PRINCIPLES OF THE AUTOMATED CONTROL FOR THE CIVIL AIRCRAFT, WHICH PROVIDE FLIGHT SAFETY

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Abstract

TsAGI generated the algorithms of FBW CS that provide all main requirements for transport aircraft control system. This paper considers a number of them, namely: angle of attack limitation, g-load factor limitation, pitch angle limitation, flight velocity limitation, algorithm of the engines automatic thrust augmentation at regimes that are close to stall. The algorithm takes into account the situation development prediction. It considers also conception of the integrated control with use of some modes realized by the Automatic Control System (ACS) consisting of autopilot (AP) and autothrottle control (AT).

1 Introduction

The implementation of digital Fly-By-Wire Control Systems (FBW CS) makes it possible to extend the abilities of systems that provide the enhancement of controllability properties and flight safety. The researches on generating the advanced transport aircraft integrated control system algorithms that are performed at TsAGI give opportunities to enhance significantly the capabilities of the most up-to-date systems and essentially improve the flight safety.

For this purpose, the main functions of the control system are to be to provide:

- the satisfactory stability and controllability properties;
- the reliable flight envelope protection; the maintenance of those parameters overriding which of will result into incident or crash. First of all it is a stall protection, prevention of wing and fuselage touchdown against the runway at takeoff and landing, speed protection on dive;
- safe and clear flight crew warning about the operational flight envelope boundary forthcoming in re of the main parameters (α, n_y ϑ, γ, V, M);
- highly control comfort.

TsAGI generated the algorithms of FBW CS that provide all the above-listed functions. Now researches of the further automation of aircraft control – the organization of the integrated control with use of some modes realized by the Automatic Control System (ACS) consisting of autopilot (AP) and autothrottle control (AT) are carried out.

The integrated control mode with pitch and bank angles hold and without pilot's participation in control is implemented in control systems of certain existing Russian and foreign airplanes. A novel conception of integrated control is intended to apply more airplane motion parameters hold modes that ACS performs.

Let us consider flight envelopes of integrated control system of civil aircraft integrating functions of FBW CS and ACS. Figure 1 shows the flight envelopes boundaries and accordingly integrated control system modes, which function within in each of flight envelopes.

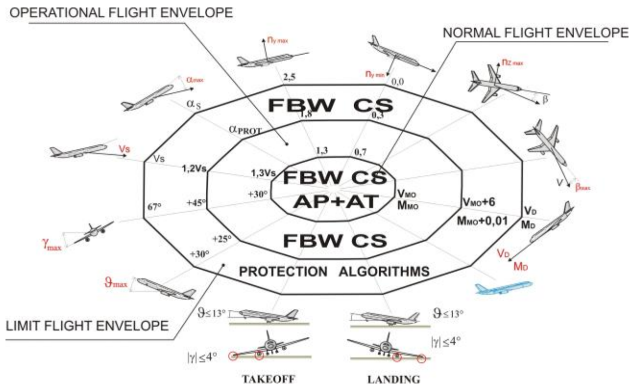

Figure 1 – flight envelopes

ACS functions within flight normal envelope. There are motion parameters limitations, for example, the minimum ($1.3V_S$) and maximum (V_{MO}) indicated airspeed (or maximum Mach number M_{MO}) limitations, the g-load factor limitation, the bank angle limitation by ACS activity. Thus, use of ACS hold regimes enhances normal flight envelope protection and control comfort.

The effective flight crew warning is realized in FBW CS at approach to operational flight envelope boundary.

Let us consider limit flight envelope boundaries the violation for which is forbidden. Speed boundaries are stall velocity V_S and the maximum indicated airspeed V_D (or the maximum Mach number M_D). For civil airplanes the value of admissible maximum g-load factor is limited by values $n_{y\,min}$ and $n_{y\,max}$. Boundary of angle of attack is stall angle of attack α_S. The maximum values of pitch, bank and sideslip angles accordingly: $|\vartheta|<\vartheta_{max}$, $|\gamma|<\gamma_{max}$, $|\beta|<\beta_{max}$. FBW CS protection algorithms of limit flight envelope boundaries provide effective limitation of these parameters.

