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FLIGHT DYNAMICS AND CONTROL OF FLIGHT VEHICLES

Methodology for Assessing the Risks of the Human Factor due to Pilot Errors in the Process of Piloting an Aircraft

A. V. Efremov[a, *], **M. S. Tyaglik**[a], **I. Kh. Irgaleev**[a], **E. V. Efremov**[a], **and T. V. Voronka**[a]

[a]*Moscow Aviation Institute (National Research University), Volokolamskoe sh. 4, Moscow, 125993 Russia*

**e-mail: pvl@mai.ru*

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Abstract—This paper analyzes the types of flight accident events, their causes and statistics on accidents at different stages of flight. By studying the subjective pilot rating, the law of its probability distribution was established as well as the possibility of using this law to assess the risk of accidents. The methodology for assessing the risk of an accident during manual control in nonstationary conditions associated with a sharp change in the controlled element dynamics is considered.

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Keywords: pilot error, flight accident, Cooper–Harper rating scale, distribution probability, pilot rating.

One of the main requirements to aircraft engineering is to ensure the safety of piloting, including by reducing the flight accidents due to pilot errors. A number of research programs carried out in our country [1] and abroad [2, 3] have been devoted to solving this problem. A number of studies on this subject have also been published in [4–8]. Determination of the main directions of work in this area requires knowledge of the flight accident statistics. Their systematization has been going on for more than 40 years. During this period, the international aviation community, different state, public, and private organizations have carried out intensive work compiling and classifying flight accidents, which is extremely important for creating a common data bank structured according to common principles. The presence of such a bank allows identifying the main causes of accidents and factors that affect their occurrence, and establishing the distribution and frequency of accidents by stages of flight. This knowledge allows us to determine the direction of work in eliminating accidents, namely, the training programs for flight personnel, activities for improving aircraft operation, modernizing and designing the modified systems.

FLIGHT ACCIDENT STATISTICS

Currently, in aviation, there exist a number of classifiers also known as taxonomies. Among these are the automated systems for ensuring the flight safety of civil aircraft of the Russian Federation (ASOBP) [9] that is based on a taxonomy, which is harmonized with the generally accepted ADREP taxonomy [10] created by ICAO. In addition to these taxonomies, others are used, in particular, the AAG [11–13], created in the United Kingdom, or the IATA taxonomy [14] developed in Canada.

In statistical research, three basic concepts are used to describe the development of events.

1. Classification of events. Among these are the aircraft accidents, incidents and emergencies.

2. Type of events or consequences, which are divided into hard landing, runway excursion, undershoot landing, tail strike against the runway, loss of control in-flight, controlled flight into terrain, gear-up landing/gear collapse, mid-air collision, ground damage, in-flight damage, off-field forced landing, alighting on water.

3. Causes and factors that led to the event. As a rule, they are divided into groups of factors, the wording of which, as well as their components, in different taxonomies are somewhat different.

Nonetheless, in each of them there are groups associated with the crew, environmental conditions, aircraft systems, and a number of others.

It should be noted that a description of events is incomplete without indicating at what stage of flight each of the event types occurred. The flight stages as well as the number of accidents that took place in 2002–2011 are shown in Fig. 1.

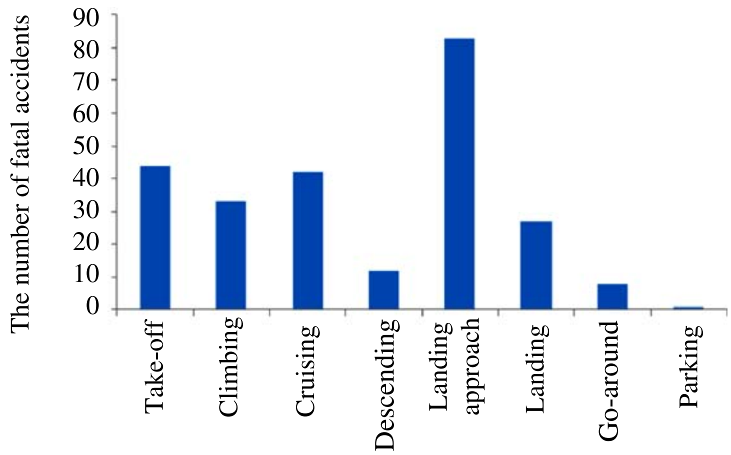

Fig. 1. The number of fatal accidents by stage of flight, 2002–2011.

