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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

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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.

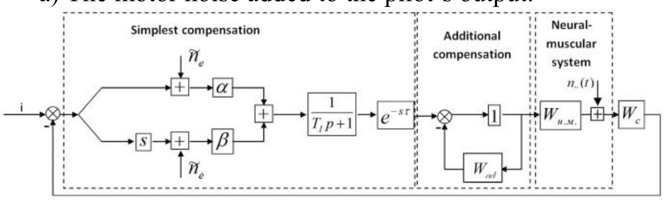

Fig. 1 The modified structural model

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 ($K_P = \alpha$; $T_L = \frac{\alpha}{\beta}$; 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 $S_{ii}(\omega) = \frac{K^2}{(\omega^2 + 0.25^2)}$, $\sigma_{em}^2 = 0.025 \deg^2$ and $\sigma_{e\exp}^2 = 0.026 \deg^2$. The usage of the previous version of the structural model [5,6] gives the result of the modeling $\sigma_{em}^2 = 0.07 \deg^2$.

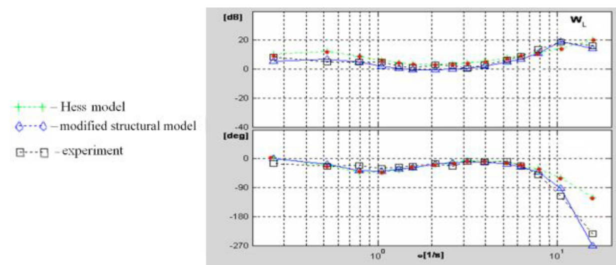

Fig. 2 Agreement between mathematical modeling and experimental results

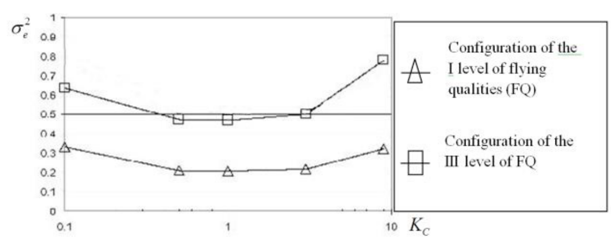

Fig. 3 Influence of gain coefficient on σ_e^2

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 $W_c \cong \frac{\varphi}{\delta_a} = \frac{K_c}{s(Ts+1)}$. The decrease of time constant T approaches this transfer function to the dynamics $W_c \cong \frac{K}{s}$ 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