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THE APPLICATION OF THE PILOT-AIRCRAFT SYSTEM APPROACH FOR OPTIMIZING 3D DISPLAY PARAMETERS

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Abstract

The paper is dedicated to defining the main parameters of the predictive display with preview: the predictive time T_{pr} and preview time T_{prev}. To that purpose, two sets of experiments were performed. One of them was the study of effectiveness of the preview display with a low bandwidth input signal, and the other set was performed for the identification of two describing functions determining the pilot responses to an error signal and input signal. On the basis of the exposed regularities, the procedure for calculating the parameters of the mathematical models of these responses is also considered.

Keywords: predictive display, preview tracking, pilot behavior model, manual control

1. Introduction

The knowledge of regularities and mathematical models of pilot behavior is necessary for describing the pilot-aircraft closed-loop system, in order to use it in the design of the aircraft subsystems (flight control system, display, inceptors) and determine a combination of their parameters which provides the best task performance and low pilot workload. In display design, the knowledge of regularities of perception, the definition of the information displayed on the primary flight display, and the ways of its presentation are of utmost importance. The pilot's ability to realize behavior as the function of perceived visual cues is the central element of the so-called "Theory of successive organization of perception" formulated in [1] the following way: "Given appropriate visual cues, the human pilot is capable of organizing his or her own perceptions (in essence, creating internal pathways) to adapt any one of the behavior modes. Indeed, a theory referred to as the successive organization of perceptions theory has been forwarded to describe this type of skill development".

The compensatory mode of pilot behavior is the most studied one. For this type of tracking task, a number of pilot's models (crossover, structural, and optimal control models) were developed at the last century and have found broad application in solving different engineering problems.

Initial studies [2, 3] of pilot behavior in pursuit and preview tracking tasks carried out in the second half of the last century with simplified controlled element dynamics demonstrated that the pilot's response to a perceived input signal leads to a considerable decrease in the variance of error with a preview time T_{prev} close to 0.5÷1 s. Increasing this time did not cause a reduction in the tracking error.

Broad investigations in this area were carried out at Delft University [4-11] for several simplified controlled element dynamics, for a rectangular power spectrum input with different bandwidths ($\omega_i \geq 1.5$ rad/s). The emphasis in these studies was made on the mathematical modeling and identification of two pilot frequency response characteristics whose outputs are the so-called "near/far view responses". The parameters of these characteristics were obtained from the preliminary measurements of two pilot describing functions, one of which described the pilot response to the input signal $i(t+T_{prev})$ and the other described the pilot response to the error signal $e(t)$. The methodology of these measurements and calculations is given in [7, 8]. All these studies exposed the effect of preview on pilot behavior characteristics, its potential for improving task performance, and the influence of the input signal bandwidth and controlled element dynamics on all these regularities. In spite of the importance of these results, all of them were performed for a high bandwidth of the input signal which is not typical for aircraft flight path motion. It required clarification of the results for a lower input bandwidth ($\omega_i = 0.2,\ 0.5$ rad/s) which is closer to the planned trajectory of aircraft path motion [12]. In addition, the dynamics of modern aircraft equipped with the display are defined by the dynamics of the aircraft-display system which is more complicated than the simple configurations investigated in [7, 8].

The current state of technology has allowed to realize a display with a 3D presentation of the planned trajectory on the screen. This technology has prompted a number of studies in defining the best way of presenting the information [3-7, 13]. Finally, the so-called "tunnel in the sky" display was proposed [13]. This display allows pilots to evaluate the current aircraft position in space and the future planned trajectory.

The following modification of this display is the so-called predictive display [14], where, aside from the tunnel, the surface moving inside of it and the predictive angle $\varepsilon_{pr} = \frac{h}{L_{pr}} + \gamma + \dot{\gamma}\frac{T_{pr}}{2}$ are also displayed. Here γ is the path angle and h is the aircraft height displacement.

