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IFAC-PapersOnLine 49-32 (2016) 159–164

Pilot behavior modeling and its application to manual control tasks

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Abstract: The modified two pilot behavior models are discussed. One of them is the structural model. Its modification allowed to get better agreement in calculation of variance of error and to evaluate the influence of some new task variables (control element gain coefficient, requirements to the accuracy) on pilot – vehicle system parameters. The other model is the composite model of pilot behavior based on neural network approach. This model provides high agreement between the simulated and experimental pilot frequency response characteristics. The structural model is used for development of the criterion for the of flying qualities prediction in lateral channel with taking into account the influence of motion cues on pilot behavior and for the preliminary design of the predictive display. As for the composite model it was used for development of the flying qualities criterion for the pitch control task based on calculation of pilot and pilot aircraft system frequency response parameters. The additional procedure - the preliminary selection of dynamic configurations from the database was proposed what allowed to get high agreement between the predicted flying qualities level evaluated by the pilots in flight tests.

Keywords: pilot-aircraft system; pilot control response characteristics; simulation; flying qualities; flight control system.

1. INTRODUCTION

The solution of many applied manual control tasks requires the knowledge of regularities of pilot behavior and its mathematical models. The basis for the investigations in this area was done by D. Mcruer and his colleagues from STI in 60-70 of the last century [1, 2]. It allowed to expose the main regularities of human-operator behavior in tracking tasks and to create a number of pilot, so-called, crossover models. The modification of the classical crossover model was "structural model" developed by R. Hess in seventies [3]. This model takes into account human-operator potentiality to close the additional inner loop by his response on perception of kinesthetic cues. The considerable efforts in the researches carried out at Moscow aviation institute [4, 5] were dedicated to the modification and development of pilot models, with goal to extend the potentialities of the model. The developed here structural model allowed to take into account the influence of aircraft dynamics on crossover frequency of the open-loop system, the perception noise, to explain the pilot ability to generate the additional adaptation in the low frequency range. However this model has the number of shortcomings too. The main of them are the impossibility to investigate the influence of the number of some task variables (controlled element gain coefficient, requirement to the accuracy of tracking) and inaccurate calculation of same pilot vehicle system parameters. These shortcomings limit the potentiality in the usage of the model for the solution of practical problems where these performances define the task solution and the following recommendations. Because of it the modification of the pilot structural model was developed what allowed to apply it for the solution of two practical tasks. One of them is the development of criterion for the lateral motion based on calculation of pilot rating defining by the variance of error. The other task is the predictive display design based on preliminary mathematical modeling of pilot controlled element dynamics system. The results of the both tasks were checked in ground-based simulation. For the solution of the other task – prediction of flying qualities level requires the preliminary calculation of pilot and pilot-vehicle system frequency response characteristics by usage the pilot model providing the best agreement between simulated and measured experimentally pilot frequency response characteristics. The developed at MAI composite model based on neural network approach corresponds to such requirements. Its application to the development of criterion for the flying quality prediction in pitch control tracking task is given below.

2. PILOT BEHAVIOR MODELING BASED ON STRUCTURAL APPROACH

2.1 Modification of the pilot structural model

The MAI's structural model is shown on fig. 1. It consists of three major elements:

- "the simplest compensation" describing the pilot's ability to select the appropriated gain coefficients α, β and lag time constant T_I, to provide the necessary features of pilot-vehicle system in crossover frequency range. This element includes also time delay (τ) effect and the noises caused by the perception of error signal and its derivative. The mathematical models for spectral densities of these noises are given in [4, 5].
- the element describing the pilot's ability to generate "the additional compensation" in low or/and

Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2016.12.207

crossover frequency ranges. The model for $W_{ad}(s)$ defining this feature is given in [6].

- The "neuromuscular system", where $W_{NM}(s)$ is the second order model [6].

$W_c(s)$ is the transfer function of the controlled element dynamics.

The novel components of this model are:

a) The motor noise added to the pilot's output.

