors (risk factors). In the Airworthiness Standards, such situations are classified as special situations. They are divided into four categories: complication of flight conditions, difficult (dangerous) situation, emergency, catastrophic situation [6], [7]. Special flight situations are characterized by a combination of aircraft properties and psycho-physiological indicators of pilots when such indicators differ from the normative ones and the flight mode differs from the “regular” one. Based on this concept in flight, five possible states of the aircraft can be distinguished. We denote them by S_i , where $i = 0, 1, 2, 3, 4$: Normal (“regular”) Flight in the absence of risk factors – S_0 ; Complication of Flight Conditions – S_1 ; Dangerous Situation – S_2 ; Emergency – S_3 ; Catastrophic situation – S_4 .

- S_0 is a “regular” situation when the flight is taking place under the expected operating conditions in the range of recommended flight modes.
- S_1 is a Complication of Flight Conditions – a “*State of the aircraft in flight*” characterized by a slight increase in the psychophysiological load on the crew or a slight deterioration in the characteristics of stability and controllability or flight characteristics of the aircraft.
- S_2 is a Dangerous Situation – a “*State of the aircraft in flight*” characterized by a marked increase in the psycho-physiological load on the crew or a noticeable deterioration in flight characteristics, stability and controllability, as well as one or more flight parameters exceeding operational limits, but without reaching limiting restrictions and design conditions. A difficult or catastrophic situation in an emergency can be prevented by the timely and correct actions of crew members, including immediate changes to the flight plan, profile and flight mode.
- S_3 is an Emergency – a “*State of the aircraft in flight*” characterized by a significant increase in the psycho-physiological load on the crew, deterioration of flight performance, stability and controllability, and leading to the exceedance of limiting restrictions and design conditions. Prevention of an emergency leading to a catastrophic situation requires high professional skills of crew members.
- S_4 is a Catastrophic Situation – a “*State of the aircraft in flight*” which implies that deaths are almost unavoidable when it occurs.

As can be seen from the formulations, all normalized indicators of special situations are qualitative in nature and can be summarized in Table I.

The Airworthiness Standards also describe the possible frequency of these situations.

Depending on the nature of the event under consideration, the following probability values relative to one hour of flight or one flight cycle are used as a numerical (quantitative) representation of the probabilities of occurrence of these situations as recurring situations:

- Repetitive $> 10^{-3}$;
- Moderately likely – from 10^{-3} to 10^{-5} ;
- Unlikely – from 10^{-5} to 10^{-7} ;
- Very small possibility – from 10^{-7} to 10^{-9} ;
- Practically impossible – $\leq 10^{-9}$.

The given indicators are widely used in the certification of aviation equipment, investigation of aircraft accidents, as well as in various interpretations in scientific works. When a special situation is taking place, i.e. when there is no corresponding aircraft’s reaction to the pilots’ actions in their attempts to counteract the effects of the risk factor, one of the above-indicated adverse events occurs: an incident or an accident [8]. All of the above can be represented in the form of a scheme shown in Figs. 1, 2, 3.

TABLE I
 NORMALIZED INDICATORS OF SPECIAL SITUATIONS IN FLIGHT WHEN EXPOSED TO AE
 (RISK FACTORS)

| Special Situation | Signs | | | |
|-----------------------------------|--|--|--|---|
| | Change of psychophysiological load on the crew | Aircraft stability and control deterioration | Output of parameters with certain restrictions | Need to change profile, flight mode or schedule |
| Flight Safety Complications (FSC) | Small | Small | – | – |
| Difficult Situation (DS) | Influent | Influent | out of service restrictions output | – |
| Emergency Situation (ES) | Significant | Significant | outside of max. calculable limits | +++ |
| Catastrophic Situation (CS) | Unparalleled | Prevention of human casualties is practically impossible | | |

