Predictive display design for the vehicles with time delay in dynamic response

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Predictive display design for the vehicles with time delay in dynamic response

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Abstract. The two ways for the improvement of flying qualities are considered: the predictive display (PD) and the predictive display integrated with the flight control system (FCS).
The both ways allow to transforming the controlled element dynamics in the crossover frequency range, to improve the accuracy of tracking and to suppress the effect of time delay in the vehicle response too. The technique for optimization of the predictive law is applied to the landing task. The results of the mathematical modeling and experimental investigations carried out for this task are considered in the paper.

1. Introduction

The precise path control task is a one of the most difficult manual control task as for the aeronautical and space vehicles because of their controlled element dynamics is characterized by the high order pole at the origin. For example the height-to-inceptor transfer function of aircraft in the landing task as well as the spacecraft in the docking task with International Space Station (ISS), has the second order pole at the origin [1, 2]. It requires the considerable pilot lead compensation what decreases the accuracy [3, 4]. Except this peculiarity, the highly augmented aircraft dynamics is characterized by the time delay [5, 6]. Such delay is caused by different filters, actuator dynamics, digital realization of aircraft flight control system laws. It achieves 0,1÷0,2 sec and even higher. It requires the considerable pilot lead compensation to avoid the pilot-induced oscillations in the closed-loop system [7]. The teleoperator control used for the docking of spacecraft with ISS and UAV (unmanned aerial vehicle) control implemented via satellite is accompanied by higher time delay (up to 1 sec for spacecraft [2], and 0.5 sec for UAV control [8]). The manual control is much more complicated in these cases. Because of it the automatic control is used more and more often.

The problem discussed in the paper is dedicated to the compensation of the time delay in their response by use of the predictive display.

2. General technique for the predictive display design.

The potentiality effect of predictive display for the landing of aircraft on the runway was shown in [9]. Such type of display was offered in [10] for the tasks of refuelling and landing the carrier. It displays 3D corridor within which the aircraft has to move. Such information allows to evaluate the current and future position of the aircraft and to transform pilot behaviour from compensatory to preview type. The predictive display shows also the surface moving inside the corridor with the aircraft velocity V, where the predictive angle $\varepsilon_{pr} = \gamma_{pr} + \dfrac{\Delta H}{L_{pr}}$ is projected. Here $L_{pr} = T_{pr} \cdot V$ is the distance between a pilot and the moving surface, ΔH is a deviation of aircraft altitude. The equation for predictive angle γ_{pr} depends on the controlled element dynamics. It is shown in [10] that for a conventional aircraft with the practical zero time delay in responses the predictive angle is defined by the equation $\gamma_{pr} = \gamma + \frac{T_{pr}}{2}\dot{\gamma}$. The use of such law allows to transform the controlled element dynamics providing the slope of its amplitude frequency response characteristics ($W_c^* = \frac{\varepsilon_{pr}(j\omega)}{x_e(j\omega)}$) in the crossover frequency range close to -20 dB/dec. It increases the accuracy and decreases the pilot workload. The technique for the definition of T_{pr} is considered in [10, 11]. It is based on the minimization variance of error ΔH ($\sigma^2_{\Delta H}$) (see the block diagram in fig.1). The procedure of minimization supposes the use of the modified pilot structural model considered in [10, 11].

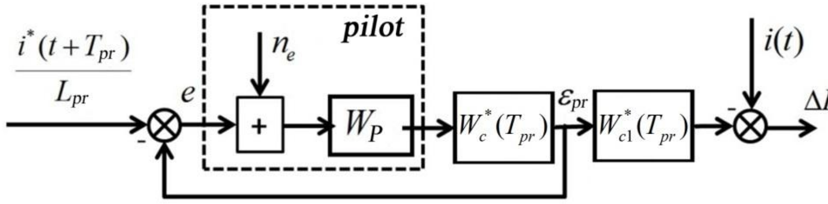

Figure 1. Pilot-aircraft system with predictive display

The results of preliminary selected T_{pr} are verified then in the ground simulation. The developed technique was adopted for investigation of the following manual control tasks:

1. Predictive display law synthesis for compensation of time delay in:
- aircraft landing;
- docking of spacecraft with the ISS.
2. The integration of predictive display and flight control system.

The analysis of the different alternative laws demonstrated that the general equation for predictive angle for all considered tasks has the following form.

$$\varepsilon_{pr} = \frac{\Delta H(t-\tau)}{L_{pr}} + \gamma_M(t) + \dot{\gamma}_M(t)\frac{T_{pr}}{2} + [\gamma(t-\tau)\cdot\gamma_M(t)]W_f, \tag{1}$$

where $W_f = \frac{K}{T_f p + 1}$, $\gamma_M(t)$ and $\dot{\gamma}_M(t)$ are calculated (with help of on-board computer) path angle and derivative, τ - time delay. The parameters T_f and K are selected by minimization of variance $\sigma^2_{\Delta H}$.

3. Predictive display law synthesis for the time delay compensation.

The principle of time delay compensation is illustrated by the fig. 2.

