AIRCRAFT FLYING QUALITIES AND FLIGHT SAFETY

A. Efremov, A. Ogloblin, A. Koshelenko,
Moscow aviation Institute
4 Volokolamskoye shosse, Moscow, GSP–3, A-80, Russia

Abstract

There are discussed the relationship between flying qualities and flight safety, the reasons provoking pilot's error, variability of pilot's behavior and its influence on his errors in manual control task. Variability of pilot subjective rating PR is considered and there is shown that PR is a random value distributed according to binomial law. The technique for flying qualities definition guaranteed the given level of flight safety is discussed. This technique is applied for estimation of flight safety in different cases of failures. The means for improvement of flying qualities and flight safety in normal and abnormal conditions are considered too.

Nomenclature

- PR – pilot rating,
- p – probability,
- r – resonant peak,
- s – Laplace operator,
- σ – mean square,
- σ^2 – variance,
- δ_e – elevator deflection,
- δ_D – direct lift control surface deflection,
- θ – pitch angle,
- DLC – direct lift control,
- ACAH – attitude control attitude hold.

1. Introduction

The basic criteria used in aircraft design are the effectiveness of piloting tasks (accuracy) and flight safety. The effectiveness provided by the choice of aircraft parameters and its flight control system according to the known requirements to the flying qualities. The last are formulated in the terms of "aircraft-flight control system" parameters. As for flight safety it is provided by means guaranteed the required level of probability accident causing by subsystem failure. It has to be less then 10^{-7} for maneuverable aircraft and less then 10^{-9} for the passenger and transport aircraft. Probability of subsystem failure leading to change of flying qualities from one to other level is also defined in flight control system design. All these requirements to the flying qualities and flight safety don't take into account the human errors or his failure. The importance of it can be seen from the following examples.

There is shown in [1] that flying qualities optimization based on consideration of pilot aircraft allows to improve the accuracy of control (the mean square of error decreases up to $60 \div 70\%$ in case of optimal aircraft dynamics [2] in comparison with aircraft dynamics corresponding to $PR = 3$) and considerable decrease of pilot's workload and compensation. The human factor doesn't take into account in flight control system design often. At the same time up to 80% of accidents take place due to human errors. These errors can be divided on two categories:

- the errors defined by wrong pilot action not provoked by aircraft;
- the errors defined by conditions provoked their appearance. The following conditions can be related to them:
  - Pilot control response variability
  - Flight control system failures causing deterioration of flying qualities
  - sharp changes of atmosphere turbulence, etc.

As a consequence these conditions lead to conflict between pilot actions and controlled element dynamics in close-loop system, degradation of flying qualities and flight safety too. Thus the tasks of flying qualities and flight safety provision are coupled. In spite of this evidence there were not carried out practically researches on establishment of relationship between parameters defined flying qualities and flying safety. Only several attempts were done in this area [3]. This problem is considered in presented paper and based on results of ground–based simulation. The deterioration of flying qualities can be aroused by several reasons. One of them is associated with the failure of any flight control system element. The other reason is associated with necessity to fulfill the piloting task characterized by the set of variables required the considerable pilot compensation. As a rule such piloting tasks are accompanying by the necessity of linear motion control (altitude, for example) with requirements of extremely high accuracy. The typical examples of such piloting tasks are refueling and landing at the carrier. These conditions create the stress of pilot and provokes him to make errors even in normal regime of flight control system functioning. The flight control systems developed for fulfillment of these piloting tasks allowed just partial improvement of flying qualities but don't provide the breakthrough in solution of the problem. There is considered below some nontraditional solution in flight control system design provided the considered improvement of flying qualities and flight safety in normal and abnormal cases with taking into account limited authorities of flight control system and potentialities on realization of developed means.

2. The relationship between aircraft flying qualities and flight safety (stationary conditions of pilot-aircraft system).