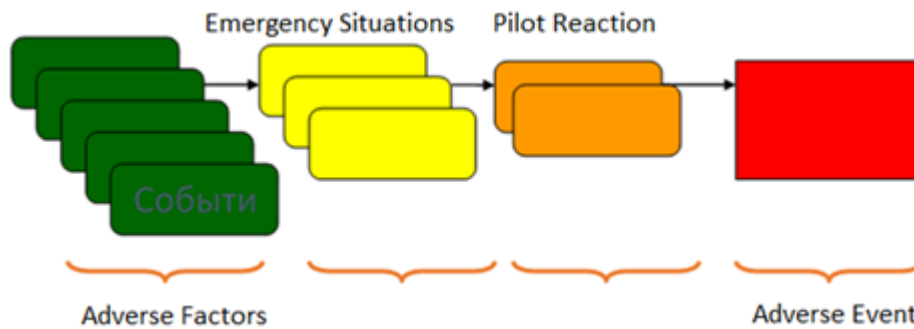


Fig. 1. Scheme of how adverse factors lead to an adverse event.

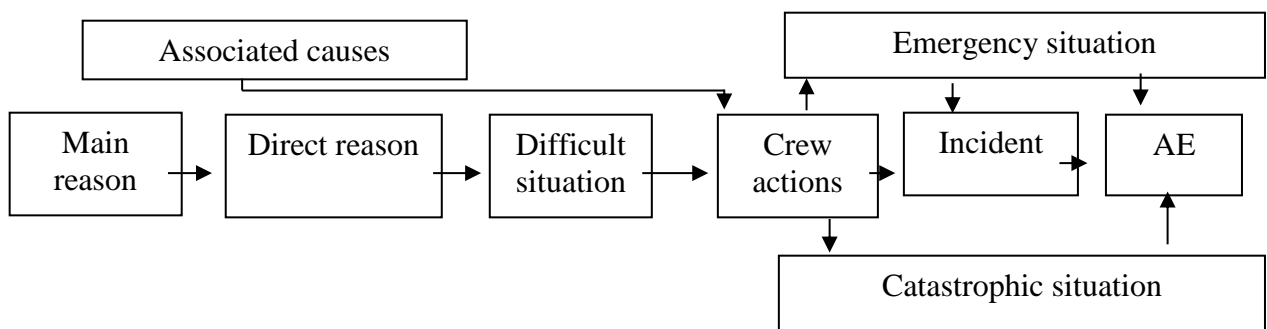


Fig. 2. Scheme of causes of the emergency and catastrophic situations.

| | | | | |
|--|---|--|--|---------------------------------------|
| Unfavourable factors | | | | |
| Aviation equipment failure | Human error | Unfavourable external factors | | |
| | | Possible Situations | | |
| Complexity of flight conditions | Complex situation | Emergency situation | Catastrophic situation | |
| Repetitive $P(1) > 10^{-5}$ | Moderately possible $10^{-5} < P(1) < 10^{-3}$ | Unlikely $10^{-7} < P(1) < 10^{-7}$ | Maybe possible $10^{-9} < P(1) < 10^{-7}$ | Almost impossible $P(1) < 10^{-9}$ |
| Normative probability of events per 1 hour of flight | | | | |

Fig. 3. Scheme of unfavourable factors.

III. QUANTITATIVE ASSESSMENT OF THE POTENTIAL DEGREE OF DANGER OF CONTINGENCIES IN FLIGHT

The main criterion for quantifying the FS level is considered to be the probability of a successful $P_{LV}(t)$ flight outcome or an unsuccessful $Q_{LV}(t)$ due to an accidental occurrence of an adverse event in flight [8]. Most AEs occur because the "Crew-Aircraft" system is affected by three types of unfavourable factors with probability: equipment failure – $P_T(t)$, personnel’s erroneous actions – $P_{CF}(t)$, adverse external influences – $P_V(t)$. The flight will end safely only if none of the groups of factors or their combinations appear in flight. When formulating this criterion, the following assumptions have been made:

- Risk factors $P_T(t)$, $P_{CF}(t)$, $P_V(t)$ constitute a group of independent events;
- The probability of two or more factors occurring over time t is negligible;
- The crew’s actions aimed at managing the effects of factor triggers are formed into a group of independent events.