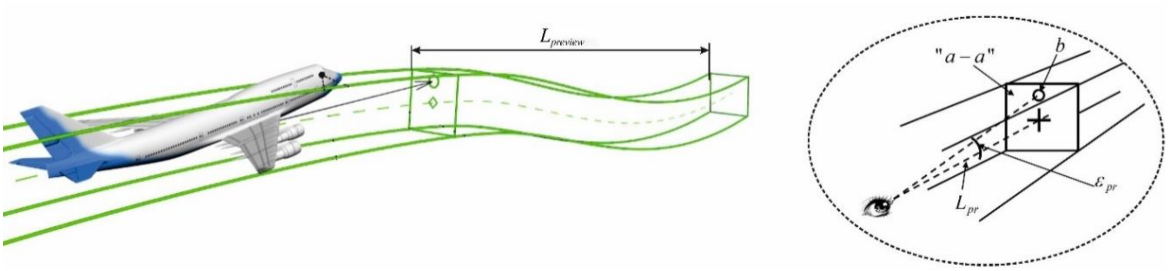


Figure 1 – Predictive display

The selection of the distance between the pilot's eyes and the surface L_{pr} (or predictive time $T_{pr} = \frac{L_{pr}}{V}$) (Fig. 1) was carried out in [14] with the use of the traditional feedback control theory, aiming to provide the expected controlled element dynamics whose output signal is the predictive angle ε_{pr}. It is shown in [12] that the controlled element dynamics of the aircraft-display system in that case have the following describing function:

$$W_c(s) = \frac{\varepsilon_{pr}(s)}{X_e(s)} = \frac{K\left(T_{pr}s^2 + 2s + \frac{2}{T_{pr}}\right)}{s^2\left(s^2 + 2\zeta\omega s + \omega^2\right)}. \quad (1)$$

The results of the investigation performed in [12] demonstrated that the use of the predictive display allows to considerably improve task performance.

The presentation on the predictive display screen of both the predictive angle $\varepsilon_{pr}(t)$ projected on the surface ("a-a") (see Fig. 1) and the future target trajectory $i(i + T_{prev})$ located behind this surface transforms the predictive display into a predictive display with preview. The task in this case is the confirmation of effectiveness of such a display in control with the controlled element dynamics characterized by the transfer function (1) and simultaneous selection of display parameters: the predictive time T_{pr} and preview time T_{prev}. The solution of these problems requires performing a set of experiments and developing the mathematical model of pilot behavior in a preview tracking task. The current paper is dedicated to resolving these issues.

2. The Ground-Based Simulation Design

Two sets of experiments were performed:

- One set for defining the effectiveness of the preview display with different input bandwidths;
- The other set for identifying the pilot responses to input and error signals in a preview tracking task.

The first set of experiments was performed with the polyharmonic input signal $i(t)=\sum_{k=1}^{15} A_k \cos\omega_k t$ with $\omega_k = K\omega_0$, $\omega_0 = \frac{2\pi}{T}$. Its amplitudes and frequencies were selected from the requirements of agreement between the power spectrum distribution of the input $i(t)$ and the power distribution of a random signal characterized by the spectral density $S_{ii} = \frac{K^2}{(\omega^2+\omega_i^2)^2}$ with $\omega_i = 0.2;\ 0.5$ and 1.0 rad/s. The control element dynamics of both this set of experiments and the other corresponded to the transfer function (Eq. 1) with the parameters of $T_{pr} = 0.9$ s, $\omega = 2.4$ 1/s, $\xi = 0.64$.

The duration of each trial was equal to T=144 s. Three operators participated in the experiments. For each input bandwidth at least 3 trials were performed using one of the MAI Pilot-Vehicle Lab simulators (Fig. 2).

