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FLIGHT DYNAMICS AND CONTROL OF FLIGHT VEHICLES

Development of Algorithms for Integration and Reconfiguration of the Flight Control System and Interfaces

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Abstract—The integration potentiality is considered for the flight control system and interface algorithms to provide the flight accuracy and safety of highly augmented aircraft in the case of low maximum elevator rate limit and in the case of failures causing its sharp decrease.

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Modern aircraft are characterized by a high level of augmentation that allows the accuracy of flight control and flight safety to be increased. The design process considered in [1–5] takes into account the typical peculiarities of modern aircraft, in particular, an increased phase delay, possible exposition of nonlinear effects, new types of aircraft response. The decrease of the longitudinal static margin that is typical for the aircraft, which have been developing for more than 45 years, requires a considerable increase of feedback ratios in the flight control system for providing the required flying qualities. It may result in reaching the rate limit $\dot{\delta}_{\max}$ and induce the instable processes [1, 3]. Nonlinear prefilters are installed in the flight control system for suppression of such unstable processes and they allow the "gross instability" to be avoided. However, the nonlinear prefilters deteriorate the aircraft handling qualities due to their equivalence to the aperiodic element dynamics [3] that increases the time delay in controlled element dynamics. It is shown in [6] that the installation of the prefilter decreases the "gross instability" but it is a reason of the so-called pilot induced oscillation (PIO) category 1. When a failure occurs in the flight control system that causes the elevator rate limit, the probability of instability growth in the system increases. The unstable process in the program trajectory monitoring, when the pilot performs the compensatory tracking task, is shown as an example in Fig. 1 for the case of the sudden decrease of the actuator limit $\dot{\delta}_{\max}$ of the statically unstable aircraft in the specific moment. Therefore, the task arises of searching for the means for the conjunction of pilot actions and flight control system with limited potentialities providing the requirements that the rate limits would not be reached and the flying qualities would not degraded considerably in normal and abnormal conditions of the precise tracking task execution.

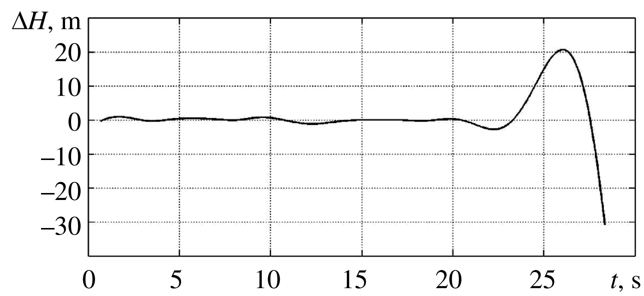

Fig. 1.

In [7], the active manipulator was proposed as a mean not causing the additional phase delay. The stiffness of this manipulator increases in the specific frequency range as the manipulator deflection velocity increases. In the present paper, the problem of decreasing the required elevator deflection rates is resolved by the reconfiguration of flight control system laws (in a sudden change of $\dot{\delta}_{\max}$) and its integration with a display predicting the path motion.

A possible way to decrease the elevator deflection rate is the decrease of the feedback gain coefficients. In this paper, the pitch rate ω_z and the normal acceleration n_z feedback gain coefficients (K_{ω_z} and K_{n_z}) were introduced for transmission of dynamics of the basic statically unstable aircraft, the transfer function of which is

$$W_C = \frac{\vartheta}{\delta_e} = \frac{\bar{M}_z^{\varphi}\left(p + \bar{Y}^{\alpha}\right)}{p\left(p^2 + 2\varsigma\omega p + \omega^2\right)}$$

($\bar{M}_z^{\varphi} = 0.5$ 1/s; $\bar{Y}^{\alpha} = 0.7$ 1/s; $\omega^2 = -0.29$; $2\varsigma\omega = 1$), into dynamic configurations HP 2.1 and HP 5.1 from the data base [8]. The average Cooper–Harper pilot rating obtained in flight tests for configuration HP 2.1 was slightly higher in comparison with pilot rating given by pilots to configuration HP 2.1. They were equal to PR = 2.3 (configuration HP 2.1) and PR = 3.5 (configuration HP 5.1). Table 1 presents the values of gain coefficients, which provide the transformation of the basic configuration into configurations HP 2.1 and HP 5.1 and the average pilot ratings.