With these assumptions, the general criterion $P_{LV}(t)$ can be represented by the product of particular analytical criteria learned for various groups of risk factors: human, technical, environmental factors $P_{LV}(t) = P_T(t) P_{CF}(t) P_V(t)$.

Obviously, the aircraft’s flight will end safely when exposed to one i -special risk factor with the probability $P_{iVi}(t)$ under the following two independent events:

- An emergency factor with the probability p_i will not occur;
- A risk factor with the probability $q_i = 1 - p_i$ will occur, and its consequences with a conditional probability R_i will be eliminated by the crew.

Then the safety criterion for the special group of risk factors will look as follows:

$$P_{LV_i}(t) = p_i \cdot q_i \cdot R_i \tag{1}$$

While for the whole set of risk factors, it will be equal to the product of the probabilities from all the particular risk factors.

$$P_{LV}(t) = \prod_{i=1}^m (P_{iVi}(t)) \tag{2}$$

It is obvious that the general criterion integrally evaluates flight safety and does not allow the evaluation of the influence of individual factors and properties of the aviation transport system on it. From the above it follows that we have four special situations and five levels of probability.

In accordance with the adopted probabilistic case study methodology, we will use the probability of favourable flight ending as the criterion for flight safety (P_{LV} or, in the adverse case, Q_{LV} ; their relation i) [5], [8]:

$$P_{LV}(t) = 1 - Q_{LV}(t) \quad (3)$$

Let us introduce the criterion of the degree of danger in a special situation, which we will denote as η . In addition, by η we shall mean the probability of non-elimination of adverse effects during the flight.

$$Q = \rho \cdot \eta, \quad (4)$$

where

- η – special situation hazard factor (probability);
- ρ – special situation margin (probability);
- Q – probability of aviation accidents.

IV. DETERMINING THE η CRITERION

During the flight, the aircraft is exposed to various types of AFs (Adverse Factors) (Failures and damage disrupt the operation of aircraft systems and assemblies, as well as erroneous actions by the crew or adverse environmental influences). They can all be classified according to different characteristics:

1. Dangerous AFs leading to the emergence of special situations of varying degrees of danger which, as a rule, require immediate and proper actions of the crew to prevent the consequences of aviation accidents.
2. Harmless AFs which are non-hazardous in nature and can be prevented by routine maintenance.

In terms of consequences and severity, AFs can be divided into four categories: catastrophic, critical, borderline and safe. Catastrophic AFs usually end in an aviation accident. This AF has a degree of danger which equals to 1 and is related to such factors as explosion, destruction of the aircraft in flight due to turbulence, complete lack of energy, fatal fire, etc. Therefore, in practice, the degree of danger of catastrophic adverse factors is taken as $\eta = 1$.

Critical failures are dangerous and can lead to an aviation accident. For the crew, the elimination of the effects of such an AF exposure is associated with the performance of complex activities under conditions of high emotional stress and time pressure. These include the failure of ECS (engine control systems) and other important aircraft units and systems, wind shear, thunderstorms; gross mistakes by the crew, etc. The degree of danger of such failures can be described by the expression $0 \ll \eta < 1$ (see Fig. 4). The AF limit can lead to flight mode interference, worsen aircraft stability and manoeuvrability, increase crew emotional stress, etc., but it does not compromise flight safety. The crew successfully deals with the effects of such an AF exposure. In this case, it can be assumed that $0 < \eta \ll 1$. Harmless AFs do not lead to dangerous consequences, they only cause minor difficulties in flight. Such a degree of hazard for AF can be taken as $\eta = 0$.