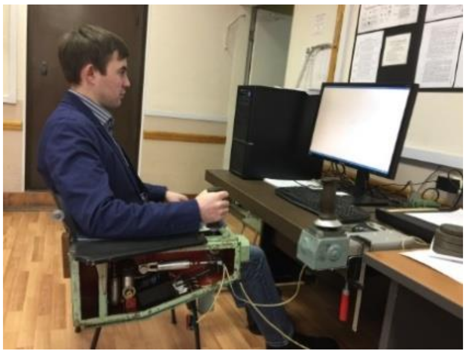


Figure 2 – Fixed-base simulator

The simulator was equipped with a sidestick and a display. On its screen the images corresponding to the preview and preview tracking task were displayed (Fig. 3). In the case of preview display the preview time T_{prev} was equal to 2 s.

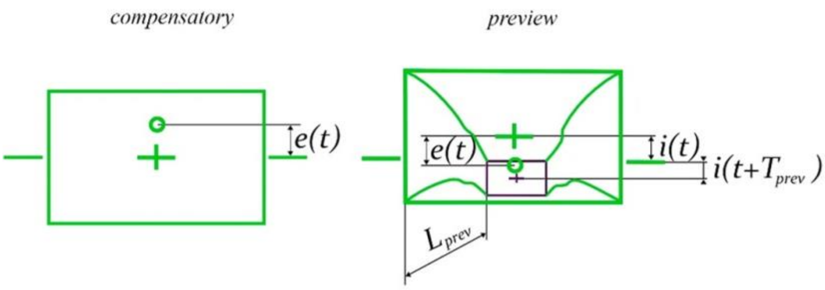


Figure 3 – Different displays used in the experiments

The following set of pilot-aircraft system characteristics was calculated after the experiments: the pilot frequency response characteristics ($W_P = \frac{c(j\omega)}{e(j\omega)}$ (Fig. 4)), measured in the conditions where the signal $i(t)$ was (preview tracking) or was not (compensatory tracking) demonstrated on the display. In addition, the closed-loop system ($\Phi = \frac{y(j\omega)}{i(j\omega)}$), variances of tracking error σ_e^2, control output σ_c^2, and its derivative $\sigma_{\dot{c}}^2$ were measured as well. The calculation of Fourier transforms of all signals was carried out by using the Fourier coefficients technique [15, 16].

The main purpose of the second set of experiments was the simultaneous definition of two describing functions, $F(j\omega)$ and $W_{pe}(j\omega)$. It requires the introduction of two uncorrelated signals, $i(t)$ and $d(t)$ [15] (Fig. 5). The latter might be considered as the atmosphere turbulence.

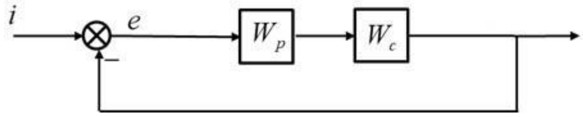


Figure 4 – Compensatory pilot-aircraft system

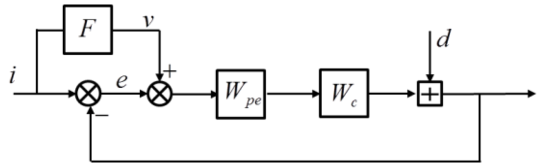


Figure 5 – Preview pilot-aircraft system

It was proposed to use the signals consisting of harmonics with orthogonal frequencies, *i* and *d*.

$$i(t) = \sum_k A_k \cos\omega_k t \, ; \, d(t) = \sum_m A_m \cos\omega_m t \, .$$

The sets of amplitudes A_k, A_m and frequencies ω_k, ω_m are given in Table 1 and 2.

Table 1. Signal $i(t)$

ω_k	0.262	0.785	1.309	2.094	3.142	5.236	7.854	15.708
A_k	2.376	-0.713	0.315	-0.188	0.097	-0.047	0.028	-0.008

Table 2. Signal $d(t)$

ω_m	0.524	1.047	1.571	2.618	3.927	6.283	10.472
A_m	-1.179	0.459	-0.278	0.123	-0.079	0.035	0.022

The sum of these harmonics is the signal $i(t)$ used in the first set of experiments.

