PROGRESS IN PILOT-IN-THE LOOP INVESTIGATIONS FOR FLYING QUALITIES PREDICTION AND EVALUATION

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Abstract

There is given the analysis of the results received in Moscow aviation Institute during last 30 years in the following pilot–in–the–loop areas:

- *the algorithms and techniques for experimental investigations and mathematical modeling of pilot control response and pilot–vehicle system characteristics in manual control tasks;*
- *applications of developed technique and methods for applied manual control tasks.*

Except it there is considered briefly the historical overview on pilot-aircraft investigations.

The brief historical overview on pilot-aircraft system investigations.

The investigations of pilot-aircraft system have its own 60 years history. The first experiments on measurements of human–operator control response characteristics were fulfilled by A. Tustin in World War II [1], although the necessity in knowledge of human operator regularities was recognized before [2]. In reality the researches in this area might be carried out in the period when the theory of control begun to use for practical application. The following progress in creation of computers allowed to extend considerably the investigations in manual control area and to expose the principle regularities of human-operator behavior at the beginning of fifties. In particular one of them is the remarkable feature – adaptation to the task variables.

All these fundamental knowledge were exposed basically by D. McRuer and his colleagues from System Technology Inc.. It led to creation of mathematical models of pilot control response characteristics. These models were linear and based on classical control theory. The parameters of them were offered to define with help of so-called “adjustment rules” [3].

These models differ by different level of complexity and describe basically the main regularities of pilot describing function in crossover frequency range. Therefore they called them as “crossover models” [3].

As for other frequency ranges, especially low frequency range, these models don’t allow to get good agreement. Partly it is associated with the fact that equations for the selection of model parameters (time delay and crossover frequency) were received from experiments with wide bandwidth (ω_i) rectangular input spectrum. The decrease of bandwidth of input spectrum (ω_i) causes the difference between recommended parameters $\omega_c(\omega_i)$, $\tau_c(\omega_i)$ and their measured values.

The “pioneer” stage in study of human behavior was finished to the middle of sixties when these models were developed.

In the second half of sixties it was proposed the new approach to mathematical modeling of human operator control response characteristics, based on modern optimal control theory [4]. It was modified in a number of researches [5,6] and was used for the different applied manual control tasks too. However, the well-known problems in choice of weighting coefficients for cost function and disagreement between model and experimental data in low frequency range limited the usage of this approach for prediction of results in applied investigations.

The structural model offered by Hess [7] is the modification of classical approach to description of pilot model. It was offered by author at the end of seventies. This model takes into account pilot's ability to use kinesthetic cues and has high potentialities in achievement of agreement with experimental results in comparison with a classical model. However the procedure for the determination of model parameters offered by author is rather far from perfection and doesn't allow to realize these potentialities.

MAI Fundamental investigations on study of regularities of pilot response characteristics.

Systematic investigations of pilot behavior regularities in closed-loop system are fulfilled in MAI at dynamics of flight and control department since 1975 with goal to receive the results for solution of applied manual control problems of highly augmented aircraft. The specific feature of highly augmented aircraft is that many peculiarities of its dynamics expose in result of interaction between pilot and aircraft. Because of these circumstances the solutions of majority applied manual control tasks require the knowledge of features of human behavior and its model except knowledge of aircraft dynamics model. All that might be received by the consideration of pilot aircraft closed-loop system shown on fig.1. The peculiarity of such system is the influence of piloting task on all its element. If the piloting task changes then the controlled element dynamics, input signal, display, etc. change too. It leads to the change of pilot response characteristics. The solution of any applied manual control task requires the development and usage the technique for experimental investigations and mathematical modeling also with taking into account this peculiarity.

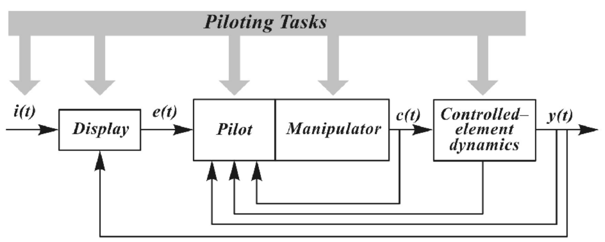

Fig. 1. Pilot–aircraft system.

