AUTOMATIC CONTROL SYSTEMS

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PREDICTION ALGORITHM OF THE AIROPLANE SPEED PROTECTION FUNCTION

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Abstract*—*Are given the prediction algorithm designing of the speed protection function of the airplane automatic flight control system to provide the active speed protection from underspeed and overspeed. The range speed automatic protection function is provided due to autothrottle speed protection and autoflight pitch speed protection.

Index Terms—Automatic flight control system; speed protection.

I. Introduction

The requirement for speed protection is based on the premise that reliance on flightcrew attentiveness to airspeed indications alone during flight guidance system FGS operation is not adequate to avoid unacceptable speed excursions outside the speed range of the normal flight envelope [1].

The speed range automatic protection function is the automatic flight control system function to prevent the indicated airspeed and Mach number overrun (overspeed or underspeed).

The speed range automatic protection function must to:

– enable for both manual and automatic flight control;

– provide the active speed protection from underspeed and overspeed;

– detect the approach to allowable speed (Mach) limits and form warning message to crew;

– form the bounds of allowable speed (Mach) limits for automatic flight within bounds of allowable speed (Mach) limits for manual flight.

The speed range automatic protection function is provided due to autothrottle speed protection and autoflight pitch speed protection [2], [3].

Autothrottle speed protection (ASP) is defined as the automatic engagement and use of the autothrottle to return the airplane to a normal flying speed (either overspeed or underspeed) through the engine controls. This function provides assistance to the pilots through the control of the throttle levers when the airplane speed is detected to be flying outside of normal operating speed limits. This airplane speed is detected to be flying outside of normal operating speed limits. This function is enabled for both automatic (autopilot and/or autothrottle engaged) and manual flight (pilot in control of primary surfaces and throttles).

Autoflight pitch speed protection (PSP) is defined as the automatic engagement and use of the autopilot to return the airplane to a normal flying speed (either overspeed or underspeed) through the elevator controls. Pitch speed protection is designed to activate when the autopilot or flight director is engaged and the airspeed is detected to be flying outside of the flying speed range (detected autoflight pitch speed or speed detected). These engage points are selected such that PSP would engage after ASP would normally engage, but prior to primary flight control law speed protection becoming active. This function is enabled only for automatic flight (autopilot and/or autothrottle engaged).

II. Problem Statement

To provide the speed range protection of the airplane without overrun due to prediction that the airplane speed (Mach number) is detected to be flying outside of normal operating speed (Mach number) limits is proposed.

III. Problem Solution

Autothrottle speed protection is automatically engaged when airspeed conditions are detected for engagement (ASP speed detected) or windshear is detected. ASP speed detected is driven for both over and under speed cases. For underspeed, airspeed is less than the greater of lowest selectable speed V_{LS} plus 3 knots (for margin) or minimum speed V_{MIN} plus 3 knots will trigger the ASP speed detected and engage low speed protection. Minimum speed V_{MIN} is the speed related to the maximum angle of attack that may be reached in manual flight control.

For overspeed protection, airspeed is greater than the smaller of maximum operating limit speed V_{MO} minus 3 knots, placard speed $V_{Placard}$ minus 3 knots and maximum speed V_{max} minus 3 knots will trigger the ASP speed detected and engage high speed protection. Once engaged, the autothrottle stays engaged until acted on by the pilot. ASP mode indication will be set while the airspeed remains below or above the autoflight airspeed limits and ASP is engaged. The ASP indication is removed when the speed falls

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within the normal flying region. Once the ASP indication is removed, the autothrottle continues to operate controlling thrust setting to the target (either target speed or thrust target as appropriate to the engaged autothrottle mode).

Autothrottle speed protection target speed is speed reference. Speed reference for the autothrottle will be the autoflight limited airspeed target (selected airspeed) in all conditions, which is the select airspeed in the flight management control panel IAS/Mach window.

The autoflight function limits the selectable airspeeds between:

– the greater of target speed V_{LS} plus 5 knots and V_{min} plus 5 knots;

– the lesser of target speed V_{MO} minus 5 knots, $V_{Placard}$ minus 5 knots and V_{max} minus 5 knots.

For autopilot engaged operation, the autothrottle will engage into the compatible mode for the autopilot active mode. For flight level change and windshear mode, ASP engages into thrust limit mode. For vertical speed, flight path angle, altitude capture/hold and approach modes, ASP engages into speed mode. For approach mode when the capture glideslope function is engaged the ASP function and PSP function are inhibited.

For manual flight operation, the autothrottle will engage in speed mode unless windshear is detected, then it will engage in thrust mode.

Autopilot pitch speed protection is automatically engaged when airspeed conditions are detected for engagement (PSP speed detected) and PSP is not inhibited from engagement. Autopilot PSP will not automatically activate during manual flight. Pitch speed protection is designed to activate when the autopilot or flight director is engaged.

Pitch speed protection would engage after ASP would normally engage, but prior to primary flight control algorithm speed protection becoming active.