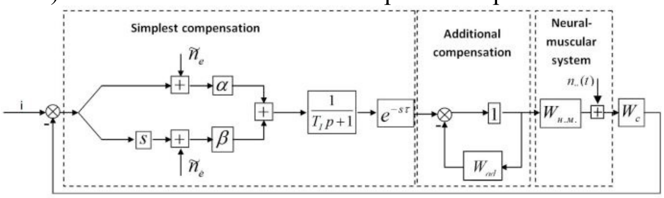

Fig. 1 The modified structural model

Its spectral density

$$S_{n_u n_u} = K_{n_u} \sigma_u^2 + \sigma_{u0}^2, \qquad (1)$$

where the residual remnant with spectral density $\bar{S}_{n_u n_u} = \sigma_{u0}^2 = 0.0002$ and $K_{n_u} = 0.003$.

b) The new cost function $J = \min(\sigma_e^2 + Q_u \sigma_u^2)$ is used for the selection of pilot model parameters ($K_P = \alpha$; $T_L = \dfrac{\alpha}{\beta}$; K_n; T_n), here K_n; T_n - parameters of $W_{ad}(s)$ instead of criterion $J = \min(\sigma_e^2)$ proposed in [4 - 6].

The element $Q_u \sigma_u^2$ in cost function and residual remnant $\tilde{S}_{n_u n_u} = \sigma_{u0}^2$ in motor noise model allow to get better agreement between the calculated variance of error and results of their measurement in experiments, to extend the potentialities of the pilot modeling. In particular it allows to investigate the influence of controlled gain coefficient and parameter "d" (accepted interval of error signal). The last one reflects the instruction which pilot has to follow during ground-based simulation, "to keep the error signal inside the interval *d*".

c) The procedure for selection of weighting coefficient Q_u consisted of:

- calculation of dependence $\sigma_{em}^2 = f(Q_u)$
- definition of the acceptable interval of error as $d = 4\sigma_{em}$

(The experiments for the single loop tracking task demonstrated that the value $4\sigma_e$ defines the interval *d* ($d = 4\sigma_e$), which does not exceed the error signal during the experiment with probability 0.95.)

d) Definition of value Q_u^* corresponding to the selected *d* and pilot model parameters calculated by minimization of criterion $J = (\sigma_e^2 + Q_u \sigma_u^2)$.

The mathematical modeling allowed to get the pilot frequency response characteristics very close to the results of ground-based simulation (fig. 2) and to select the optimal values of control element gain coefficient K_{Copt} (fig. 3). Except it the calculated values of variance of error (σ_{em}^2) corresponded to the values measured in experiments ($\sigma_{e\exp}^2$) with high accuracy. For example, for one of the dynamic configuration in the tracking task with the input spectral density $S_{ii}(\omega) = \dfrac{K^2}{(\omega^2 + 0.25^2)}$, $\sigma_{em}^2 = 0.025 \text{ deg}^2$ and $\sigma_{e\exp}^2 = 0.026 \text{ deg}^2$. The usage of the previous version of the structural model [5,6] gives the result of the modeling $\sigma_{em}^2 = 0.07 \text{ deg}^2$.

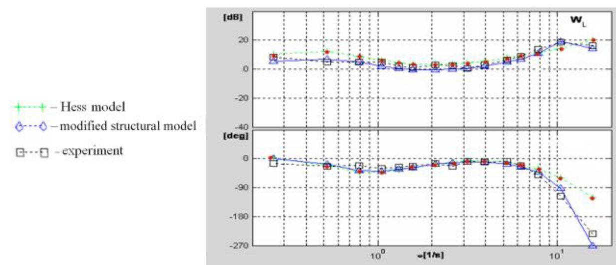

Fig. 2 Agreement between mathematical modeling and experimental results

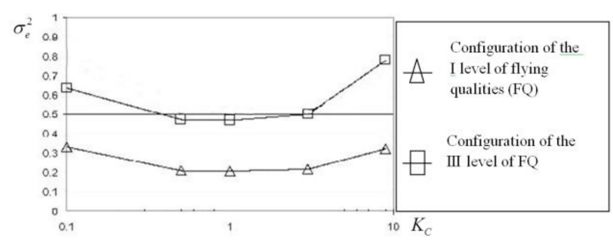

Fig. 3 Influence of gain coefficient on σ_e^2

This modification demonstrates that the change of gain coefficient K_c or interval *d* leads to the same trend pilot frequency response characteristics and variance of error changes as it tasks place in ground-based simulation.