Within the framework of the SAFEMODE project partners (as part of the Horizon 2020 EU Research and Innovation program) research was carried out to develop the methods for mathematical modeling and experimental studies of the pilot–aircraft system in normal and emergency situations to conduct a predictive analysis of human factor-related risks. In the framework of these studies, the flight accident data presented in the work of the Interstate Aviation Committee (IAC) [15], the UK Civil Aviation Authority [11–13], and the International Aviation Transport Association [14] was analyzed. This data covers more than 1200 accidents that occurred between 1980 and 2018. At different time intervals, the statistics are slightly different, however, general patterns remain. The largest number of fatal accidents (approximately 42–46%) occurs during approach and landing, although these flight phases are the shortest and comprise about 2–4% of the total flight duration. It is in this phase of flight that the pilot is actively involved in controlling the aircraft.

The data (Fig. 2) shows that the percentage of accidents associated with pilot error was 66 % in the 1997–2006 period. Similarly, close values were observed in 1980–1996 (67%). In 2002–2011, it decreased to 52%.

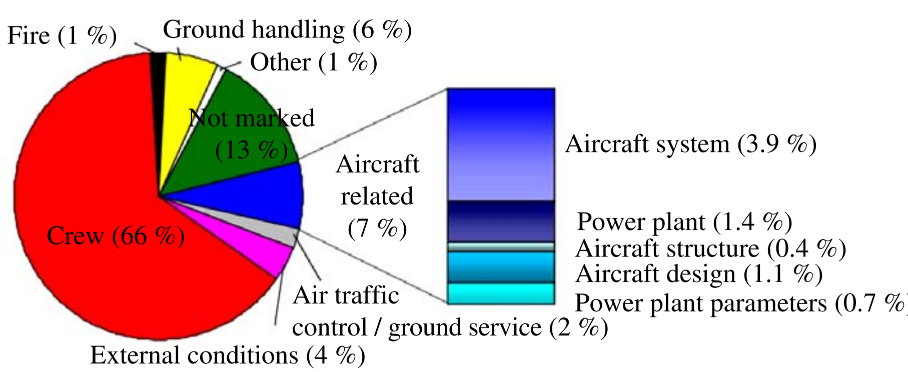

Fig. 2. The ratio of the number of accidents and their causes, 1997–2006.

A high percentage of accidents due to pilot error is characteristic of the CIS countries and the Russian Federation. According to the IAC, out of 75 incidents involving these aircraft from 2000 to 2018, 44 were related to crew errors.

The analysis of events given in [14], covering 305 incidents that occurred in 2014–2018, demonstrated that the major part of incidents is related to hard landing (44), runway excursion (73), undershoot (11), and tail strike (18). All these incidents are caused by unstabilized approach, which is largely determined by poor pilot control at this stage of the flight.

Table 1 shows the percentage of accidents for each of these events associated with the poor pilot control factor.

Table 1

Accidents and their main causes	Event type					
	Hard landing	Runway excursion	Under-shoot	Tail strike	Loss of control	Controlled/uncontrolled flight into terrain
Number of accidents	44	73	11	18	25	10
Poor pilot control (in percentage terms)	81	45	56	88	53	33

In many ways, errors in pilot actions lead to another very dangerous result—Loss of Control In-flight (LOC-I). The LOC-I (25 incidents in 2014–2018) can be caused by incorrect pilot actions and loss of spatial orientation, as well as a number of others. The LOC-I category is fairly general, comprising various causes. These include, among others, exceeding the critical angle of attack and Pilot Induced Oscillation events (PIO events).

It should be noted that the highly automated passenger aircraft that appeared in the past 25 years have slightly changed the statistics. The number of accidents caused by system failures or errors in control system algorithms leading to unforeseen aircraft response has increased. The number and percentage of accidents has also increased due to the deterioration of interaction between the pilot and the aircraft (PIO events). The percentage of accidents due to this factor has increased to 15% for aircraft with a fly-by-wire control system [16]. The percentage of accidents that occurred due to this factor, among the 275 aircraft that crashed between 1996 and 2010, amounted to only 2%.

In general, errors in pilot actions occurring in the process of piloting an aircraft are the primary cause of aircraft accidents.