If the primary flight control algorithm pitch speed protection becomes active, the autopilot and flight director will be disengaged, which removes autoflight pitch speed protection, to prevent interactions between the primary flight control envelope protections and the autoflight protections. Autothrottle speed protection will remain engaged.

Pitch speed protection speed detected is driven for both over and under speed cases. For underspeed, airspeed is less than the greater of V_{LS} and V_{min} will trigger the PSP speed detected and engage low speed protection. For overspeed protection, airspeed is greater than the smallest of V_{MO}, $V_{Placard}$ and V_{max} will trigger the PSP speed detected and engage high speed protection. These engage points are selected such that PSP would engage after ASP would normally engage, but prior to primary flight control algorithms speed protection becoming active.

Pitch speed protection target speed is speed reference. Speed reference for the autopilot will be the autoflight limited airspeed target (selected airspeed) in all conditions.

The target speed used by PSP will be the autoflight selected airspeed. This is the same value as used by the ASP function and is limited by the autoflight airspeed limits.

Pitch speed protection target speed are.

1. The greater of target speed V_{LS} plus 5 knots or V_{min} plus 5 knots.

2. The lesser of target speed V_{MO} minus 5 knots or $V_{Placard}$ minus 5 knots or V_{max} minus 5 knots.

Lowest selectable speed V_{LS} for the low speed protection with prediction can be calculated by formula:

$$V_{LS} = V_{min}^{pr} + \Delta V(\delta_{fl}) - K_{nx} n_{XT}, \qquad (1)$$

where $V_{min}^{pr} = f(\text{IAS}, \alpha_{sign}, \alpha, \alpha_0)$ is the minimum protection speed, kmph; IAS is the indicated airspeed, kmph; α_{sign} is the alarm angle of attack (AOA), deg; α is the actual AOA, deg; α_0 is the angle of attack at zero lift, deg; $\Delta V(\delta_{fl})$ is the indicated airspeed margin, kmph; δ_{fl} is the flap deflection, deg; $K_{nx} = 100$ kmph/g is the prediction coefficient; n_{XT} is the horizontal load factor in the trajectory frame of axis.

Speed margin is depended from position of the flap. For example,

$$\Delta V(\delta_{fl}) = 20 - 0{,}3\delta_{fl}.$$

The item $K_{nx} n_{XT}$ in the equation (1) is necessary to prevent underspeed and to provide engagement ASP before when actual IAS will be less than the greater of lowest $V_{LS} + 3$ knots and $V_{min} + 3$ knots.

Autothrottle speed protection speed detected for low speed protection can be calculated by formula

$$V_{det}^{ASP} = V_{min}^{spr} + \Delta V(\delta_{fl}) - K_{nx} n_{XT} + 3 \cdot 1.852.$$

The condition for engagement ASP function is

$$\text{IAS} \le V_{det}^{ASP}.$$

Pitch speed protection speed detected for low speed protection can be calculated by formula:

$$V_{det}^{PSP} = V_{min}^{spr} + \Delta(\delta_{fl}) - K_{nx} n_{XT}.$$

The condition for engagement PSP function is

$$\text{IAS} \le V_{det}^{PSP}.$$

Pitch speed protection target speed and ASP target speed for low speed protection can be calculated by formula:

$$V_{tag} = V_{\min}^{pr} + \Delta V(\delta_{fl}) + 5 \cdot 1.852.$$

Let us research the protection function due to the real example of the controlled flight. The control object can be introduced the transport aircraft An-124 [4]. Proportional-integral autopilot was designed for transport aircraft An-124. The control law of the hold speed mode of elevator channel is given by

$$\frac{T_i s}{T_i s+1}\delta_{el} = \frac{T_i s}{T_i s+1}[K_{\omega z}\omega_z + K_\vartheta(\vartheta - \vartheta_0) - K_{\omega y}|\omega_y|] + K_V(V_{\text{tag}} - V),$$

where T_i is the isodromic time constant, s ; δ_{el} is the elevator deflection angle from the balanced position, deg; $K_{\omega z}$, K_ϑ, $K_{\omega y}$, K_V are feedback gains constant of the elevator speed channel with respect to pitch rate, pitch angle, yaw rate and IAS, respectively; ω_z is the pitch rate, deg/s; ϑ is the pitch angle, deg; ϑ_0 is the pitch angle for time when autopilot is engaged; ω_y is the yaw rate, deg/s; V is the actual indicated airspeed, kmph.

The control law of the hold speed mode of the autothrottle channel is given by

$$s\delta_{thr} = \frac{s}{T_1 s+1}[K_{nx}^{\text{AT}} n_x + K_\vartheta^{\text{AT}}(\vartheta - \vartheta_0 + K_V^{\text{AT}}(V_{\text{tag}} - V)] + K_{\tilde{V}}^{\text{AT}}(V_{\text{tag}} - V),$$

where δ_{thr} is the throttle levers deflection angle, deg; T_1 is the isodromic time constants, s; K_{nx}^{AT}, K_ϑ^{AT}, K_V^{AT}, $K_{\tilde{V}}^{\text{AT}}$ are feedback gains constant of the autothrottle speed channel with respect to horizontal body load factor, pitch angle and IAS, respectively; n_x is the horizontal body load factor.