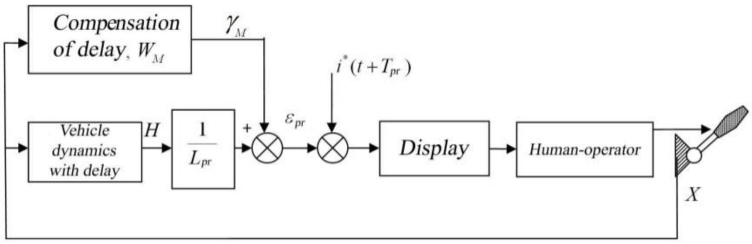

Figure 2. Compensation of time delay

Here $i^*(t+T_{pr})$ - the predictive program trajectory projected on the display screen in the form of 3D corridor with the centre line. The predictive angle ε_{pr} is projected on the surface moving inside the 3D corridor.

In the landing task of the highly augmented aircraft the nonzero time delay in its dynamic can be suppressed by the law

$$\varepsilon_{pr} = \frac{\Delta H(t-\tau)}{L} + \gamma_m(t) + \dot{\gamma}_m(t)\frac{T_{pr}}{2}, \tag{2}$$

which is a special case of equation (1), derived from condition $W_f = 0$. The mathematical modelling of pilot-aircraft system allowed to get optimum value T_{pr}. In particular it was obtained that $T_{pr_{opt}} = 1.4$ sec what is higher than T_{pr} obtained for the case when the time delay is zero.

It can be shown that for the spacecraft teleoperator control height motion in the docking task the summand $\dot{\gamma}_m(t)\frac{T_{pr}}{2}$ and W_f in eq. (1) have to be zero. In that case this equation transforms in the following

$$\varepsilon_{pr} = \frac{\Delta H}{L_{pr}} e^{-\tau s} + \gamma_M, \tag{3}$$

It provides the following controlled element dynamics transfer function $W_C = \frac{K(T_{pr}s + e^{-\tau s})}{T_{pr}s^2(Ts+1)}$ (T – time constant of the thruster dynamics). The use of predictive information provides the slope of $\frac{dlg|W_C|}{dw} \cong -20\,dB/dec$ in the range 0.6÷6 1/sec what improves the accuracy considerably. The optimization of T_{pr} allowed to get its optimum value equal to 16÷18 sec.

The experiments on ground-based simulators demonstrated that the use of predictive display allows to suppress the time delay effect considerably (see fig. 3, where $\sigma^2_{\Delta H}$ - variance of error in glideslope tracking, $\sigma^2_{\Delta H\max}$ - variance of error in glideslope tracking for the case of uncompensated time delay).

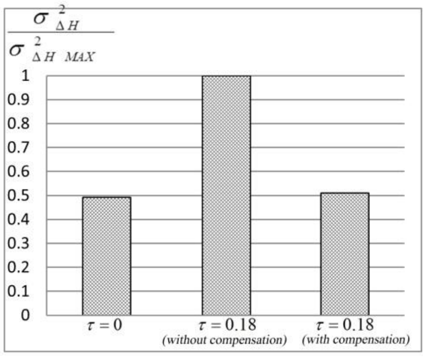

Figure 3. The results of ground-based simulation

The use of predictive display allows decreasing the docking error by about 3 times.

4. The integration of predictive display and the flight control system.

In the frame of the considered investigation the integration of predictive display with the flight control system of the aircraft employing the direct lift control (DLC) was studied. This surface was used for provision of control of the angle of attack changes without having to change the pitch angle $(\alpha = \text{var},\ \vartheta = const)$ [12, 13]. The investigation demonstrated that realization of such mode requires the installing a prefilter into the flight control system $W_{pr} = \frac{s+\omega_f}{s}$ (where $\omega_f = 0.2\ 1/\sec$) for suppression the static error in glide slope tracking. The integration of flight control system with predictive display required to modify the equation (1) for predictive angle and to eliminate the summand $\dot{\gamma}\frac{T_{pr}}{2}$ in it. Optimization of predictive display law demonstrated that the increase of time delay required the proportional increase of predictive time T_{pr} too. The experimental investigations executed on ground-based simulator confirmed that the integration of DLC and display allows to suppress the effect of time delay in glideslope tracking task in turbulence and calm atmosphere conditions (fig. 4, 5) and to improve the accuracy in several times.

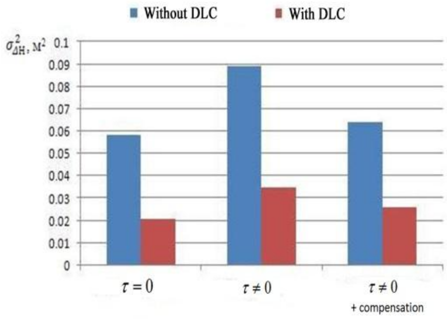

Figure 4. Effect of DLC use (mathematical modeling)

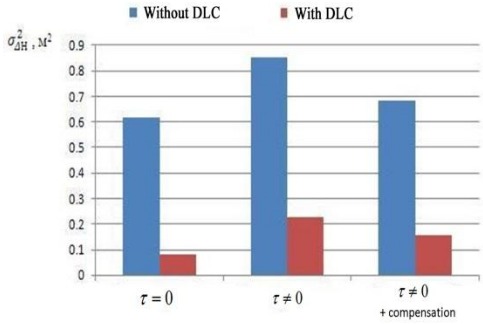

Figure 5. Effect of DLC use (experimental investigations)

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