2.2 The application of the modified structural model to applied manual control tasks.

a) Development of flying qualities criterion in bank control tracking task with taking into account motion cues

Mathematical modeling is used frequently for analysis of the flight test results. One of such flight test result given in [7] is the different requirements to the lateral flying qualities exposed in bank tracking task when the ground fixed-based simulation and in-flight simulators were used for their definition. In these experiments the aircraft dynamics was close to the following transfer function $W_c \cong \dfrac{\varphi}{\delta_a} = \dfrac{K_c}{s(Ts+1)}$. The decrease of time constant *T* approaches this transfer function to the dynamics $W_c \cong \dfrac{K}{s}$ what leads to the decrease of the error signal. Because of this effect the decrease of the time constant *T* is the requirement to this parameter following from the fixed-based simulation. In the actual flight the decrease of T causes the simultaneous increase of linear acceleration n_y resulting from the rotation of pilot head around the X axis. Such acceleration causes the negative effect on pilot perception of the piloting process. This result explains the limitation of accepted interval of time constant *T*. For the first level of flying qualities this interval is equal to ($T = 0.3 \div 0.85$, s). The experiments carried out at one of Moscow aviation institute moving-based simulator for the different controlled element gain coefficients and time constant *T* demonstrated that the pilot ratings PR≤3.5 are provided for $T = 0.23 \div 0.9$ s. The following rule has been proposed for calculation of pilot rating PR depending on the partial ratings: PR_{vis} – rating of the visual modality and PR_{vest} rating of the acceleration n_y perceived by pilot in the bank angle tracking task:

$$PR = \max(PR_{vis}, PR_{vest}) - 3, \quad (2)$$

where $PR_{vis} = -1.75 + 5.25\ln(-4 + 2.5\sigma_e)$;

$PR_{vest} = 23.4 - 14\ln(-4 + 2.5\sigma_e)$;

σ_e - mean square error of the bank angle;

The equation (2) was obtained as a result of analysis of experiments executed on moving-based simulator for wide range of dynamic configurations tested preliminary in flight tests.

Because of the structural model allowed to calculate σ_e with high accuracy it was used to define PR for these configurations. The results of such calculation given on fig. 4 demonstrate that the first level of flight qualities (PR≤3.5) is provided by time constant T belonging to the interval 0.26-0.95 s what is close to the results of ground-based and in-flight simulation.

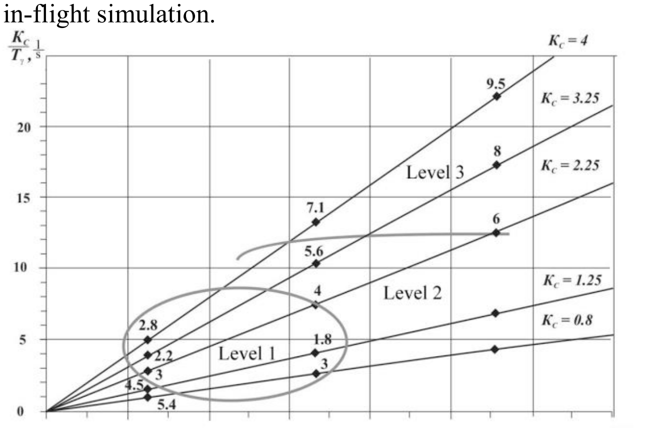

Fig. 4 Flying qualities requirements in bank control task (results of mathematical modeling)

b) Flight control and predictive display design for the docking task

The structural model was used in the design of predictive display proposed for the compensation of time delay (τ up to 2 s) accompanying the teleoperator control (so-called "TORU") regime at the docking of spacecraft with International Space Station. The scheme of compensation is shown on fig. 5.