Consider the following initial condition of the flight to test the low speed protection function:

– not change the balanced throttle levers before engagement ASP function;

– the autopilot is engaged in pitch mode;

– the autothrottle is armed.

The control law of the pitch mode of elevator channel is given by

$$\frac{T_i s}{T_i s+1}\delta_{\text{el}} = k_{\omega z}\omega_z + k_\vartheta(\Delta\vartheta - \Delta\vartheta_{\text{giv}}),$$

where $\Delta\vartheta = \vartheta - \vartheta_0$ is the deflection of the actual pitch angle ϑ from the initial pitch angle ϑ_0 ; $\Delta\vartheta = \vartheta_{\text{giv}} - \vartheta_0$ is the deflection of the given pitch angle ϑ_{giv} from the initial pitch angle ϑ_0.

After 5 s of flight simulation the given pitch is increased on 4 degree (Fig. 1) and aircraft is decelerated (Fig. 2).

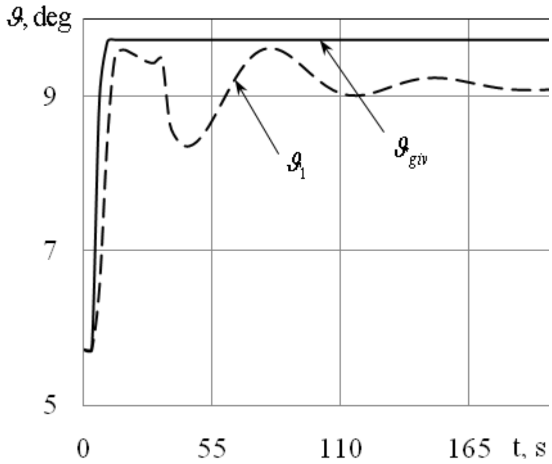

Fig. 1. Given pitch angle ϑ_{giv} and actual pitch angle ϑ_1 when the prediction is disengaged

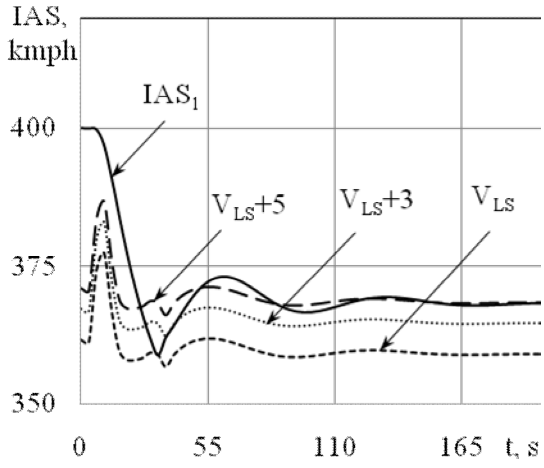

Fig. 2. Indicated airspeed IAS_1. Speed detected V_{LS} + + 3 knots and target speed V_{LS} + 5 knots when prediction is disengaged. V_{LS} is lowest selectable speed

The testing results of the low speed protection function are illustrated on the Figs 1–10 when prediction coefficient is equal zero $K_{nx} = 0$.