It was mentioned above that the appearance of accident is defined in terms of probability of FCS element failure in one flight hour. At the same time a pilot is an element of closed-loop pilot aircraft system during the fulfillment of piloting task and his wrong actions ("pilot's error or failure") can cause the accident too. This circumstance allows to apply mentioned above requirement on subsystem reliability to a pilot too. In a manual control task pilot's errors are associated with variability of his parameters (gain coefficient, time delay etc.). Such phenomenon can decrease the stability of pilot–aircraft system for a short interval or lead to a loss it at all. The deterioration of flying qualities is accompanied by increase of remnant spectral density, pilot compensation, mean square error and an decrease of amplitude and phase margins of pilot aircraft open–loop system. As a consequence it increases probability of stability loss and accident even. They use well known Cooper Harper scale for evaluation of flying qualities (fig.1).

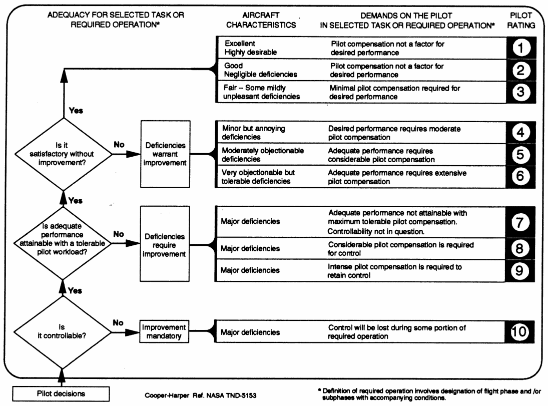


Fig. 1.

The deterioration of flying qualities corresponds to the increase of pilot opinion rating, *PR*. Rating *PR* = 10 means that the piloting process is impossible and any pilot's attempt to control leads to accident. The results of experimental investigation with use of Cooper Harper scale demonstrate variability of Pilot Rating. It can reach up to 3 – 5 units from experiment-to-experiment, from pilot-to-pilot for the same task variables. The variability of *PR* corresponding to the different configuration from HAVE PIO data base is shown on fig. 2.

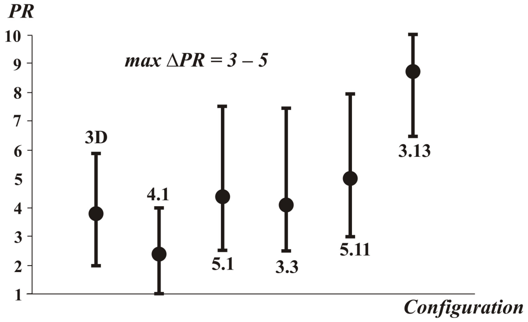


Fig. 2

The variability is a feature of random value. The specific features of pilot rating as a random value are the following:

- *PR* is the whole number;
- *PR* is a number consisting of the limited set of numbers.

These features show that the random value PR has to correspond to binomial law. According to [2] the probability of mean rating $\overline{PR}$ can be defined from the following equation

$$P\left(\overline{PR}\right)=C_9^{PR-1}P^{PR-1}(1-P)^{10-PR} \tag{1}$$

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

Mean square error of random $\overline{PR}$ distributed according to binominal law

$$\sigma_{PR}=\sqrt{\frac{\left(\overline{PR}-1\right)\left(10-\overline{PR}\right)}{9}}$$

The special investigation was fulfilled to check the suggestion on binomial law of *PR*. For that purpose there were fulfilled ground-based simulation of landing task with different dynamic configurations from HAVE PIO data base. No less then 17 runs were fulfilled for each configuration (table 1).