The equations for the Fourier transforms of the signals $c(j\omega)$ and $e(j\omega)$ in this case are the following:

$$c(j\omega) = W_{pe}(j\omega)e(j\omega) + i(j\omega)F(j\omega)W_{pe}(j\omega)$$

$$e(j\omega) = i(j\omega) - \left[(e(j\omega) \cdot W_{pe}(j\omega) + i(j\omega) \cdot W_{pe}(j\omega) \cdot F(j\omega)) \cdot W_c(j\omega) + d(j\omega) \right]$$

From these equations it is possible to obtain the frequency response characteristics $W_{pe}(j\omega)$ on the frequency of the disturbance signal $d(t)$ $W_{pe}(j\omega) = \dfrac{c/d\big|_{\omega_m}}{e/d\big|_{\omega_m}}$.

As for $F(j\omega)$, its equation is then $F(j\omega) = \dfrac{c/i\big|_{\omega_k} + c/d\big|_{\omega_m}}{c/d\big|_{\omega_m}}$.

Due to the frequency response characteristics $c/i\big|_{\omega_k}$, $c/d\big|_{\omega_m}$ in the right part of this equation being calculated on different frequencies, the definition of $F(j\omega)$ requires interpolation of $c/i\big|_{\omega_k}$, $c/d\big|_{\omega_m}$ on common frequencies. The experiments to identify $W_{pe}(j\omega)$ and $F(j\omega)$ were performed on the same MAI Pilot-Vehicle Lab simulator that was used in the first set of experiments. The total duration of each trial was 144 s.

The experiments were performed for the preview display only, with different preview times $(T_{prev} = 0;\, 2;\, 3\ s)$. At least 3 trials were performed for each of them and the results were averaged for the following interpolation.

3. The Results of the Experiments and Their Discussion

The results of the experiments demonstrated that task performance improves in preview tracking in comparison with compensatory tracking especially for the higher input bandwidth. In particular, for $\omega_i = 0.2$ rad/s the decrease in the variance of error σ_e^2 was only 12%, while in the experiments with $\omega_i = 1.0$ rad/s the variance σ_e^2 decreased by 2.5 times with the preview display (Table 3).

Table 3

$\sigma_{c,e}^2$, sm²	$\omega_i = 0.2$, rad/s	$\omega_i = 0.5$, rad/s	$\omega_i = 1.0$, rad/s
$\sigma_{c\,comp}^2 / \sigma_{c\ prev}^2$	5.5/0.43	17.4 / 2.5	32.7/14.1
$\sigma_{e\,comp}^2 / \sigma_{e\ prev}^2$	0.20/0.18	0.97/0.48	2.8/1.12

The measurement of the variance of pilot control input σ_c^2 demonstrated more sufficient influence of the preview display with its decrease. However, the effect of bandwidth on this regularity is the opposite (Table 3). For the lower bandwidth the variance σ_c^2 was almost 13 times less in comparison with compensatory tracking. In the experiments with $\omega_i = 1.0$ rad/s, σ_c^2 decreased only by a factor of 2.2. The results of the experiments also demonstrated that a preview tracking task does not require rapid pilot actions. In particular, in the experiments with the input bandwidth $\omega_i = 0.5$ rad/s, the variance of pilot control input derivative is 3.5 times lower in comparison with compensatory tracking (Fig. 6)

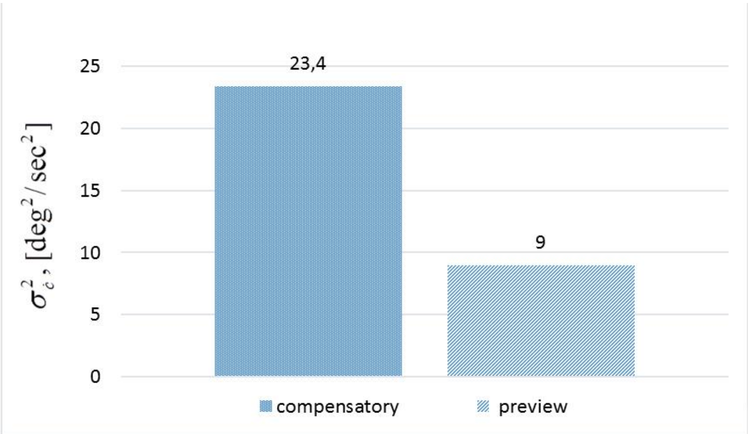


Figure 6 – Variance $\sigma_{\dot{c}}^2$ for a preview and compensatory tracking tasks