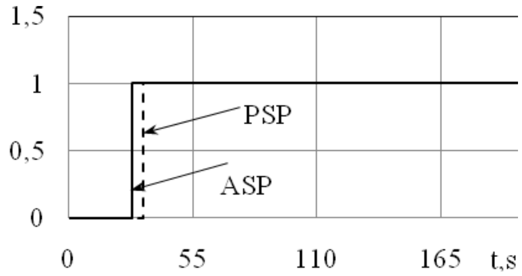

Fig. 3. ASP and PSP triggering when prediction is disengaged

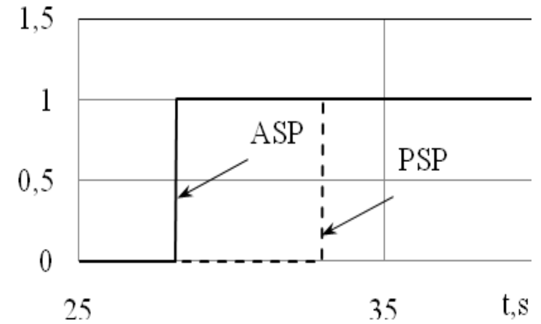

Fig. 4. ASP and PSP triggering when prediction is disengaged for time 28–33 s

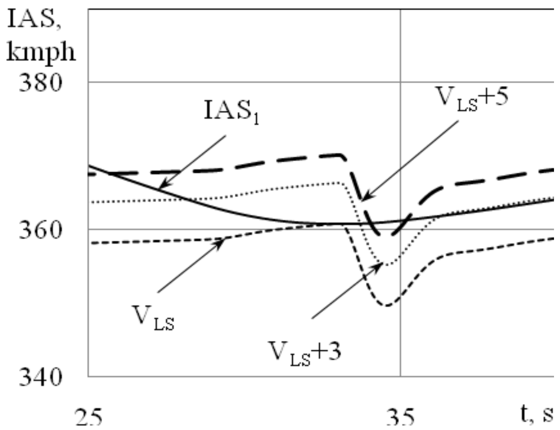

Fig. 5. Indicated airspeed IAS_1. Speed detected $V_{LS}+$ + 3 knots and target speed $V_{LS}+5$ knots when prediction is disengaged and time is 28–33 s

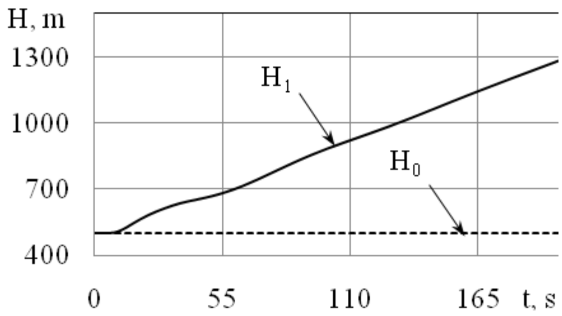

Fig. 6. Initial altitude H_0 and actual altitude H_1 when prediction is disengaged

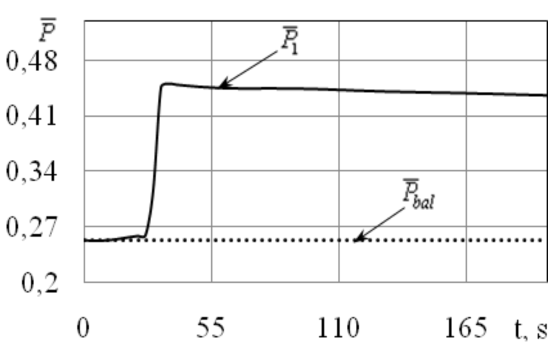

Fig. 7. Related balanced thrust $\bar{P}_{bal}$ and related actual thrust $\bar{P}_1$ when prediction is disengaged

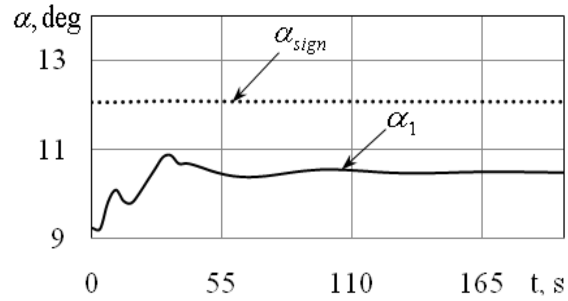

Fig. 8. Alarm AOA α_{sign} and actual AOA α_1 when prediction is disengaged

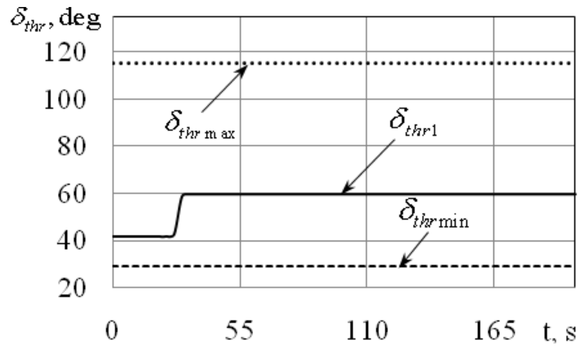

Fig. 9. Maximum throttle levers angle $\delta_{thr\max}$, actual throttle levers angle δ_{thr1} and minimum throttle levers angle $\delta_{thr\min}$ when prediction is disengaged

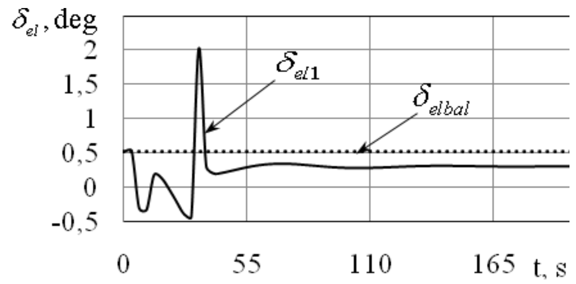

Fig. 10. Balanced elevator angle δ_{elbal} and actual elevator angle δ_{el1} when prediction is disengaged

The testing results of the low speed protection function are represented on Figs 11–21 when the prediction is engaged and coefficient $K_{nx}=100$.