Table 1

Configuration	2.1	4.1	3.8	3.8	3.12	5.10
Number of run	22	22	24	20	19	17
$\overline{PR}$	2.86	2.75	3.1	3.7	6.4	7.35

For each of it the mean $\overline{PR}$, distribution and mean square error were calculated. The results shown on fig. 3a, b demonstrate good agreement with binomial law dependences p ($\overline{PR}$) (fig. 3a) and $\sigma\left(\overline{PR}\right)$ (fig. 3b). The variability of pilot rating allows to suppose that if the pilot rating will be close to *PR* = 10 then the average probability of accident will be high and visa versa (the smaller values $\overline{PR}$ correspond to low probability of accident). Taking into account the binomial law of *PR* there is possible to calculate the probability of flying qualities evolution with *PR* = 10 for case when the mean *PR* = $\overline{PR}$.

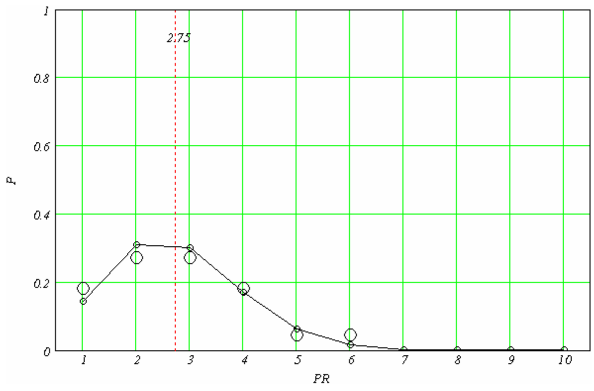


Fig. 3a

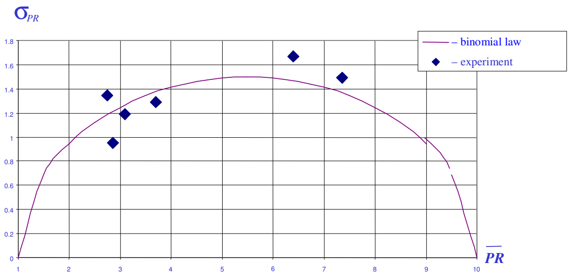


Fig. 3b.

The results of such calculations are shown on fig. 4. This result allows to agree the requirements to flying qualities level with probability of accident.

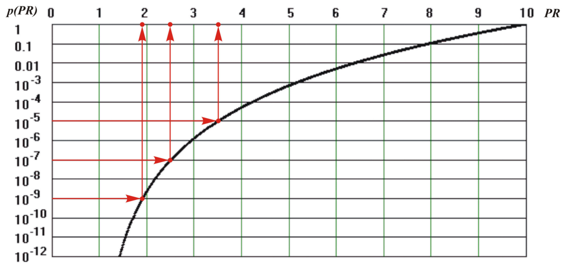


Fig. 4.

There is seen that the accepted boundary of the first level flying qualities *PR* $\le$3,5 corresponds to p (*PR* = 10) = 10^{-5}. This value is higher considerably in compassion with 10^{-7} or 10^{9} – requirements to flight control system elements. Taking into account that pilot is an element of closed loop system requirement to his reliability (10^{-5}) makes his "weak" element in pilot-aircraft system. The reliability of pilot can be improved only by change of requirements to aircraft flying qualities. According to the fig.4 the requirements to flying qualities for maneuverable aircraft *PR* $\le$2,5 and for transport or passenger aircraft $PR \le 1{,}9$ guarantee the probability of accents equal to 10^{-7} and to 10^{-9} correspondingly. Except the requirements to probability of an accident caused by flight control system failure there are the requirements to probability of transform from one level of flying qualities to the other one due to sudden limitation of subsystem authority. When flying qualities deteriorate the probability of transformation from the first level (*PR* = 1, 2, 3) to the second (PR = 4, 5, 6) is equal to $p \le 10^{-2}$ and probability of transformation from the second level to the third one (PR = 7, 8, 9) is equal to $p \le 10^{-4}$. The pilot is an element of the closed-loop system and the proposed probabilities might be used for him too. With goal to check this suggestion it was used the equation (1) received above and were estimated the probability of ratings PR = 4, 5, 6 for the different initial ratings $\overline{PR}$=1, 2, 3 and probability of PR = 7, 8, 9 for initial $\overline{PR}$=4, 5, 6. The results shown at fig. 5, demonstrated that accepted probability of transform from the first to the second level can be reached only in case when $\overline{PR}$=1, 2. As for possible transformation from the second to the third level the probability is always higher 10^{-4}. These results demonstrate the necessity to overlook definition of probabilities of possible flying qualities deterioration.