For fulfillment of experimental investigations of pilot aircraft system it was developed at MAI a number of techniques allowed to measure characteristics of the pilot control (the first group) and psycho physiological (the second group) responses. The unified Fourier coefficients technique [8] was developed for the measurement of the first group characteristics. It allows to estimate pilot describing function $W_p(j\omega)$, remnant spectral density $S_{n_e n_e}(\omega)$ (fig. 2). All frequency and spectral characteristics of pilot aircraft systems are calculated with required accuracy. The technique is used for estimation of wide set of frequency, spectral and integral characteristics in single-loop, multi-loop, multi-channel, multi-modality systems in stationary and unstationary control tasks.

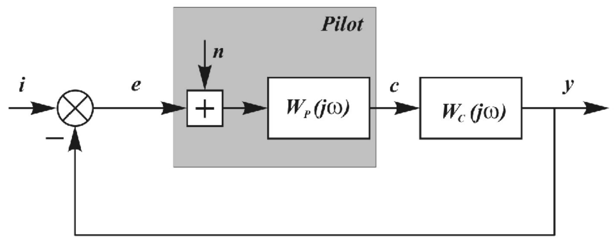

Fig. 2. Single loop Pilot–aircraft system.

For estimation of flying qualities with help of Cooper–Harper scale it was developed the technique allowed to get good agreement between ground–based and in–flight simulation.

The technique differs for different type of simulators but the main principle is the same–definition of task performances (Cooper–Harper scale metrics) by the preliminary stage of experiments. It might be done by fulfillment of experiments with dynamic configurations characterized by PR = 4 and PR = 6 in–flight experiments. Improvement of agreement between in–flight and ground–based simulations achieves by simultaneous evaluation of flying qualities in longitudinal and lateral channels and by perfection of simulation of visual and kinesthetic cues too.

The efficiency of definition of task performances during the preliminary stage of experiments is shown on fig. 3.

There are given pilot ratings (PR) corresponding to Have PIO dynamic configurations [10].

These results are received in experiments for cases when the desired and adequate metrics (d_{des} and d_{ad}) were demonstrated on display screen and without it.

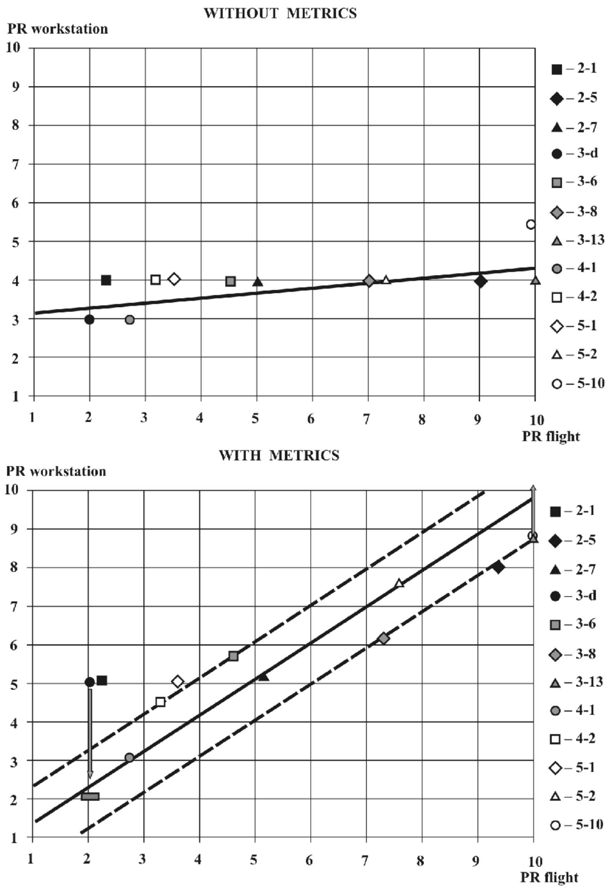

Fig. 3. Influence of metrics.

Use of developed techniques for experimental investigations allowed to expose a number of new regularities of human behavior. Some of them are the following:

- Pilot's ability to generate additional adaptation in low frequency range (fig. 4). This peculiarity increases with decrease of input signal bandwidth.