Table 1

Configuration	Coefficients		
	K_{ω_z}	K_{n_z}	PR
HP 2.1	4.14	1.59	2.3
HP 5.1	2.62	1	3.5

It is seen that the gain coefficients providing the dynamics HP 5.1 are lower than the values of coefficients providing the dynamics HP 2.1. The structural scheme for the flight control system is given in Fig. 2.

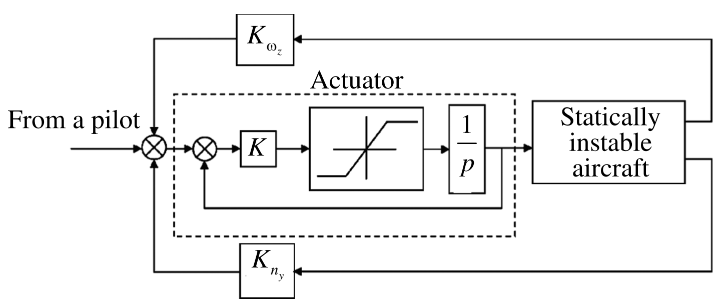

Fig. 2.

The other mean that allows us to decrease the required elevator deflection rates is the display predicting the aircraft path motion. The potentiality of such a display that makes it possible to improve the controlled element dynamics was demonstrated in [9–12]. Its dynamics in that case is

$$W_C^* = \frac{\varepsilon(p)}{X(p)} = \frac{K_C\left(\frac{T_{pr}}{2}p^2 + p + \frac{1}{T_{pr}}\right)}{p^2\left(p^2 + 2\varsigma\omega p + \omega^2\right)},$$

where $T_{pr} = \frac{L_{pr}}{V}$, L_{pr} is the distance between the pilot and the surface, where the vector of velocity is projected (Fig. 3).

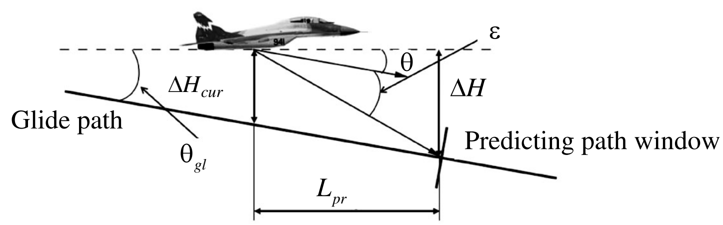

Fig. 3.

In a wide frequency range from $1/T_{pr}$ up to ω, the slope of the amplitude frequency response characteristics $\frac{d\log\left|W_C^*\right|}{d\log\omega}$ is higher than –40 dB/dec and phase frequency response characteristics is lower than 180 deg. It does not require the considerable pilot lead compensation in comparison with a case of aircraft altitude control dynamics.

The technique for optimization of predictive time T_{pr} [12] is based on the mathematical modeling of the pilot–aircraft system using the structural model of pilot behavior (Fig. 4) and calculation of the dependence $\sigma^2_{\Delta H} = f\left(T_{pr}\right)$ for each value T_{pr}.

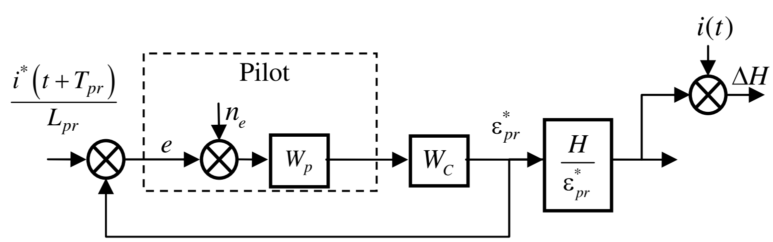

Fig. 4.

According to this technique, the predictive time was $T_{pr} = 0.8$ s for configuration HP 2.1 and with taking into account the actuator dynamics with the rate limit $\dot{\delta}_{\max} = 60$ deg/s. For configuration HP 5.1 and with the same rate limit, the predictive time was equal to 1.4 s.

When the failure occurs that results in decreasing the maximum elevator rate limit, it is necessary to increase the predictive time T_{pr} because it extends the interval, where the slope of amplitude frequency response characteristics is close to –20 dB/dec. It excludes the necessity of pilot lead compensation.

The mathematical modeling performed demonstrated that the decrease of $\dot{\delta}_{\max}$ down to 30 deg/s increases the optimal predictive time T_{pr} up to 1.4 s and its decrease to 15 deg/s increases T_{pr} to 1.9 s.