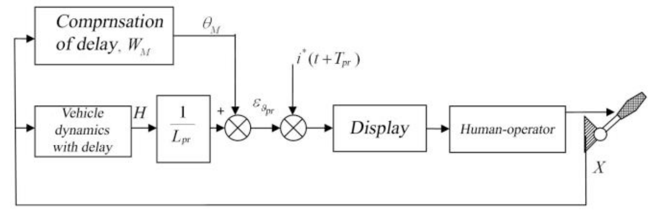

Fig. 5 The pilot-vehicle system with the compensation loop

The block "compensation of delay" here is the model of vehicle path motion dynamics calculated by on-board computer without taking into account time delay. The linearized controlled element dynamics (vehicle + predictive display dynamics for that case is $W_c^* = \frac{\varepsilon_{pr}}{\delta_e} = \frac{K_c(e^{-s\tau} + sT_{pr})}{T_{pr}(T_{en}s+1)}$, where T_{pr} - predictive time, T_{en} is the constant time of the engine dynamics. Such dynamics is characterized by considerable better flying qualities in comparison with case when the predictive display is not used. The frequency response characteristics of this transfer function shown on fig. 6 has the slope of amplitude frequency response close to -20 dB/dec in the frequency range ω =0.6÷6 1/s and considerable better phase frequency response characteristics what evidently has to simplify the piloting process.

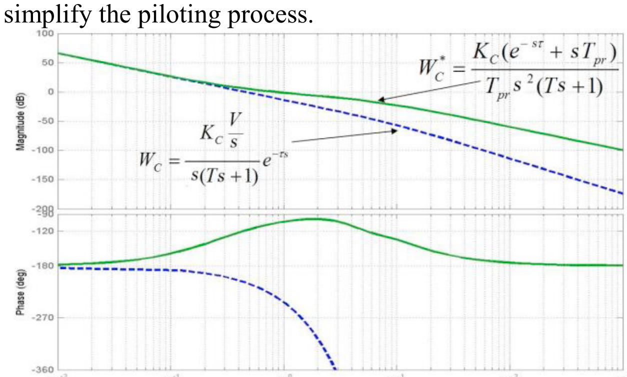

Fig. 6 Controlled element frequency response

For the definition of optimal predictive time T_{pr} it was considered the pilot-vehicle system (fig. 7) and the parameters of structural model were defined for each T_{pr} by minimization of criterion $I = \sigma_\varepsilon^2 + Q_u\sigma_{cu}^2$.

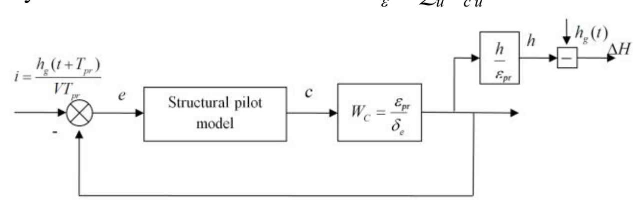

Fig. 7 Pilot-aircraft system with predictive display

The variance of the current height $\sigma_{\Delta H}^2$ was calculated for each T_{pr} too. The dependence $\sigma_{\Delta H}^2 = f(T_{pr})$ allowed to get the optimal value T_{pr} equal to 17-18 s. The experimental investigations were executed at MAI simulator with stereoscopic visual system.