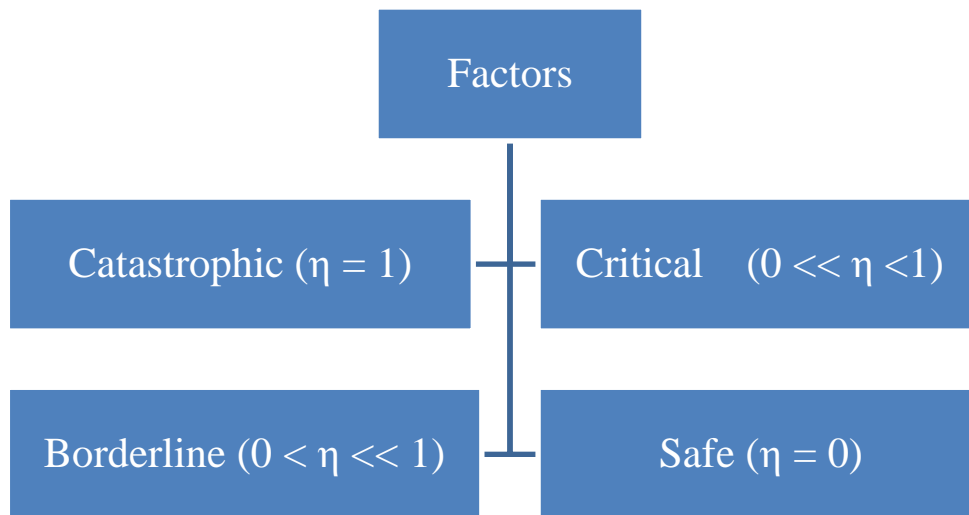


Fig. 4. Expression of the degree of adverse factors.

The given ranges of hazard variation are rather uncertain and require clarification both in terms of the content of the concept and in terms of the value of the quantity. To resolve this contradiction, we will assume the below statements. Logically evaluating the links between specific situations and their frequency, it is possible to formulate them in a different way:

3. Catastrophic events, whether aggravated by the action of the adverse event or by a combination thereof, may be attributed to events that are virtually impossible, with a frequency of less than 10^{-9} ;
4. Emergencies caused by the same reasons can be attributed to near-unlikely events with a frequency of $10^{-7} \div 10^{-9}$;
5. Dangerous situations caused by the same reasons can be attributed to unlikely events – their frequency is $10^{-7} \div 10^{-5}$;
6. Complication of flight conditions due to moderately probable and frequent events – the frequency is $10^{-5} \div 10^{-3}$.

Using the above-formulated frequency of occurrence of different hazardous situations, we will determine the probabilities of non-prevention of different special situations from the assumption that a certain aircraft during its service gives the same degree of risk for each of the four special situations, i.e. unfavourable probability of flight completion, $Q = \rho \cdot \eta$. Assuming that a certain in-service aircraft fleet gives the same degree of risk for each of the four special situations, the unobserved value of the probability of AF effect elimination $Q = \rho \cdot \eta$ can be determined based on the following example: Since the probability of a catastrophic situation occurring within one flight hour (one flight) is defined as the day-night level (Ldn) of 10^{-9} , while in special situations the probability of occurrence of complex flight conditions is 10^{-3} , which results in the probability of elimination the value, that is, the probability that the situation will not turn into a catastrophic one, must be greater than or equal to 10^{-6} . And if the effect of the adverse factor leads immediately to an emergency situation, the frequency of which is set to 10^{-7} , the normalized value, that is, the probability that the situation does not go catastrophic, must be greater than or equal to 10^{-2} , and so on. Then, for each of the four possible situations, the degree of hazard and the nature of the AF hazard can be written down as follows:

- Catastrophic situation: $\eta = 1$;
- Emergency situation: $10^{-2} < \eta < 1$;
- Dangerous situation: $10^{-4} < \eta < 10^{-2}$;
- Complication of flight conditions $10^{-6} < \eta < 10^{-4}$.

From the above it follows that the comparison of the gradation of special situations by consequence severity (non-elimination of consequences) with the gradation of special situation occurrence

frequency q is one of the guiding principles for assessing both the aircraft and flight safety. The full relationship between specific situations, their consequences, incidence and degree of danger are based on the above judgments. Such a link makes it possible to classify special situations according to the value of relative probability of non-eliminating the adverse factor effects. In view of the above, the relationship between specific situations, their frequency, consequences and degree of severity (probability of non-eliminating the effects of adverse effects) can be presented in tabular form. So, to adjust the classification of situations, as well as to assess the level of flight safety, when statistical material is available, it is necessary to know the relative probability of non-eliminating adverse effects (aviation failure) as the sole hazard criterion.