In addition to the ways of automatization considered, it is interesting to investigate the integration of these means when the deterioration of flying qualities occurring with transformation of dynamic configuration HP 2.1 to configuration HP 5.1 in the moment of decreasing $\dot{\delta}_{\max}$ is compensated by the use of predictive display improving the controlled element dynamics.

The experiments were executed at the MAI ground-based simulator used widely for solution of different problems. The simulator is equipped with the stereoscopic visual system providing the 180×50 degrees angles of view (horizontally and vertically, correspondingly).

As an input signal tracking by the pilot, the program trajectory reflecting the maneuver and following motion along the glide slope was generated. The piloting landing task is the 3D path control of tracing the glide slope with an angle of 2 deg 40′ and carrying out the flare up to the touchdown with the runway.

The program trajectory was visualized in each experiment with the help of proposed display including the 3D corridor, the predictive window, and the predictive point that has to be coincided with the center of predictive window by the pilot in the process of glide slope tracking.

The accuracy of the program path tracking was evaluated by the variance according to the formula

$$\sigma_{\Delta H}^2 = \frac{\sum_{i=1}^{N}\left(H_{i\,prog} - H_i\right)^2}{N-1},$$

where $H_{i\,prog}$ is the altitude of the program trajectory at the ith moment of time; H_i is the aircraft altitude at the same moment; N is the number of measurements.

In the main part of experiments, the sharp reduction of rate limit $\dot{\delta}_{\max}$ was carried out at the 20th second for the HP 2.1 configuration piloting. The landing task was studied for the following versions.

1. Dynamic configuration HP 2.1 with an actuator characterizing by the elevator rate limit equal to 60 deg/s during the whole duration of experiment.

2. Simulation of the failure situation leading to a decrease of the elevator rate limit from 60 to 30 deg/s.

3. Simulation of the failure situation leading to a decrease of the elevator rate limit from 60 to 30 deg/s with simultaneous change of the predictive time T_{pr}.

4. Simulation of the failure leading to a decrease of the elevator rate limit from 60 to 30 deg/s with simultaneous change of coefficients transforming the configuration HP 2.1 in the configuration HP 5.1.

5. Simulation of the failure leading a decrease of the elevator rate limit from 60 to 30 deg/s with simultaneous change of predictive time and coefficients transforming the configuration HP 2.1 in the configuration HP-5.1.

6. Simulation of the failure leading to a decrease of the elevator rate limit from 60 to 15 deg/s with simultaneous change of predictive time and coefficients transforming the configuration HP 2.1 in the configuration HP 5.1.

The results of experimental investigations are given in Fig. 5. It is thus evident that the decrease of the elevator rate limit to 30 deg/s leads to the considerable deterioration of the program trajectory tracking accuracy. The mean square error $\sigma_{\Delta H}$ of the glide slope tracking for configuration HP 2.1 increases from 0.19 up to 1.12 m.

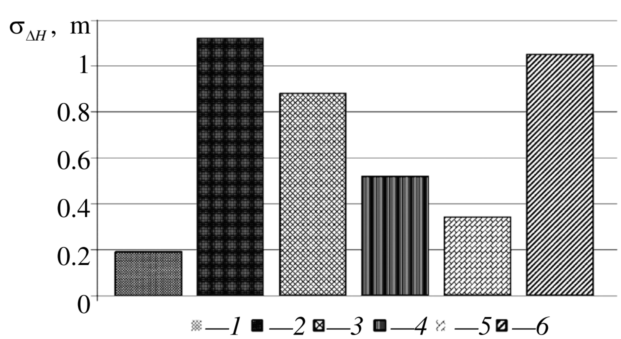

Fig. 5.

The increase of predictive time from 0.8 up to 1.4 s increases the accuracy of the tracking task in about 1.4 times ($\sigma_{\Delta H}$ = 0.88 m) and the change of the feedback coefficients causing the transformation dynamics from HP 2.1 to HP 5.1 allows improving the accuracy of the tracking task up to $\sigma_{\Delta H}$ = 0.52 m.