The measurements of the pilot describing functions $W_p = \frac{c(j\omega)}{e(j\omega)}$ also demonstrated the difference in $W_p(j\omega)$ obtained with the preview and compensatory displays practically for all input bandwidths. As an example, Fig. 7 demonstrates this effect, obtained in the experiments with $\omega_i = 0.5$ rad/s.

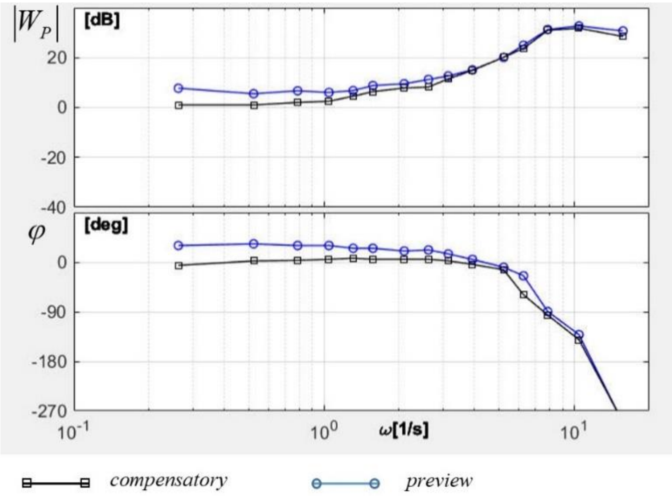
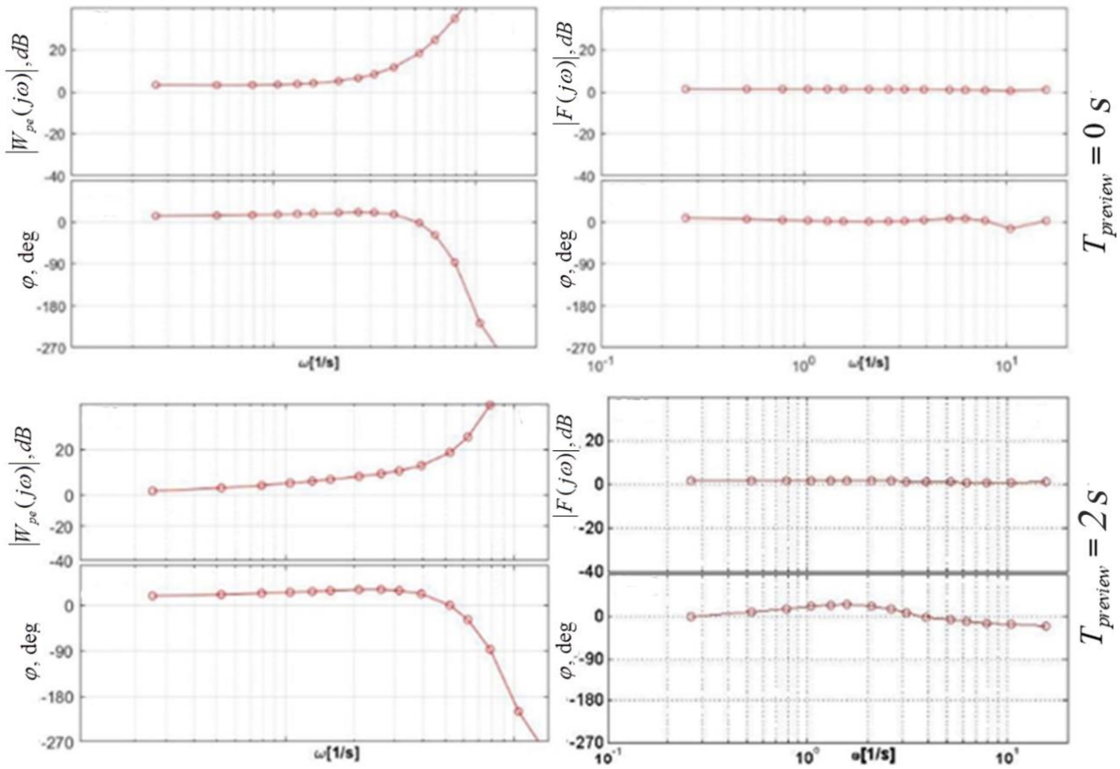