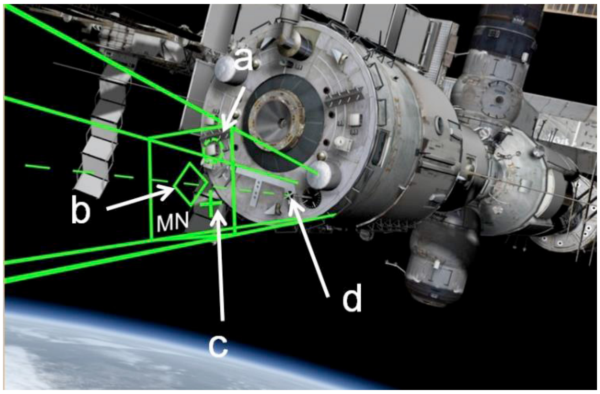

Fig. 8 The predictive display for the docking task

The predictive information was presented on the display in the form of symbol which position is proportional to the projection of spacecraft velocity measured relatively ISS (symbol a, fig. 8). It was calculated in ISS board computer assuming the absence of time delay occurring during transmitting of signals and transformation of data. Such symbol is displayed on the surface MN (fig. 8) located at the distance $L_{pr} = VT_{pr}$ and moving in front of the spacecraft inside the corridor with velocity, V, equal to the velocity of its motion relatively ISS. The center of such corridor is presented by rhombus "b". The crossing of its axes lies on the line passing through the target located at the ISS. Except these symbols the center of the screen "c" is reflected on the screen too. Thus the operator task is the combining the predictive symbol "a" with the center of the window (rhombus "b") and with symbol "c" by use the thrusters control. The experiments confirmed the theoretical results. It was shown also the necessity to use angular velocity feedbacks in addition to predictive display. It allows to decrease the pole order in the origin of the controlled element dynamics and to suppress the effect of eccentricity causing in case when the linear thrusters are switched on. Such automation provides the variability of contact point not exceeding 10 mm what is proportional to the variability reached in case of the absent of delay ($\tau = 0$, s) (fig. 9). The variability of component of velocities and angles decreases up to 10 times too.

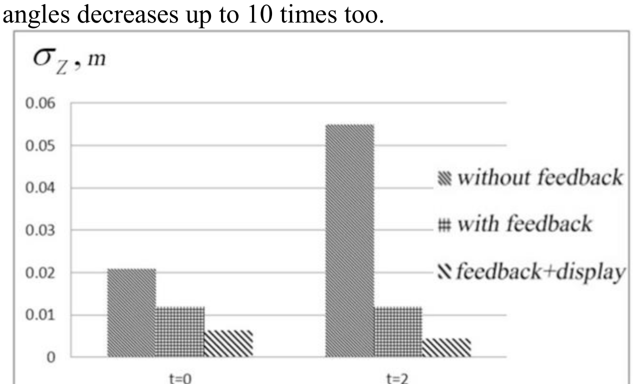

Fig. 9 Influence of time delay on variability of contact point

3. COMPOSITE MODEL OF PILOT BEHAVIOR

3.1 Brief description of composite model

The composite model is based on consideration that pilot control response characteristics corresponding to a dynamic configuration $W_C(j\omega)$ are generated by use the pilot experience to control the similar configurations. The development of composite model based on the neural network approach requires:

- to define a set of neural network models (NNM) $W_{pi}(j\omega)$. Each of them corresponds to some specific dynamic configuration $W_{Ci}(j\omega)$. The definition of each $W_{pi}(j\omega)$ model is carried out from consideration of the closed loop pilot-aircraft system;
- to define the composite pilot model $W_{p*}(j\omega)$ for prediction of pilot-aircraft characteristics in case of configurations $W_{Ci*}(j\omega)$ not included in the set $\{W_{Ci}(j\omega)\}$.

The development of each NNM $W_{C*}(j\omega)$ consists of the following steps:

1) selection of criterion for pilot models training;
2) generation of training set;
3) determination of model structure.

The solution of these tasks allows to obtain some versions of the pilot NNM for cases of linear and nonlinear aircraft pitch dynamics [8]. The NNM structure for a linear dynamic configuration $W_C(j\omega)$ is demonstrated on fig. 10. The values of weight coefficients W_i and b are the different for each NNM. There are 40 NNMs altogether represented in [8] corresponding to 40 aircraft dynamic configurations described in [9, 10, 11]. The rules needed for determination of values of parameters $\Delta\tau$ and T_y as functions of the frequency response parameters of $W_C(j\omega)$ are given in [8].

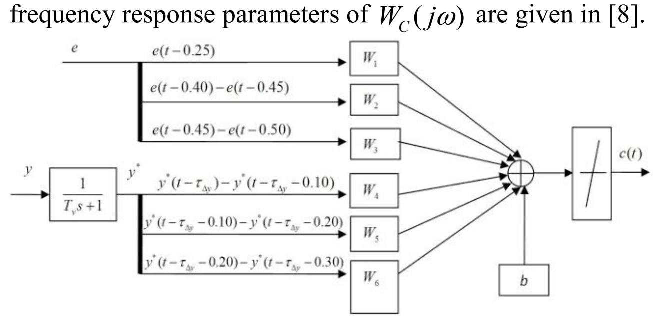

Fig. 10 Pilot neural network model

The comparison of pilot NNM frequency response characteristics and pilot describing functions measured in experiments acquired on MAI fixed-base simulator demonstrated high adequacy level of NNMs for the whole frequency range and for all dynamic configurations.