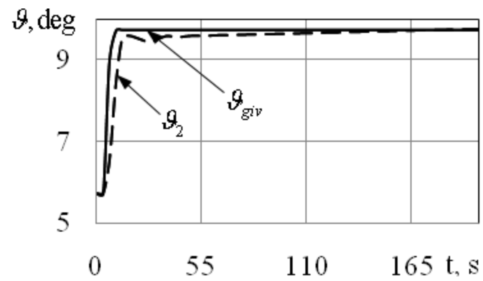

Fig. 11. Given pitch angle ϑ_{giv} and actual pitch angle ϑ_2 when prediction is engaged

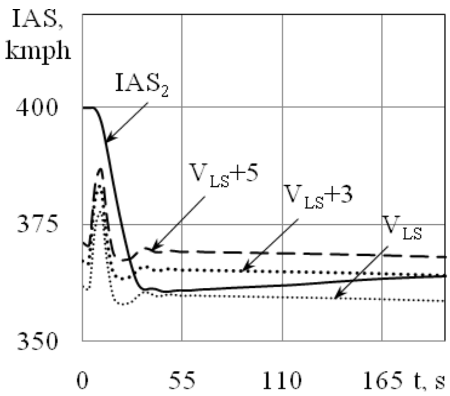

Fig. 12. Indicated airspeed IAS_2 with respect to ASP speed detected V_{LS} + 3 knots and target speed V_{LS} + + 5 knots when prediction is engaged

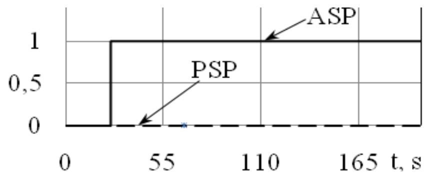

Fig. 13. ASP and PSP triggering when prediction is engaged

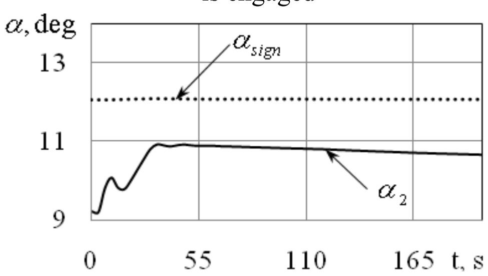

Fig. 14. Alarm AOA α_{sign} and actual AOA α_2 when prediction is engaged

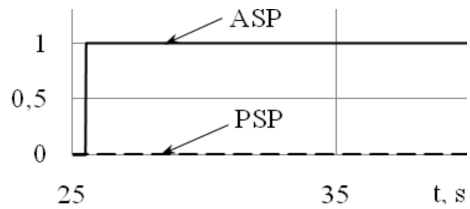

Fig. 15. ASP and PSP triggering when prediction is engaged for time 25.4 s

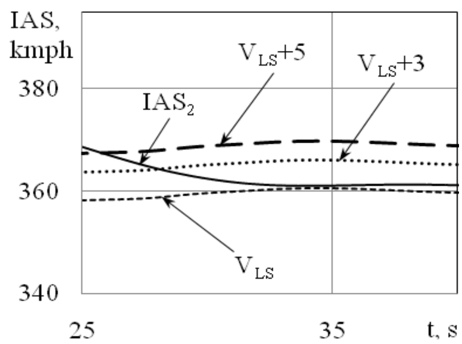

Fig. 16. Indicated airspeed IAS_2. Speed detected V_{LS} + + 3 knots and target speed V_{LS} + 5 knots when prediction is engaged and time is 25.4 s

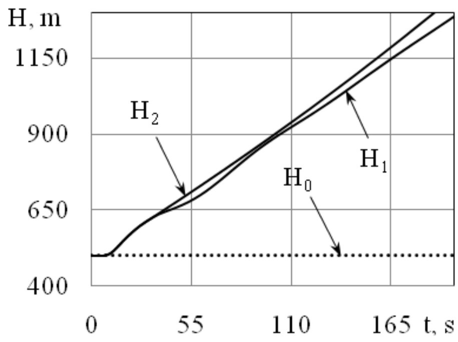

Fig. 17. Initial altitude H_0. Actual altitude H_1 when prediction is disengaged. Actual altitude H_2 when prediction is engaged

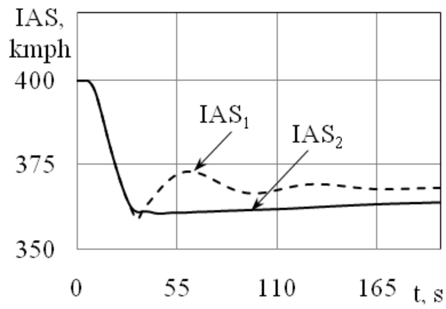

Fig. 18. Indicated airspeed IAS_1 and IAS_2 when prediction is desengaged and engaged, respectevly