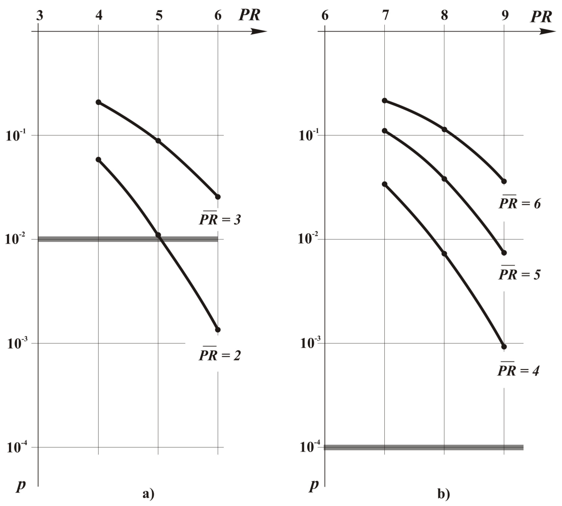


Fig. 5.

3. Flying qualities and flight safety in unstationary cases.

The considered above source of pilot's errors is associated with pilot's variability of his control response characteristics. The other source of his errors might be associated with flight control system failure. At least two such failures are considered below.

1. Failure which does not expose the nonlinear effects of flight control system
2. Failure exposing the limited potentialities of flight control system

There are considered below the several aspects of pilot aircraft system investigations in these cases.

3.1. The technique for definition of allowable flying qualities deterioration with taking into account unstationary pilot-aircraft system response characteristics.

This technique is developed for case when failure does not expose the nonlinear effects of flight control system. The specific peculiarity of pilot actions exposing after the sharp deterioration of flying qualities caused by flight control system element failure is the conservation of pilot stereo type of behavior during a specific time. It causes the considerable deterioration of pilot aircraft response characteristics and can lead to the loss of stability for a short time. This unstationary interval is accompanied by considerable deterioration of flying qualities. To the end of unstationary interval pilot adapts his behavior to new control element dynamics and piloting process is continued with "worse" flying qualities. The typical error signal time response *e(t)* is show on fig. 6 for considered case.

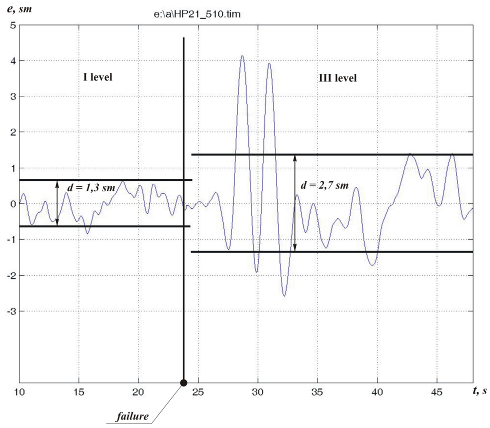


Fig. 6.

The significant deterioration of piloting process and flying qualities takes place during the interval of transfer (typically 8 – 10 s) from initial flying qualities to the changed flying qualities characterizing by ratings PR_1 and PR_2 correspondingly. The pilot rating taking place in this interval PR_3 is always higher PR_1 and PR_2. If the difference $\Delta = PR_2 - PR_1$ is high then rating PR_3 may reach 10 even. Because of this circumstance the requirements to rating PR_2 characterizing flying qualities after failure has to be take into account. If we suppose that during interval of unstationary characteristics pilot has to continue piloting task with adequate task performance and PR_3 = 6.5 then pilot rating after failure has to be less 6.5

3.2. Development of means for suppression of flying qualities deterioration caused by limited potentiality of flight control system.