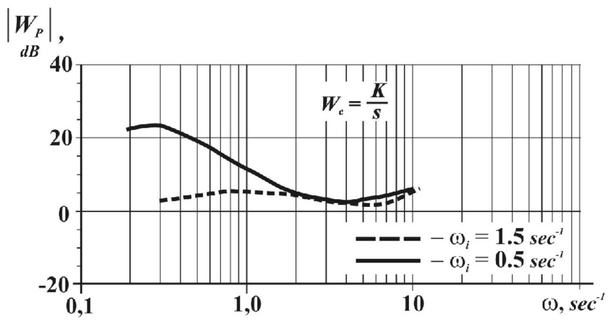

Fig.4. Low frequency adaptation.

- Pilot's ability to generate complicated actions in crossover frequency range for aircraft dynamics corresponding to the real. The estimated pilot frequency response characteristics cannot be described with help of known pilot's crossover model [8] in that case (fig. 5).

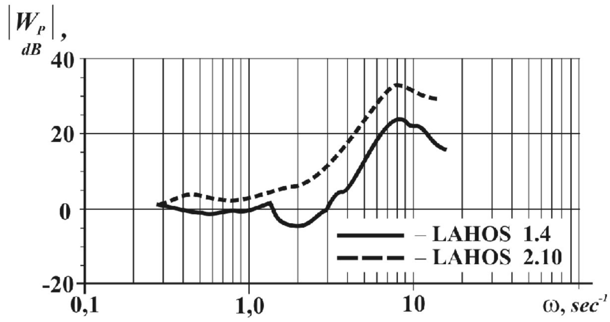

Fig. 5. Complicated pilot's actions.

- The considerable influence of requirements to the accuracy on pilot control and pilot–aircraft system response characteristics and pilot's subjective opinion rating too. For example, the decrease of requirements to allowable level of error from 0.5 up to 2 sm leads to decrease of resonance peak of closed loop system in 4 times, considerable decrease of lead time induced by pilot and significant improvement of subjective pilot ratings (pilot rating PR changes from 8.5 up to 3.5 ÷ 2).
- Possibility to use Weber–Fechner law for description of relationship between subjective pilot rating and minimum interval d where pilot keeps the error signal during experiment (fig. 6).

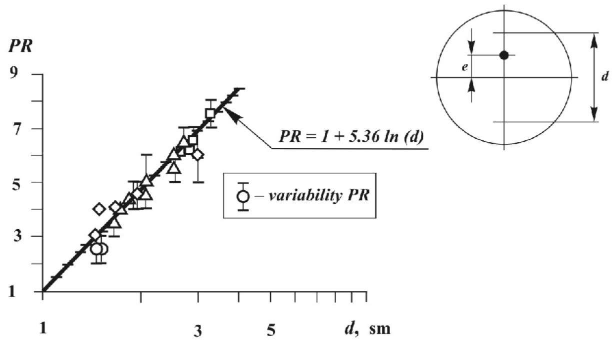

Fig. 6. Agreement of Pilot rating with Weber–Fecher law.

- Pilot's subjective rating is defined by the worst rating of factors influenced on his opinion. For example, in dual channel task pilot rating (PR_{Σ}) corresponds to the worst rating between longitudinal (PR_{ϑ}) and lateral (PR_{γ}) flying qualities. This result was exposed in experimental investigations with several test pilots and shown on fig. 7.

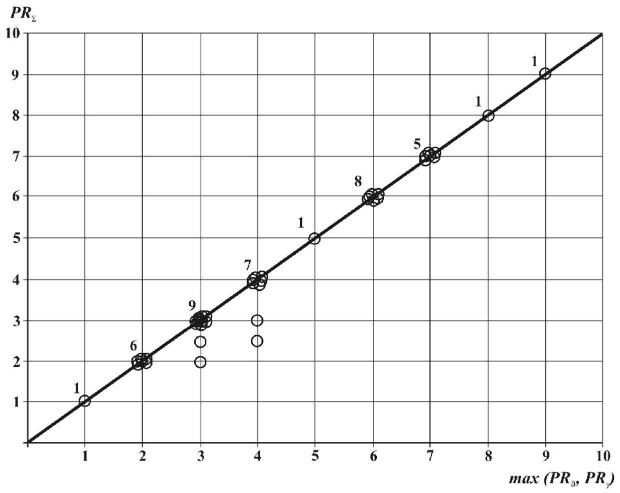

Fig. 7. Correlation between PR_Σ and partional ratings.