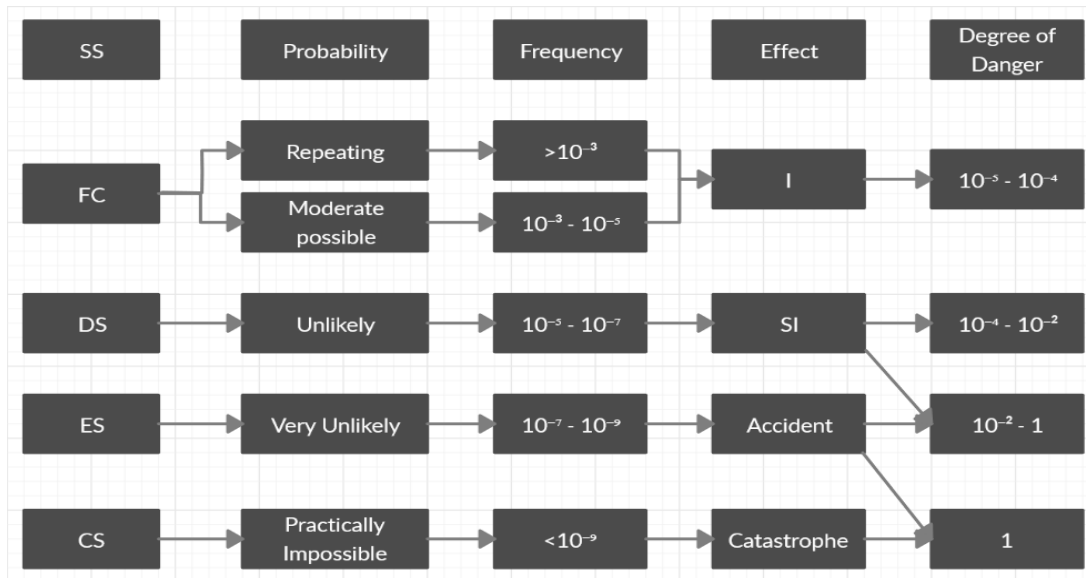


Fig. 5. Accepted Designations:

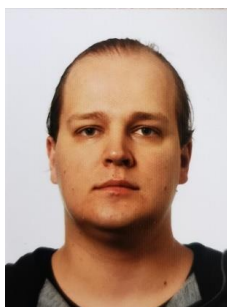
SS – Special Situation, FC – Flight Complications, DS – Dangerous Situation, ES – Emergency Situation, CS – Catastrophic Situation, I – Incident, SI – Serious Incident.

V. CONCLUSION

1. Abnormal situations in flight arise when an aircraft in normal flight mode is exposed to one or more unfavourable factors. Therefore, such situations have a pronounced random nature due to the randomness of exposure to adverse factors in time and space.
2. For the quantitative assessment of safety in practice, two approaches are used: deterministic and statistical. In the first case, a deterministic model is used, the behaviour of which is completely predetermined by the accepted conditions and can be predicted arbitrarily accurately. In the second case, a statistical model is considered, the behaviour of which can be predicted only with a certain probability. From the point of view of quantitative measurement, probabilistic criteria are very complex and can only be used in particular cases.
3. To assess the degree of danger of contingencies, it is convenient to use the Airworthiness Standards governing the list of such situations and probability of their occurrence in flight. The degree of danger can be determined from the assumption that during the aircraft's life each of the four emergency situations will give the same level of risk.
4. By combining all non-contingency situations with their normalized indicators and using this assumption, we can quantitatively determine the degree of their danger (risk level) in the form of probabilistic indicators. These indicators also characterize the likelihood of the crew's actions required to avoid a catastrophe, which, in their turn, should become a basis for the development of a program for preparing crews to act in emergency situations, including flight simulator training.

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