ESTIMATING THE PROBABILITY OF AN ACCIDENT IN MANUAL CONTROL

Thus, the participation of the pilot in the process of active control of the aircraft entails a certain risk of an accident. To determine the degree of such a risk, as well as to purposefully search for means of reducing it, knowledge of the probabilistic assessment of the possibility of an accident when piloting an airplane is necessary. One of these assessments, called the human factor risk model, is based on the relation between the probability of an accident and the average Cooper-Harper pilot rating (PR) of the aircraft flying qualities, identified using ground-based simulation. In this experimental research, the pilot performed the task of landing an aircraft with various dynamic characteristics. In order to create conditions close to an unstabilized landing during the experiments, initial deviations from the glide path, wind disturbances, deterioration of visibility conditions up to the beginning of the flare were introduced. In total, experiments were conducted with six aerodynamic configurations from the Have PIO database [17], belonging to the first, second, and third level of PR ratings. For each of these configurations, from 17 to 24 experiments were carried out. In each of them, three landings were carried out and after each such series the pilot assigned a PR rating.

Figure 3 shows, as an example, the values of estimates for two configurations in all experiments.

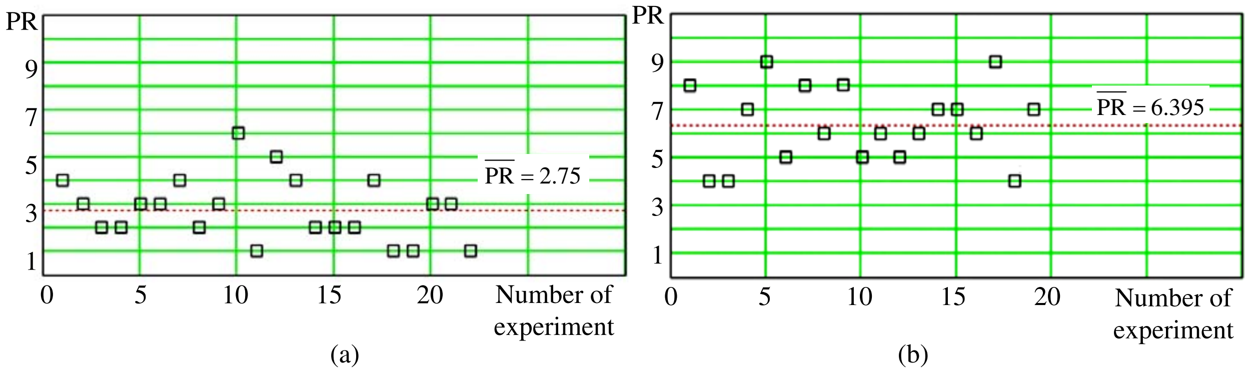

Fig. 3. PR pilot ratings: (a) HP-4.1 configuration; (b) HP-3.12 configuration.

As can be seen, the ratings obtained in the experiments are random variables. The average rating value for the HP-4.1 configuration is 2.75 (i.e., this configuration belongs to the first level of flying qualities), and for the HP-3.12 configuration, $\overline{\text{PR}}$ = 6.395 (i.e., the configuration is at boundary of the second and third levels of flying qualities).

Figure 4 shows the rating probability distribution for these configurations.

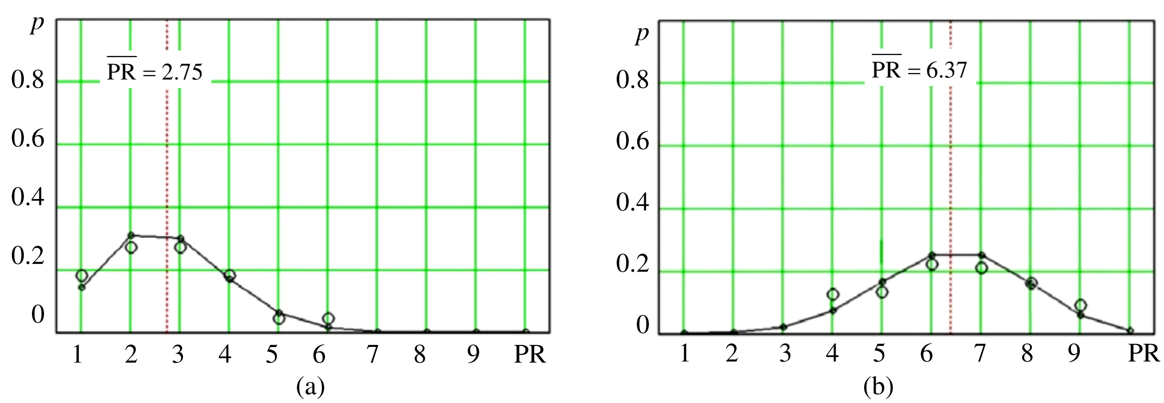

Fig. 4. Rating probability distribution: (a) HP-4.1 configuration; (b) HP-3.12 configuration.