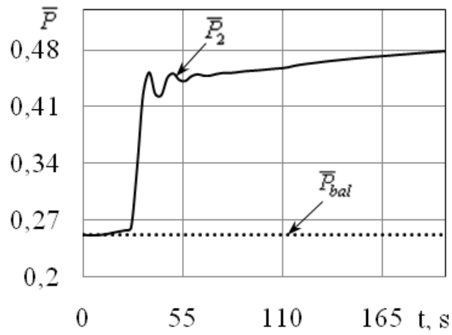

Fig. 19. Related balanced thrust $\bar{P}_{bal}$ and related actual thrust $\bar{P}_2$ when prediction is engaged

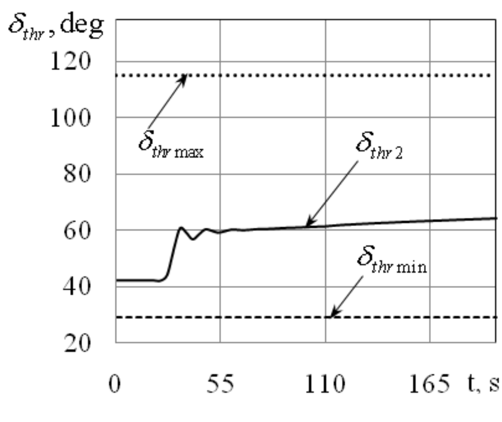

Fig. 20. Maximum throttle levers $\delta_{thr\max}$, actual throttle levers δ_{thr2} and minimum throttle levers $\delta_{thr\min}$ when prediction is engaged

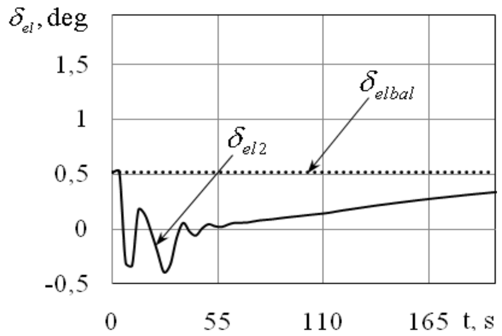

Fig. 21. Balanced elevator position δ_{elbal} and actual elevator deviation δ_{el2} when prediction is engaged

You can see that ASP function with prediction provides the active speed protection from underspeed and the aperiodic process of stabilization of the target speed by autothrottle (Fig. 18). The triggering time of ASP is less than time when prediction isn't used. The difference in time is 2.64 s.

The approach to calculate and engage high speed protection function is same like for low speed protection function.

Autothrottle speed protection speed detected for high speed protection with prediction can be calculated by formula:

$$V_{\text{det}}^{\text{ASP}} = V_{\text{MO}} - K_{nx} n_{\text{XT}} - 3 \cdot 1.852.$$

The condition for engagement ASP function is $\text{IAS} \geq V_{\text{det}}^{\text{ASP}}$.

Pitch speed protection speed detected for high speed protection can be calculated by formula:

$$V_{\text{det}}^{\text{PSP}} = V_{\text{MO}} - K_{nx} n_{\text{XT}}.$$

The condition for engagement PSP function is $\text{IAS} \geq V_{\text{det}}^{\text{PSP}}$.

Pitch speed protection target speed and ASP target speed for high speed protection can be calculated by formula:

$$V_{\text{tag}} = V_{\text{MO}} - 5 \cdot 1.852.$$

The testing results show that the quality of the protection of the high indicated airspeed is equal to low indicated airspeed protection. Let's view the autothrottle Mach protection (AMP) and pitch Mach protection (PMP) functions. To protect the maximum operating limit Mach number M_{MO} the next different approach is used.

1. Autothrottle Mach protection when mach detected for high Mach protection with prediction can be calculated by formula:

$$M_{\text{det}}^{\text{ASP}} = M_{\text{MO}} - K_{nx}^{M} n_{\text{XT}} - 0.003,$$

where $K_{nx}^{M} = 0.1$.

The condition for engagement ASP function is

$$M \geq M_{\text{det}}^{\text{ASP}}.$$

2. Autothrottle speed protection target Mach for high Mach protection can be calculated by formula: $M_{\text{tag}}^{\text{ASP}} = M_{\text{MO}} - 0.005$.

3. Pitch speed protection Mach detected for high Mach protection with prediction can be calculated by formula:

$$M_{\text{det}}^{\text{PSP}} = M_{\text{MO}} - K_{nx}^{\text{M}} n_{\text{XT}}.$$

The condition for engagement PSP function is

$$M \geq M_{\text{det}}^{\text{PSP}}.$$

4. Pitch speed protection target Mach for high Mach protection can be calculated by formula:

$$M_{\text{tag}}^{\text{PSP}} = M_{\text{MO}} - K_{nx}^{\text{M}} n_{\text{XT}} - 0.005.$$

The control law of the hold Mach mode of elevator channel is given by

$$\frac{T_i s}{T_i s + 1} \delta_{el} = \frac{T_i s}{T_i s + 1} \left[K_{\omega z} \omega_z + K_{\vartheta} (\vartheta - \vartheta_0) - K_{\omega y} |\omega_y| \right] + K_M (M_{\text{tag}}^{\text{PSP}} - M),$$

where K_M is the feedback gain constant of elevator channel with respect to Mach number.