- Pilot's ability to use actively kinesthetic cues in case when controlled element dynamics has the increased time delay. This peculiarity was exposed in fulfillment of special experiments where, except the command input signal, it was used the additional one causing the stick deflection. The results demonstrated that the closure of inner loop leads to considerable lead compensation. As a consequence it causes the decrease of amplitude margin in pilot–aircraft system and increase of pilot–induced oscillation.
- Change of a number of task variables: mean square of input signal σ_i, display gain coefficient K_D and allowable interval of error d don't change pilot–aircraft frequency response in case when μ – criteria ($\mu = \sigma_i \dfrac{K_D}{d}$) is constant.

Mathematical modeling of pilot behavior in manual control tasks.

Except the techniques for experimental investigations it was developed at MAI the mathematical modeling of pilot aircraft system based on three approaches. The first one, so-called structural approach, reflects the psycho-physiological processes in perception and development of strategy of behavior in the best way.

One of such models allowed to get the good agreement with experimental results is shown on fig. 8. It is the modification of Hess model. Its difference from the original is shown on table 1.

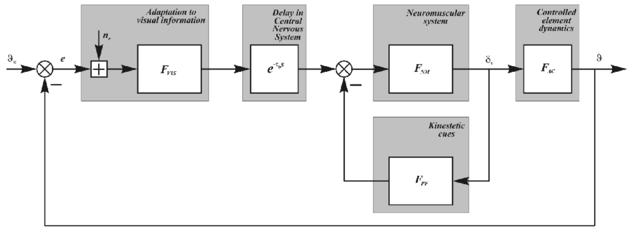

Fig. 8. Modified Hess model.

Table 1

	Original model	Modified model
F_{VIS}	K_L	$K_L \dfrac{T_L s+1}{T_1 s+1}$
choice of F_{VIS} parameters	by use of requirement to ω_C	by use of minimization procedure for σ_e^2
ω_C	constant	is defined by use of minimization of σ_e^2
F_{PF}	$\dfrac{1}{F_{PF}} e^{-\tau_0 s} F_{AC} =$ $= \dfrac{K_1}{\omega_C} e^{-\tau_0 s}$	$\dfrac{F_{VIS} F_{NM}}{1+F_{PF} F_{NM}} e^{-\tau_0 s} F_{AC} =$ $= \dfrac{K_1}{\omega_C} e^{-\tau_0 s}$
NMS parameters	constant	is defined by the developed rules
remnant n_e	$n_e = 0$ (for linear system)	$n_e \neq 0$ (for linear system)

The modified version of remnant spectral density model $S_{n_e n_e}$ developed in [8] is defined by the following equation

$$S_{n_e n_e} = \frac{K^2}{1+T_L^2 \omega^2}$$

where $K^2 = \pi \dfrac{\sigma_{e_i}^2 + T_L^2 \sigma_{e_i}^2}{\dfrac{1}{K_{ne}} - \int\limits_0^\infty |\Phi|^2 d\omega}$,

Φ – frequency response characteristics of close-loop system;

$K_{n_e} = \dfrac{0.01}{1-\Delta f}$, Δf is a fraction of attention shared to the manual control task ($0 < \Delta f \le 1$)

It is shown in [8] that taking into account remnant leads to decrease of allowable pilot aircraft system parameters ranges in comparison with ranges received by well-known criteria. The effect of remnant takes into account by the so-called σ-criteria of stability

$$\sigma^2 = \frac{1}{K_{n_e}} - \int_0^\infty |\Phi|^2 d\omega > 0$$

It gives more narrow ranges of allowable pilot aircraft system parameters. The second approach to the mathematical modeling of the pilot aircraft system is based on use of modern optimal control theory. The developed algorithms and techniques [9-12] include:

- A number of numerical algorithms;
- Recommendations for the choice of weighting coefficients of extended cost-function $I = Q_e\sigma_e^2 + Q_u\sigma_u^2 + Q_{\dot{u}}\sigma_{\dot{u}}^2$

  $Q_e = f(d)$, d is allowable interval of error signal (in particular $Q_e = 1;0.5;0.2$ with d equal to 0; 0.75 and 2 sm correspondingly).
- Modified model of the motor noise $V_u = V_u^0 + p_{0u}\sigma_u^2$

  The values of a number of model parameters are given in table 2 [8].