Figure 4 shows the binomial law of rating probability distribution, whose expression has the following form:

$$p(\text{PR}) = C_9^{\text{PR}-1} p^{\text{PR}-1} (1-p)^{10-\text{PR}},$$

where $p = \dfrac{\overline{\text{PR}} - 1}{9}$; $C_9^{PR-1} = \dfrac{9!}{(\text{PR}-1)!(10-\text{PR})!}$.

The mean value $\overline{\text{PR}}$ for each dynamic configuration corresponded to the values given above. Comparison of the results of experimental data processing with the binomial distribution law shows that they are in good agreement, which allows us to conclude that the pilot rating is a random variable characterized by the binomial distribution law.

According to the description of the Cooper–Harper scale, the rating of PR = 10 corresponds to the case of loss of control by the pilot, and, consequently, loss of the aircraft. In this regard, it is of interest to determine the probability of achieving this assessment in the case of erroneous pilot actions at various average values.

Figure 5 presents this dependence obtained according to the binominal distribution law.

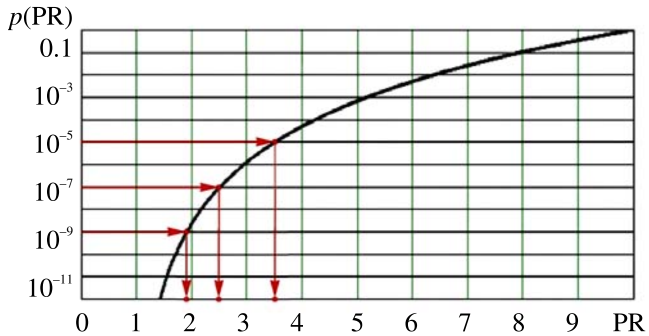

Fig. 5. The dependence of the probability of a flight accident on the average rating of flying qualities.

As you can see, if the flying qualities belong to the second level and, especially, the third level, then the probability of a catastrophic accident due to erroneous pilot actions is high. Only for the first rating level does its value decrease to an acceptable level. So, for PR = 3.5, the probability of reaching the PR = 10 rating (i.e., the probability of a catastrophic accident) is close to $p(\mathrm{PR}) = 10^{-5}$. This value corresponds to the well-known requirements for the acceptable probability of in-flight control system failure for Class I aircraft (maneuverable aircraft). Thus, if the same requirements are applied to the pilot as to control systems, the maximum value defining the boundary between Levels 1 and 2 of pilot ratings corresponds to the requirements for the probability of control system failure or, in relation to the pilot, the probability of his erroneous actions.

For civilian aircraft, flight safety requirements are much more stringent. They correspond to the acceptable probability of control system failure of 10^{-9} per flight hour. If these requirements are applied to the pilot, then taking into account the obtained dependence of $p = f(\mathrm{PR})$, erroneous pilot actions, which will not lead to an emergency situation, require that the flying qualities of the aircraft be characterized by a rating of $\mathrm{PR} < 2$.

In the event of an accident, which can cause a deterioration in the aircraft flying qualities, the probability of a catastrophic accident due to erroneous pilot actions will increase not only due to a deterioration in the dynamics of the aircraft, as mentioned above, but also due to the pilot not having enough time to adapt quickly. In this nonstationary pilot adaptation process, flying qualities can degrade significantly, which can lead to loss of controllability of the aircraft.

In order to assess the influence of the unstationary nature of the process in the pilot-aircraft system, occurring after a change in the dynamic properties of the aircraft, a series of experiments was carried out. When choosing the conditions for their performance, we used the results obtained in [18], where the problem of compensatory tracking was studied. During its implementation, the pilot sought to keep the error signal within a certain interval *d*. The experiments were performed under the conditions of an input signal characterized by the spectrum $S_{ii} = \dfrac{K^2}{\left(\omega^2 + \omega_i^2\right)^2}$ at $\omega_i = 0.5$ 1/s, $\sigma_i^2 = 4\ \mathrm{cm}^2$ for different dynamic configurations from the databases given in [19, 20]. The studies carried out using one of the ground-based simulators of the Moscow Aviation Institute, made it possible to establish a relation between the PR assessment by the pilot and the range *d*, having the following form:

$$\mathrm{PR} = 1 + 5.36d.$$

It was also shown that if the error signal is kept within the range of $d = d_{des} = 1.3$ cm, then the controlled element belongs to Level 1 of flying qualities. If the error is kept within the range of

$d = d_{ad} = 1.75$ cm, then the controlled element belongs to Level 2. If the error exceeds the range of $d = d_W = 2.75$ cm then the flying qualities do not belong even to Level 3.