The simultaneous reconfiguration of the display and flight control system allows the accuracy to be increased by 34 % additionally in comparison with the case, when the semi-automatic control system is reconfigured only. In this case, the tracking accuracy is $\sigma_{\Delta H}$ = 0.34 m. In the case, when the elevator rate limit decreases to 15 deg/s, the glide slope tracking task cannot be realized practically (see Fig. 1) without simultaneous reconfiguration of the display and the control systems. In the latter case, the tracking task might be executed but with a considerable error ($\sigma_{\Delta H}$ =1.05 m). However, the control process is stable in that case.

The integration of display and flight control system, when the predictive time T_{pr} and feedback coefficients are selected simultaneously, allows us to track the program trajectory in normal conditions also, when the rate limit $\dot{\delta}_{\max}$ is constant all the time with the very small rate limit ($\dot{\delta}_{\max}$ = 15 deg/sec). In that case, the stable piloting process is realized although with the worse accuracy in comparison with the case of higher $\dot{\delta}_{\max}$.

Thus, the research demonstrated that even for the extremely low $\dot{\delta}_{\max}$ the integration of flight control system with display allows the piloting task to be carried out effectively.

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REFERENCES

1. *Aerodinamika, ustoychivost' i upravlyaemost' sverkhzvukovykh samoletov* (Aerodynamics, Stability and Controllability of Surersonic Aircraft), Byushgens, G.S., et al., Eds., Moscow: RAN, 1998.
2. McRuer, D.T. et al., *Aviation Safety and Pilot Control: Understanding and Preventing Unfavorable Pilot-Vehicle Interactions*, Washington, D.C.: National Academy Press, 1997.
3. Aleshin, B.S., Bazhenov, S.G., Didenko, Yu.I., et al., *Sistemy distantsionnogo upravleniya magistral'nykh samoletov* (Remote Control Systems for Airliners), Moscow: Nauka, 2013.
4. Garkushenko, V.I. and Vinogradov, S.S., Improvement of Handling Qualities for the Aircraft Longitudinal Motion, *Izv. Vuz. Av. Tekhnika*, 2016, vol. 59, no. 4, pp. 46–51 [Russian Aeronautics (Engl. Transl.), vol. 59, no. 4, pp. 489–494].
5. Gus'kov, Yu.P. and Zagainov, G.I., *Upravlenie poletom samoletov* (Aircraft Flight Control), Moscow: Mashinostroenie, 1980.
6. Efremov, A.V. and Ogloblin, A.V., Development and Application of the Methods for Pilot-Aircraft System Research to the Manual Control Tasks of Modern Vehicle, *Proc. AGARD Conference on Dual Usage of Military and Commercial Technology in Guidance and Control*, Neuilly-sur-Seine Cedex, France, 1995, no. 556, pp. 15.1–15.12.
7. Efremov, A.V., Rodchenko, V.V., and Boris, S., Investigation of Pilot Induced Oscillation Tendency and Prediction Criteria Development, *Final Report WL-TR-96-3109*, Wright Lab USA, 1996.
8. Bjorkman, E., Silverthorn, J., and Calico, R., Flight Test Evaluation of Techniques to Predict Longitudinal Pilot Induced Oscillations, *Proc. Astrodynamics Conference*, Williamsburg, 1986, pp. 967–979.
9. Theunissen, E., Sennes, U., and Sachs, G., Predictive Flightpath Displays for Improved Manual Control Performance, *Proc. 22nd Congress of Int. Council of the Aeronautical Sciences*, Harrogate, UK, 2000, Paper ICAS 2000-6.9.3, pp. 693.1–693.10.
10. Sachs, G., Perspective Predictor/Flight–Path Display with Minimum Pilot Compensation, *Journal of Guidance, Control, and Dynamics*, 2000, vol. 23, no. 3, pp. 420–429.
11. Efremov, A.V., Tyaglik, M.S., Irgaleev, I.Kh., and Gorbatenko, S.A., Predictive Information Design for the Novel Generation of Display for the Highly-Augmented Aircraft, *Izv. Vuz. Av. Tekhnika*, 2017, vol. 60, no. 2, pp. 87–92 [Russian Aeronautics (Engl. Transl.), vol. 60, no. 2, pp. 257–262.
12. Efremov A.V. and Tyaglik M.S., The Development of Perspective Displays for Highly Precise Tracking Tasks, *Aerospace Guidance, Navigation and Control, Selected Papers of the 1st CEAS Specialist Conference on Guidance, Navigation and Control*, Germany, Springer, 2011, pp. 163–174.