The control law of the hold Mach mode of the autothrottle channel is given by

$$s\delta_{thr} = \frac{s}{T_1 s + 1} [K_{nx}^{\text{AT}} n_x + K_{\vartheta}^{\text{AT}} (\vartheta - \vartheta_0) + K_M^{\text{AT}} (M_{\text{tag}}^{\text{ASP}} - M)] + K_{\dot{M}}^{\text{AT}} (M_{\text{tag}}^{\text{ASP}} - M),$$

where $K_M^{\text{AT}}, K_{\dot{M}}^{\text{AT}}$ are feedback gains constant of autothrottle channel with respect to Mach number.

The testing results of the high Mach protection function are demonstrated below (Figs 22–29).

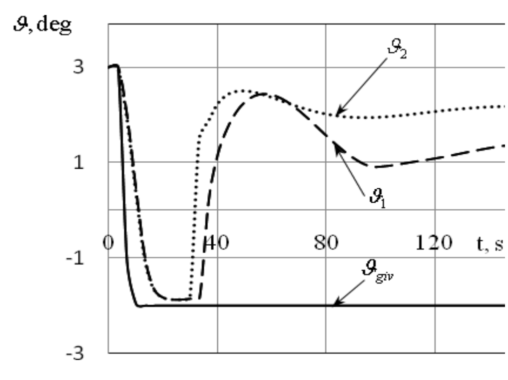

Fig. 22. Given pitch angle ϑ_{giv}. Pitch ϑ_1 is actual pitch angle when prediction is desengaged. Pitch ϑ_2 is actual pitch angle when prediction is engaged

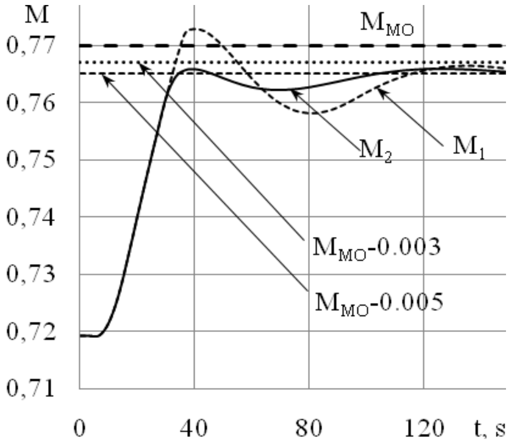

Fig. 23. Mach number M_1 is actual M when prediction is desengaged. Pitch M_2 is actual M when prediction is engaged. M_{MO} is maximum operating limit Mach number

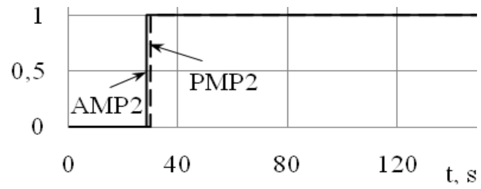

Fig. 24. AMP2 and PMP2 triggering when prediction is engaged

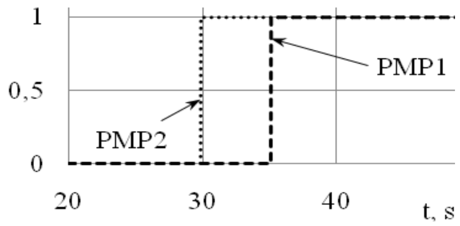

Fig. 25. Pitch Mach protection function (PMP1) without prediction is trigged. Pitch Mach protection function (PMP2) with prediction is trigged

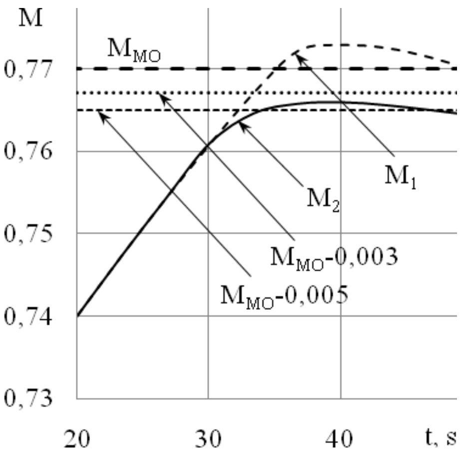

Fig. 26. Mach number M_1 is actual M when prediction is desengaged. Pitch M_2 is actual M when prediction is engaged. M_{MO} is maximum operating limit Mach number. Testing time 20…60 s

The time when PMP function is predicted less than time when prediction isn't used. The difference in time is 5,5 s (Fig. 25). You can see that PMP function with prediction provides the active Mach protection from overshoot and the aperiodic process of stabilization of the target Mach by elevator (Figs 23, 26).