Figure 7 – Pilot describing functions for preview and compensatory tracking

In the case of preview tracking, the resonant peak of the closed-loop system $F(j\omega)$ decreases by up to 30%. All the results discussed above were obtained for the same preview time $T_{prev} = 2$ s. The influence of T_{prev} on the variance of error studied in [17] demonstrated that the function $\sigma_e^2 = f(T_{prev})$ has a minimum close to 2.4 s.

The second set of experiments associated with the identification of the two describing functions $W_p(j\omega)$ and $F(j\omega)$ was performed for different preview times $T_{prev} = 0; 2; 3$ s. The results of the identification are shown in Fig. 8.



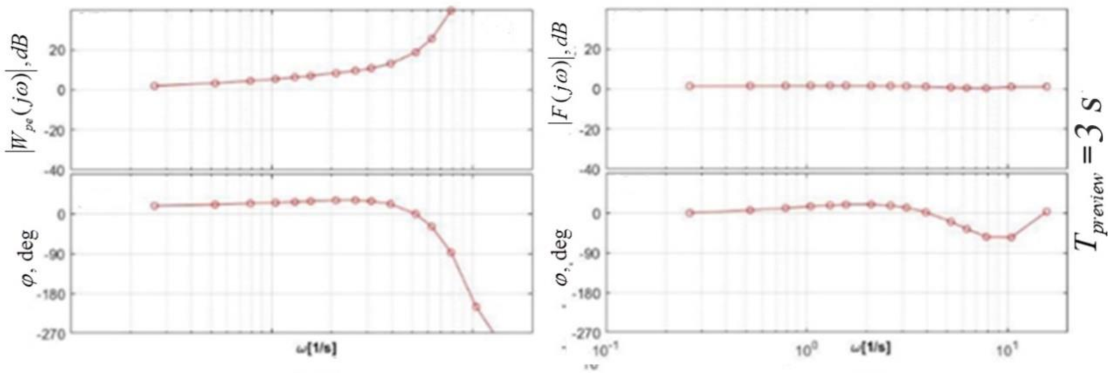


Figure 8 – Frequency response characteristics of $W_{pe}(j\omega)$ and $F(j\omega)$

4. Mathematical Model of Pilot Behavior in a Preview Tracking Task

Taking into account the experimental results of the preview information perception $i(t+T_{prev})$, the following model $F(j\omega)$ was proposed in the form of the additional input $v(t)$ summarized with the error signal (Fig. 9).

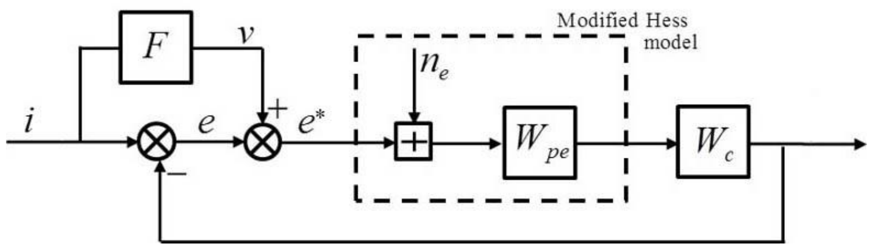


Figure 9 – Pilot model in a preview tracking task

Here $F(j\omega)$ is the model of perception whose output is the signal $v(t)$

$$v(t) = K_1 \frac{[i(t+\Delta t) - i(t)]}{\Delta t \cdot V} + K_2 \frac{[i(t+2\Delta t) - i(t+\Delta t)]}{\Delta t \cdot V} + ... \qquad (2)$$

This signal is essentially a weighted sum of trajectory segment slopes of the same length $\Delta t \cdot V$, shown in Fig. 10. It determines the process of the pilot perceiving the future planned trajectory.