Table 2

T_{N_1}, s	$\tau_1 s$	V_u	p_{0y_1}	p_{0y_2}	p_{0u}	$Q_{\dot{u}}$, 1/deg^2
0.05	0.25	0.02	0.005	0.05	0.003	0.01

(T_{N_1} is given from experiments with a side stick)

- Procedure for the choice of controlled element gain coefficient K_c.

  The both models allowed to estimate frequency and spectral characteristics of pilot control response with high accuracy.

The developed techniques for investigation of pilot aircraft system is the bases for system approach to the solution of applied manual control tasks. It supposes the consideration of plurality of piloting tasks where the variables of each of them are chosen from the requirements of adequacy to the considered task. The subject of study is regularities of pilot behavior used then for the development efficient solutions. This approach received wide application in solution of different applied manual control tasks.

The third approach for description of pilot control response characteristics developing at MAI is based on artificial neural network (ANN).

A technique is suggested to synthesize an based model of pilot control actions using data obtained from experimental investigations for pilot's activity. The ANN model uses a network with TDNN (Taped Delay Neural Network)type architecture based on a combination of a multi-perceptron and a taped delay line for input signals. This architecture allows to consider not only a value of input vector for some current time but also a prehistory of the value for several backward time steps. Some parameters are varied for the ANN model including input time delays, number of hidden layers, number of neurons within hidden layers, type of activation functions used in the neurons. A training of the network was carried out with error backpropagation technique. A training set for this network was generated using experimental data mentioned above. An efficiency of the synthesized ANN model was tested within closed loop of an "aircraft-pilot" system. Result obtained from the computational experiments show more close accordance with source experimental data than in case of conventional quasilinear models describing a pilot's control actions.

The application of Pilot-aircraft systems investigation for applied manual control tasks.

a. Development or criteria for flying qualities and PIO prediction. Methods for investigation of pilot-aircraft system were used widely for development of two types of criteria for flying qualities and pilot-induced oscillation (PIO) prediction.

The first type is defined in terms of pilot compensation parameters and closed loop system characteristics. Such type of criteria allows to predict the levels of flying qualities. The second type is based on requirements to flying qualities by calculation of pilot subjective rating.

In the frame of the first type criteria there were developed two of them in MAI. The first one is the criteria for the prediction of flying qualities and (PIO) too in longitudinal motion. The possibility of simultaneous prediction of flying qualities and PIO was shown in [16]. It was established here the relationship between Cooper-Harper ratings (PR) and pilot-induced oscillations ratings (PIOR): PR = 2·PIOR−0.5.

The boundaries of the first and second levels of flying qualities in pitch control tracking task are shown on fig. 9 [15] as the requirements to parameters: resonance peak (r) of amplitude closed-loop system and pilot compensation parameter W.

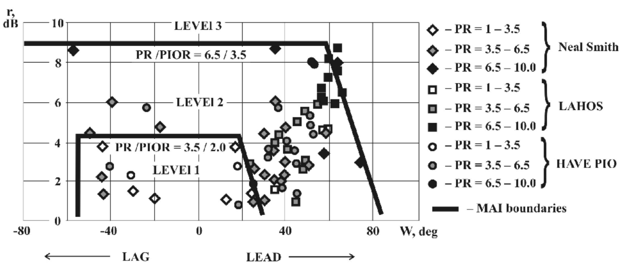

Fig. 9. Criteria for Flying qualities prediction in angular longitudinal motion.

The last one is defined as a maximum difference between pilot phase frequency response characteristic exposed in experiments with investigated dynamic configuration W_c and optimal control dynamics $W_{c_{opt}}$. The optimal control dynamics is defined in [8] by use the Wiener approach with taking into account the pilot psycophysiological limitations – time delay, multiplicative pilot's remnant and requirement of the simplest type of pilot behavior ($W_p = K_p e^{-j\omega\tau}$, $S_{n_e n_e} = p_0 \sigma_e^2$).