This aspect of relationship between flying qualities and flight safety is aroused in cases of when:

- Flight control system failure exposing the nonlinear dynamics of some elements
- Aggressive type of control or gross maneuverability is required for fulfillment of the piloting tasks.

In all these cases pilot output or its velocity signals are too high when the input signal for the limiters is reached. These reasons lead to a deterioration of flying qualities and to an increase of pilot compensation as a consequence. It causes the further degradation of flying qualities and to development of accident. There are offered the ways for suppression of this phenomenon.

3.2.1. Synchronized prefilter.

This nonlinear is based on synchronization of pilot action with limited potentialities of flight control system. There are used the prefilters in practice of aircraft flight control system design (fig. 7).

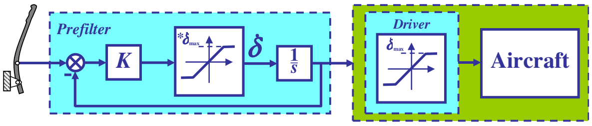
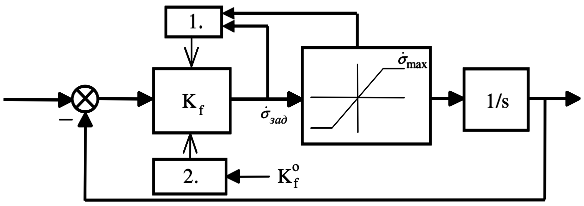


Fig. 7.

The logic of these prefilters to limit the signal transmitting from pilot to actuator. The purpose of proposed prefilter is to synchronize pilot's actions and limited potentialities of flight control system by linearization of pilot-aircraft system characteristics. The block scheme and law of such prefilter are shown on fig. 8.



law 1: quick change of K_f

law 2: restoration of initial gain coefficient K_f^o

Fig. 8.

The effectiveness of nonlinear prefilter was checked in pitch tracking task for the stationary conditions. The rate of elevator deflection for standard and developed prefilters are shown on fig. 9. The pilot ratings for standard prefilter was $PR = 9$ and for developed one– 3 – 4. Taking into account the equation (1) it means that probability of accident for standard prefilter are p=0.35 and for proposed one $p = 10^{-6} – 5{\cdot}10^{-5}$.

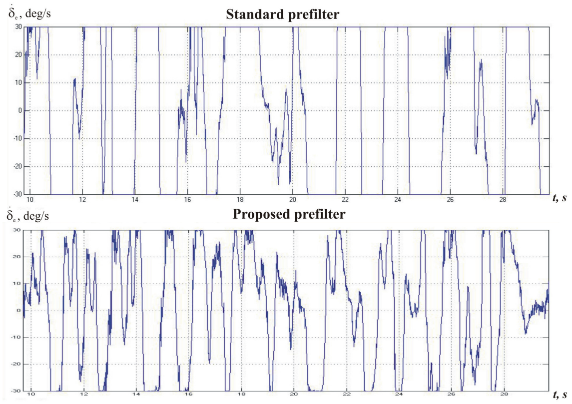


Fig. 9.

The measurement of pilot aircraft system characteristics variance error σ_e^2 and resonant peak (r) of closed-loop system shown on fig. 10 demonstrate that in case of sudden decrease of rate limit developed prefilter allows to keep these characteristics. More then this in unstationary interval of rate limit deviation the pilot rating is stayed practically the same $PR_3 = 4 – 5$.