Except the agreement between the modeling and experimental pilot describing function each mathematical model has to provide the ability to predict the results of experiments. The last one is a potentiality to predict the pilot behavior correctly for such set of the task variables (for example, controlled element dynamics W_C), for which pilot describing functions were not defined before.

The determination of such predictive ("composite") model corresponding to a configuration $W_C(j\omega)$ requires the knowledge of frequency response characteristics of the neural network pilot models calculated before for the dynamic configurations $W_{CK}(j\omega)$ and $W_{CM}(j\omega)$ which dynamic characteristics are close to $W_C(j\omega)$. It requires to solve following tasks for definition of the composite model:
1) determination of configurations $W_{CK}(j\omega)$ and $W_{CM}(j\omega)$ from the set of configurations investigated previously $\{W_C(j\omega)\}$ and close to $W_C(j\omega)$.
2) calculation of quasilinear pilot model $W_p(j\omega)$ corresponding to the controlled element dynamics $W_c(j\omega)$. The last one is calculated by using linear interpolation for frequency response characteristics of NMM $W_{p1}(j\omega)$ and $W_{p2}(j\omega)$ corresponding to the dynamics $W_{c1}(j\omega)$ and $W_{c2}(j\omega)$.
The developed technique was used to for calculation of a set of models $W_p(j\omega)$ corresponding to the different configurations. The comparison of composite model with the structural pilot models for one of $W_C(j\omega)$ shown on fig. 11 indicates that the composite model has the better predictive properties.

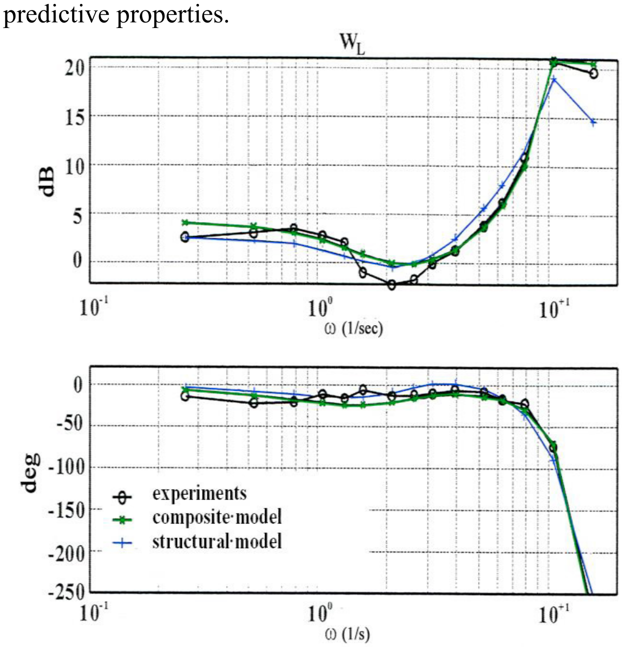

Fig. 11 Describing functions of the different models

Its amplitude frequency response characteristic differs from the experimental data in low ($\omega < 0.8, 1/s$), crossover (($0.8 \le \omega \le 3, 1/s$), and high ($\omega > 3, 1/s$) frequency ranges no more than 0 dB, 2 dB, 0 dB correspondingly. The amplitude frequency response characteristic of structural model differs from the experimental data in the same frequency ranges no more than 1.5 dB, 2.5 dB, 1.5 dB. As for the phase frequency response characteristics the composite model demonstrates its better agreement with experimental data in low and high frequency ranges