In the terms of parameters r, W there were defined the requirements to the first and second levels of ratings and for refueling piloting task too. Such requirements are the criteria for flying qualities prediction in this task is shown on fig. 10 [16].

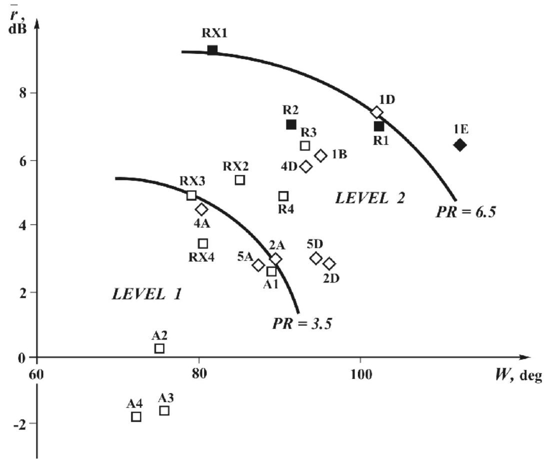

Fig. 10. Criteria for flying qualities prediction in path motion.

The general approach for definition of criteria of the second type is the suggestion that rating PR is the maximum between partional pilot ratings of preliminary selected parameters (criteria) of control processes (a_i a_j): $PR = \max(PR_{a_i}; PR_{a_j})$.

Analysis of experimental investigations fulfilled for a wide range of dynamic configurations demonstrated that in pitch tracking task such parameters are the accuracy σ (mean square error) and lag type phase compensation $\Delta\varphi$. The last one is defined as a maximum difference between pilot phase characteristic in case of generation of lag type of compensation and pilot phase frequency response characteristic corresponded to proportional type of his behavior. Thus $PR = \max(PR_\sigma; PR_{\Delta\varphi})$ in this piloting task. The equations for PR_σ and $PR_{\Delta\varphi}$ (table 3) shown for two types of pilot behavior model are received as a result of data reduction of wide experimental investigations.

Table 3

	Structural model	**Optimal model**
PR_σ	$PR_\sigma = 11(1+\ln(-0.4+1.68\sigma_e))$	$PR_\sigma = 11(1+\ln(-0.052+1.126\sigma_e))$
$PR_{\Delta\varphi}$	$PR_{\Delta\varphi} = -0.11(14+\Delta\varphi)$	$PR_{\Delta\varphi} = -0.11(0.952+\Delta\varphi)$

Calculation of these ratings allows to define predicted pilot rating for investigated configuration. The comparison of calculated ratings with their experimental values demonstrates low variability between them (less than one unit).

For dual channel task of pitch and bank control the summarized pilot rating:

$$PR_{\Sigma} = \max(PR_{\theta}, PR_{\varphi}),$$

where partial ratings PR_{θ} and PR_{φ} (rating of flying qualities in pitch (PR_{θ}) and bank (PR_{φ}) channels) are defined by equations:

$$PR_{\theta(\varphi)} = 1 + 5.36 \ln \frac{\sigma_{\theta(\varphi)}}{\sigma_{\theta(\varphi)}^{opt}},$$

where $\sigma_{\theta(\varphi)}$ and $\sigma_{\theta(\varphi)}^{opt}$ – mean square error on pitch (θ) or bank (φ) angles calculated by consideration of pilot-aircraft system (with usage of pilot optimal control model) for investigated configuration $W_c(j\omega)$ and optimal aircraft dynamics $W_c^{opt}(j\omega)$.

In case when pilot percepts simultaneously visual ("vis") and vestibular ("vest") cues the total pilot rating (PR_{Σ}) is defined by partial ratings PR_{vis} and PR_{vest}. Analysis of experimental data received in ground-based simulation of bank target and stabilization tasks with (and without) motion cues exposed the importance of two types of modalities in formation of PR_{Σ}.