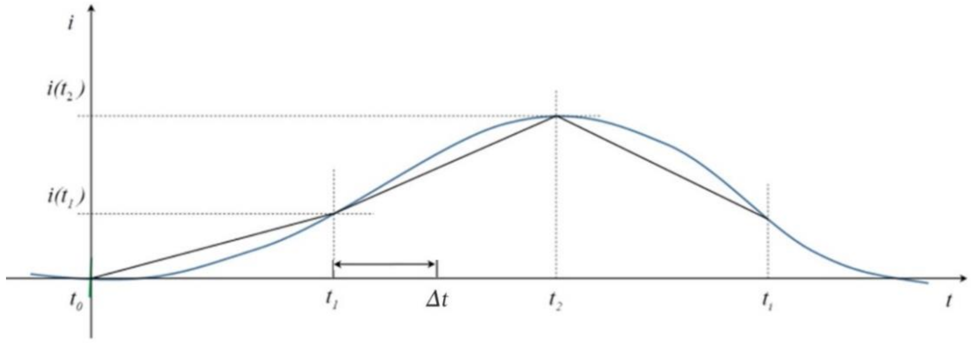


Figure 10 – Formation of the signal $v(t)$

The weights K_i determine the degree of importance for the pilot of the average trajectory segment slopes, located at different distances behind the predictive window.

This model $F(j\omega)$ was integrated in the proposed model of the pilot-aircraft system in a preview tracking task shown in Fig. 9.

Here the modified Hess structural model $W_{pe}(j\omega)$ was used in the inner closed loop system.

The description of this model and the model of the remnant spectral density $S_{n_e n_e}(\omega)$ are given in [17] in detail. The simultaneous selection of all parameters of the structural model and the weighting coefficients K_i of the perception model $F(j\omega)$ was proposed in [17]. The results of the proposed optimization procedure were:

- The dependence of $\sigma_e^2 = f(T_{prev})$ and T_{prev}^{opt} close to those obtained in the experiments (Fig. 11).

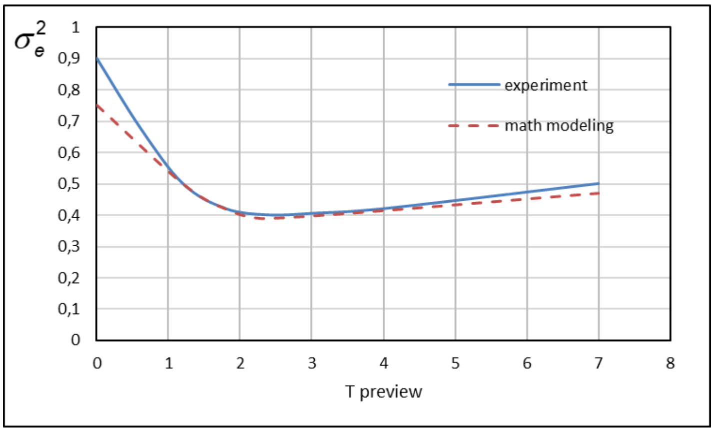


Figure 11 – Influence on the variance of error

- The regularity in weighting coefficients – a decrease in the weights K_i with an increase in "*i*" and the possibility of limiting the number of segments Δt to 6.
- The successful agreement between the $W_p(j\omega)$ obtained through experiments and mathematical modelling (Fig. 12).