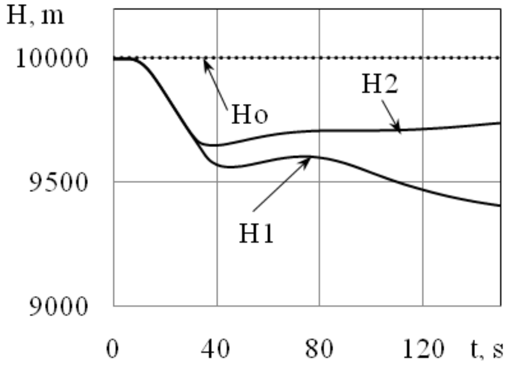

Fig. 27. Initial altitude H_0 = 10000 m. Actual altitude H_1 when prediction is disengaged. Actual altitude H_2 when prediction is engaged

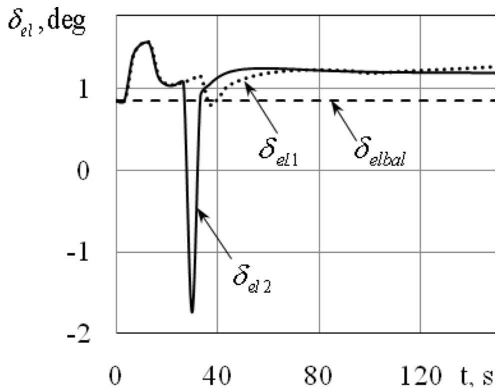

Fig. 28. Balanced elevator position δ_{elbal}. Actual elevator deviation angles δ_{el1} and δ_{el2} when prediction is desengaged and engaged, respectivly

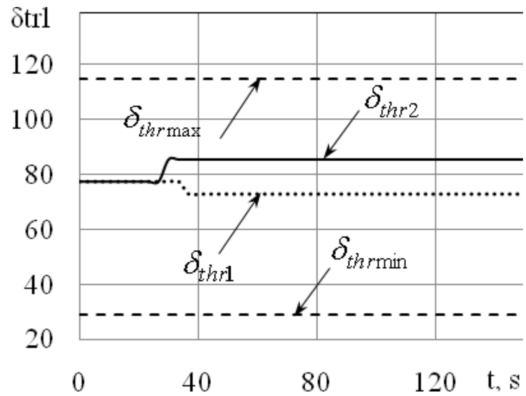

Fig. 29. Maximum throttle levers angle $\delta_{thr\max}$ and minimum throttle levers angle $\delta_{thr\min}$. Actual throttle levers angles δ_{thr1} and δ_{thr2} when prediction is disengaged and engaged, respectivly

Analysis of simulation results above shows the next summary.

CONCLUSION

Thereby, resultant algorithms of the task can be used for dynamic design of optimum structures of estimation systems of linear time-invariant systems with arbitrary dynamic behavior of control object and measuring system subject to real operating conditions. The algorithms are relatively simple, transparent, easily reconstructed for particular cases of estimation tasks and can be generalized for situations arising when solving the tasks of aircraft dynamics identification in operating (non-special) modes. They can be useful for creating and upgrading flight control systems, navigation, etc.

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С. В. Морозов, В.С. Морозов. Прогнозуючий алгоритм функції захисту швидкості повітряного судна

Розроблено алгоритм функції захисту діапазону швидкості літака транспортного типу з прогнозом зміни приладової швидкості та числа Маха. Функція захисту діапазону швидкості літака може бути реалізовано штатними алгоритмами автоматичного керування швидкісними параметрами за допомогою автомата тяги та керма висоти. Прогнозування зміни приладової швидкості або числа Маха літака запропоновано виконувати за допомогою оцінювання траєкторного повздовжнього перевантаження при заданому діапазоні експлуатаційної швидкості або числа Маха. Результати дослідження показують, що послідовне використання автомата тяги та каналу керма висоти з урахуванням прогнозу зміни швидкості або числа Маха забезпечує запобігання перебігу експлуатаційного діапазону швидкісного параметра.

Ключові слова: система автоматичного управління польотом; захист швидкості.

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С. В. Морозов, В.С. Морозов. Прогнозирующий алгоритм функции защиты скорости воздушного судна

Разработан алгоритм функции защиты диапазона скорости самолета транспортного типа с прогнозом изменения приборной скорости и числа Маха. Функция защиты диапазона скорости самолета может быть реализована штатными алгоритмами автоматического управления скоростными параметрами через автомат тяги и канала руля высоты. Прогноз изменения приборной скорости или числа Маха обеспечивается путем оценивания продольной траекторной перегрузки при заданном эксплуатационном диапазоне скорости или числа Маха. Результаты исследований показали, что последовательное применение автомата тяги и канала руля высоты с учетом прогноза изменения приборной скорости или числа Маха обеспечивает отсутствие выхода скоростного параметра за эксплуатационный диапазон.

Ключевые слова: система автоматического управления полетом; защита скорости.

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