As a result it was received the following equation

$$PR_{\Sigma} = \max(PR_{vis}, PR_{vest}) - 3,$$

where $PR_{vis} = -1{,}75 + 5{,}25 \ln(-4 + 2{,}5\sigma_e)$

$$PR_{vest} = 23{,}4 - 14 \ln(-4 + 2{,}5\sigma_e).$$

The developed mathematical modeling of pilot-aircraft system with help of structural model allowed to get good agreement predicted PR_{Σ} and experimental data.

The boundaries of aircraft parameters (aperiodic time constant T_{φ} and gain coefficient K_c) corresponded to the first and second level of pilot ratings and calculated by mathematical modeling are shown on fig. 11.

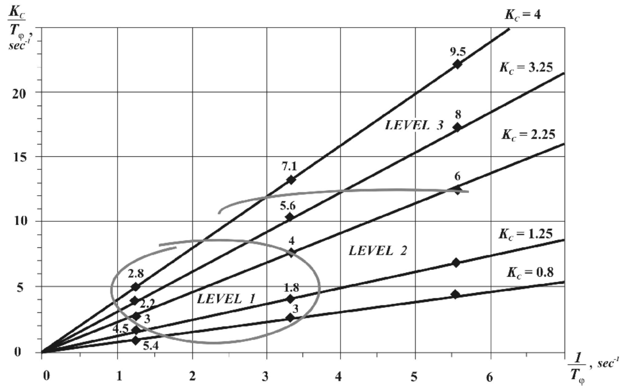

Fig. 11. Criteria for prediction of flying qualities prediction in bank control task.

<u>b. Improvement of agreement between ground–based and in–flight estimation of flying qualities</u>. Disagreement between ground–based and in–flight experiments was demonstrated in [11] with limited number of configurations corresponding to the third level of pilot ratings. More detail experimental investigations showed that disagreement between in–flight and ground–based investigations takes place in the first and third level of pilot–ratings too. The difference between the best and the worst PR received in investigations of considered data base is so–called "interval of ratings", (ΔPR). It is equal to 9 in–flight investigations with Have PIO data base and only 3.5 and 5 in ground–based–simulations fulfilled in [17] or [18]. The goal of fulfilled investigations was to develop technique providing the improvement of agreement between ground–based and in–flight simulations for the different piloting tasks.

It was done for a number of piloting tasks: landing, aim–to–aim tracking, refueling. The technique for definition of task performances was discussed above.

There were fulfilled 2060 experiments with 107 dynamic configurations. The adequate and desired performances for these piloting tasks are given in tables 4, 5 and 6.

Table 4

Landing

	Longitudinal error ΔX	**Lateral error** ΔY	**Touchdown velocity** V_{TD}
Desired	± 75 m	± 1.5 m	1.5 m/s
Adequate	± 150 m	± 7 ÷ 8 m	2.5 m/s

Table 5

Refueling

	Longitudinal error ΔX	**Lateral error** ΔY	**Contact velocity**
Desired	Less of 40% radius of basket		0.9 … 1.4 m/s
Adequate	Less of 60% radius of basket		0.5 … 1.8 m/s

Table 6

Aim–to–aim tracking

	Angular error
Desired	5.0 mrad
Adequate	15.0 mrad

The agreement between in flight and ground based investigations fulfilled according to the developed technique is shown on fig. 12.

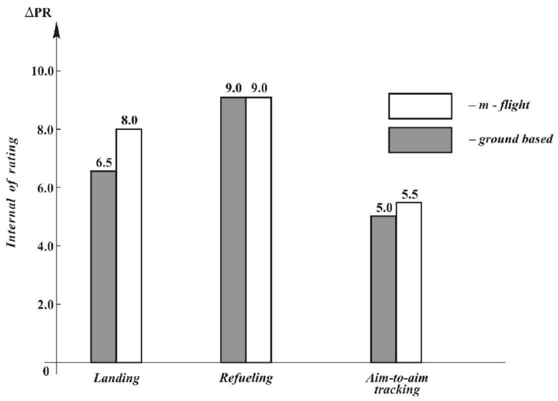

Fig. 12. Intervals of rating for different piloting tasks.

Conclusion

The developed techniques for experimental investigations of pilot–aircraft system and its modeling allow to expose new regularities of pilot behavior in wide range of piloting tasks and to use widely them for prediction of system characteristics. These techniques are the efficient tool for flying qualities prediction and their evaluation in ground based investigations.

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