3.2 Application of composite model to the flying qualities criterion development.

Because of the better accuracy of pilot composite model frequency response characteristics it was used for development of aircraft longitudinal flying qualities criterion defined in the terms of the following parameters - the resonant peak of closed-loop system r and the phase compensation parameter $\Delta\varphi_p = \max(\varphi_p|_{W_C} - \varphi|_{W_{Copt}})$. Here $\varphi_p|_{W_C}$ is the phase frequency response of the pilot model acquired for a configuration W_C and $(\varphi_p)|_{\omega_{opt}}$ is the pilot phase frequency response corresponding to the best aircraft dynamics W_{Copt} which does not require any pilot compensation actions ($\varphi_p = -57.3\omega\tau$). These parameters were selected in [12] for the definition of MAI criterion used for PIO and flying qualities prediction. The MAI criterion was developed in result of experiments where operators carries out pitch tracking tasks with dynamic configurations from well-known database [9-11]. The parameters r and $\Delta\varphi_p$ were measured after each experiment. In current paper the parameters r and $\Delta\varphi_p$ were calculated for each dynamic configurations and NNMs corresponding to these configurations. The parameter $\Delta\varphi_p$ is found in the crossover frequency range. If the $\Delta\varphi_p$ parameter has both negative and positive values then both of these values are plotted on the area of r, $\Delta\varphi$ parameters [12]. Each point of this area corresponds to the pilot rating which was obtained in flight tests using Cooper-Harper rating scale. These experimental data allows to define the boundaries of the areas of first and second levels of pilot ratings, corresponding to the PR=3.5 and PR=6.5 values. From two values $\Delta\varphi^+$ and $\Delta\varphi^-$ the point corresponding to the “worst” level of flying qualities has to be left on the plot r, $\Delta\varphi_p$.

The available databases were analyzed to improve prognostic capability of the MAI criterion. Such analysis demonstrates that many results of flying qualities evaluation included in the databases are not reliable because only one or two flight experiments were carried out for some configurations and in many cases the pilot ratings were related to different levels for the same configuration. As a result of this analysis it was decided to select only such configurations for which pilot gave pilot ratings belonging to the same level in two or more number of experiments. Such selection reduced the number of configurations up to 20. The consequence of this selection was the modification of the first and second level flying qualities ranges (fig. 12) of MAI criterion in comparison with the ranges acquired for 40 configurations. Probability of correct prediction for flying qualities was increased up to 95%. In comparison with the case when all 40 configurations were taken into account for the definition of boundaries the probability of correct prediction of selected 20 configurations was equal to 67.5 % only.

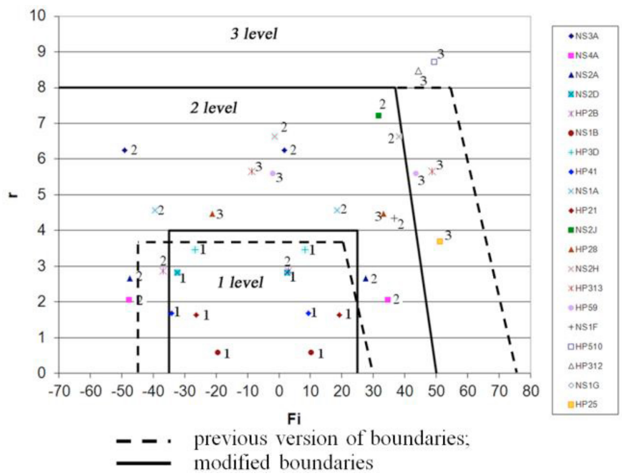

Fig. 12 Modified MAI criterion

CONCLUSION

The modified structural model of pilot behavior reflecting pilot control response characteristics in compensatory tracking tasks are characterized by the improved agreement with the experiments. The best agreement of the calculated describing function with experiments was demonstrated by the composite model. The modified structural model allows to calculate accurately the variance of error and to apply it study the influence of some additional variables on pilot and pilot-aircraft system characteristics which were not exposed with the previous versions of model. Such variables are controlled element gain coefficient, acceptable interval of accuracy. The structural model was applied to the predictive display design in the docking task of spacecraft with ISS and for the development criterion for lateral flying qualities prediction with taking into account influence of motion cues. The ground-based simulations confirmed the high efficiency of proposed predictive display and demonstrated agreement with recommendations for the selection of parameters of aircraft dynamics in lateral motion obtained by the mathematical modeling. The developed composite model was used for development of the longitudinal flying qualities criterion in combination with proposed rule for the selection of dynamic configurations from the known database. The modified criterion allowed to improve the probability of correct prediction of flying qualities level up to 95 %.

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