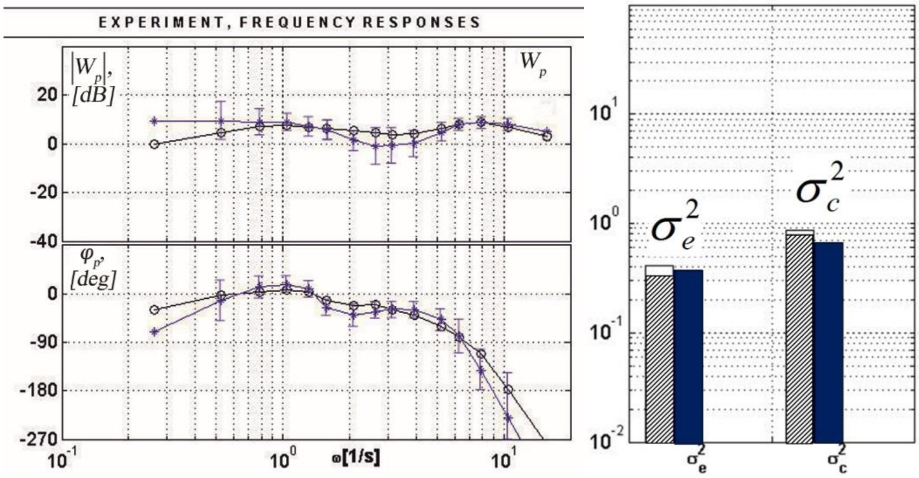


Figure 12 – Comparison of the experiment (⊖—⊖, ▨) with mathematical modeling (+—+, ■)

The shortcoming of the optimization procedure developed in [17] is the considerable time duration necessary for computer execution of the calculations. The proposed modified procedure for determining the pilot model in a preview tracking task is based on the experimental results discussed above. According to those results, the describing function $W_{pe}(j\omega)$ does not depend on the preview time T_{pr} . Taking this into account, the procedure consists of two stages:

1. The selection of parameters of the pilot structural model $W_{pe}(j\omega)$ in the inner loop of the model given in Fig. 9. This procedure is carried out through consideration of the compensatory

system (i.e. $F(j\omega)=0$) by minimization of the variance of error σ_e^2 according to the algorithms examined in [12, 17]. Performing this procedure for different T_{pr} allows to define the value T_{pr}^* providing the best task performance.

2. The definition of parameters of the model $F(j\omega)$ (in particular, the weighting coefficients K_i of the signal $v(t)$). The calculations of these gain coefficients are carried out by minimization of the variance of error for the parameters of the describing function $W_{pe}(j\omega)$ which are selected earlier. This procedure also allows to define the preview time T_{prev}.

This two-stage modified procedure provides the same accuracy of determining pilot model parameters in preview tracking as the initial version of the procedure. In addition, the duration of computer calculations decreases by 5-7 times.

Thus, the result of the procedure are the parameters T_{pr}^* and T_{prev} of the predictive display with preview providing the best task performance. The results of the mathematical modeling demonstrated that $T_{pr}^*=0.9$ s and $T_{prev}=2.4$ s for the considered controlled element dynamics and input signal with the bandwidth $\omega_i=0.5$ 1/s.

5. Conclusion

The experiments which were carried out using a ground-based simulator with the dynamics corresponding to Eq. (1) demonstrated a considerable difference in all characteristics for preview and compensatory tracking tasks. Preview tracking allows not only to improve task performance but to also considerably reduce pilot workload. These effects depend quantitatively on the input bandwidth. For $\omega_i=0.5$ 1/s the variance of pilot control input decreases by 7 times and the variance of its derivative decreases by 3.5 times with the preview display in comparison to the compensatory display. The experiments on the identification of two describing function characterizing pilot behavior in a preview tracking task demonstrated the independence of the pilot describing function $W_{pe}(j\omega)$ in the inner loop from the preview time. This result allows to propose the procedure for separate definition of predictive and preview time constants. The values of these constants correspond to the results of the experiments.

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