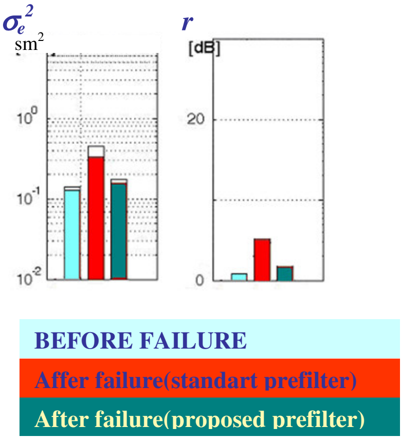
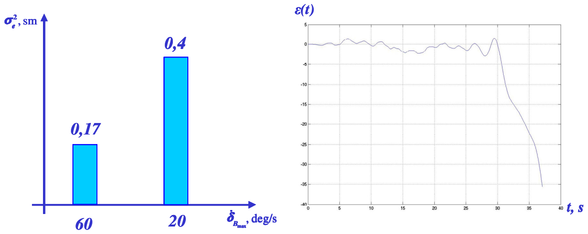


Fig. 10.

3.3. Use of direct lift control principle for improvement of flight safety and flying qualities.

The desire on improvement of flying qualities is accompanying by increased feedback signal gain coefficient used in new types of flight control system (ACAH–type, for example). All these means lead to increase of required control surface deflections and its rates. When these signals reach the limitation the nonlinear effects can take place in closed- loop system and gross instability can be exposed even for unstable configurations. As an example it was investigated the refueling task of several configurations with ACAH type of flight control system realized by prefilter $Wpr = \dfrac{Ts+a}{Ts+1}$ $a < T$. This mean allows to improve considerably the accuracy but it requires the considerable rate of elevator deflection (up to 40 deg/s). In abnormal case when rate limit will decrease twice (up to 20 deg/s), all pilot-aircraft system characteristics will deteriorate. For example mean square error increases several times (fig. 11a) or the unstable processes take place (fig. 11b).



a) b)

Fig. 11.

The flight safety problem can be decided by use the additional control surface and use it for direct lift control (DLC). It might be canard, an interceptor, etc. The DLC surface allows to decouple linear and angular motion to realize new forms of motion. One of such form–flight with constant pitch angle (θ = const) was realized in ground-based investigation of refueling task. It was shown that its utilization allows to decrease considerably the rates of control surfaces. The rates of elevator ($\dot{\delta}_e$) and DLC surface ($\dot{\delta}_D$) become less then 0.5 and 8 deg/s correspondingly (fig. 12). It means that in case of hydraulic failure the piloting task can be fulfilled without any deterioration of accuracy and flying qualities. More then this, use of DLC allows to improve the accuracy of final stage of refueling in 1.5 – 2 times and pilot rating decreases 1.5 – 2 unit. According to the previous consideration it decreases the probability of accident considerably.

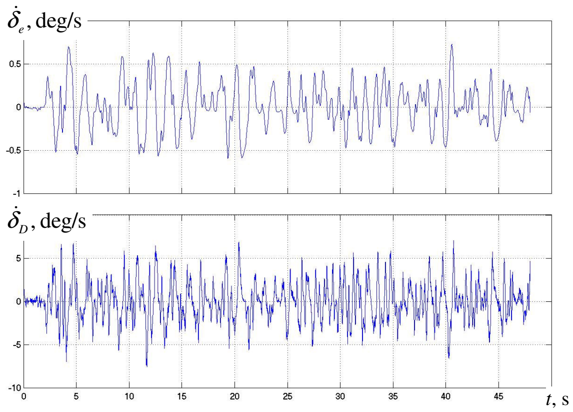


Fig. 12.

4. Conclusion

There is shown that pilot rating *PR* is a random value distributed according to the binomial law. This result allowed to define the relationship between the probability of pilot's error causing the accident and pilot rating and to make more precise the requirement to the first level of flying qualities. There are developed the means for improvement of flying qualities and suppression of effects of Flight Control System failures allowed to keep flight safety level and flying qualities too.

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