In this work, the values d_{des}, d_{ad}, d_W were plotted on the display screen, and the values of the process $e(t)$ were recorded. The studies have shown that a sharp deterioration in the controlled element dynamics is always accompanied by a deterioration in the accuracy of piloting, and in a certain time interval, in which the pilot does not have time to adapt to the changing dynamics, errors can reach significant values.

It is shown in Fig. 6 that with a sharp change in the controlled element dynamics, when the controlled element transitions from Level 1 to Level 3 of flying qualities in the initial period of 8–10 seconds, the pilot error can go beyond the values of d_W, which indicates the possibility of an accident. Thus, the greatest danger is posed not by just piloting with unsatisfactory handling qualities, but by a sharp deterioration of these dynamics characteristics during the piloting process. In this case, the pilot at first does not recognize the occurrence of a failure without changing the stereotype developed by him when controlling the element before the failure occurred, and then only adapts for 3–4 seconds to the changed conditions.

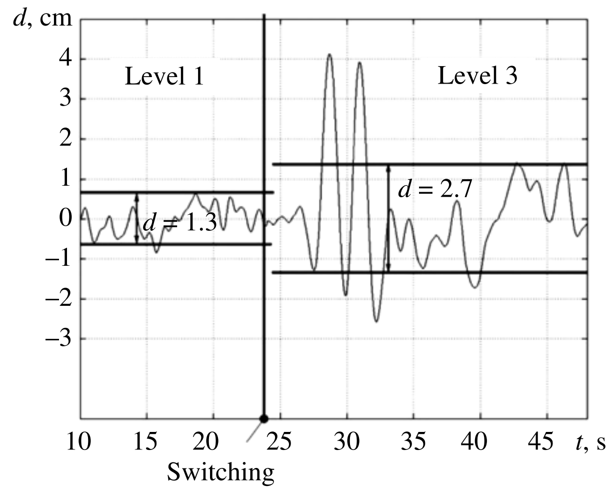

Fig. 6. Change in the levels of pilot ratings in the event of a failure.

In the work using the Wavelet transform [21], estimates of the frequency response characteristics of the pilot actions in an open-loop pilot–aircraft system were obtained. Their analysis showed that the duration of the pilot actions adaptation process, which caused a change and subsequent restoration of the crossover frequency, as well as the phase margin of the open-loop system, was also 3–4 seconds (Fig. 7).

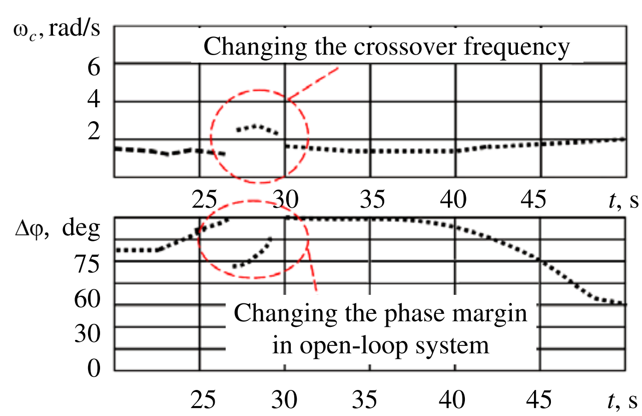

Fig. 7. Change in the characteristics of the open-loop pilot–aircraft system in the event of a failure.

The analysis of more than 1200 aircraft accidents carried out in the paper showed that when landing, 42–46 % of accidents occur at the stage of glide path motion and flare, and approximately half of them are due to unstabilized motion of the aircraft along the glide path. The main factor determining such unstabilized motion is pilot errors in manual control (from 50 to 88 % for different events).

In the paper, a methodology was developed for assessing the risk of an accident for this factor based on the obtained dependence of the probability of its occurrence on the average flight rating. It is shown that with a pilot rating close to PR = 2, the probability of a flight accident due to pilot error is 10^{-9}.

A risk assessment technique is also proposed for experimental research using a ground-based simulator in case of control system failures.

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