This paper considers a number of them, namely:

- angle of attack limitation;
- g-load factor limitation;
- angle of pitch limitation;
- flight velocity limitation;
- algorithm of the engines automatic thrust augmentation at regimes that are close to stall. The algorithm takes into account the situation development prediction.

2 Control system protection algorithms

Figure 2 shows the representative values of angle of attack. The α_{PROT} value correlates to the on-threshold for the control system protection algorithm of angle of attack. The α_{MAX} value correlates to the maximum attainable angle of attack under total longitudinal control lever deflection. The α_{Cymax} value correlates to the value of angle of attack that corresponds to the maximum lift coefficient. A α_{FLOOR} additional value is included between α_{PROT} и α_{MAX} in a number of aircraft. Under this value been overrated the engines will be automatically commuted to operate in maximum thrust.

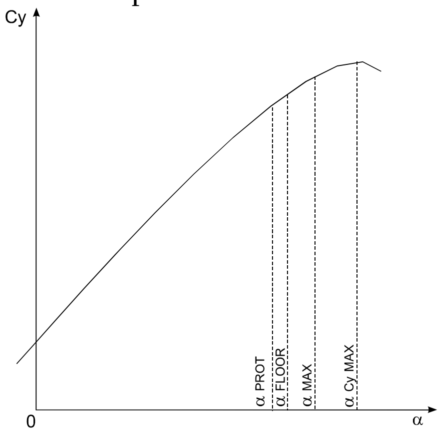

Figure 2 – the representative values of angle of attack

Figure 3 shows the general structure of longitudinal control algorithm. The algorithm is composed of the strait chain, the static and integrated feedback for pitch angular rate and normal g-load factor. The yellow color denotes the elements that form the angle of attack limitation algorithm. In the static sub-circuit the angle of attack feedback link is connected when α magnitude of a certain α_l value is exceeded. The feedback link of angle of attack in integrated sub-circuit is connected when α magnitude of a certain α_{PROT} value is exceeded. It is to be noted that the angle of attack static feedback link enhances also the closed “aircraft-control system” loop stability at high angles of attack where the aircraft local longitudinal static instability in re of angle of attack takes place.

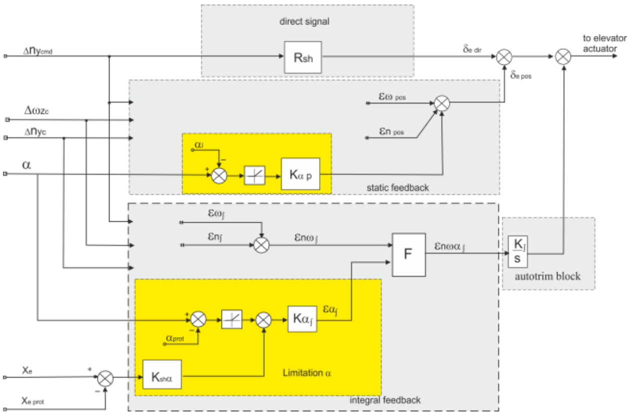

Figure 3 – the general structure of longitudinal control algorithm

The system is adjusted in such a way that to actualize the static characteristic of the longitudinal control lever deflection in re of the angle of attack during short-period moving (See Figure 4). The lever balancing position is equal to zero under angle of attack that corresponds to straight steady flight as the system is integrated. The static characteristic is composed of three portions. The central portion ($X_{e0}<X_e<X_{e\ prot}$) corresponds to the $X_e^{n_y}$ parameter optimal value. The right portion ($X_{e\ prot}\leq X_e\leq X_{emin}$) corresponds to the angle of attack integral feedback link connection. The angle of attack value that is close to α_{prot} is actualized when $X_e=X_{e\ prot}$. The maximum α_{max} angle of attack value is actualized under the full longitudinal control lever backward deflection. By analogy, under the full longitudinal control lever forward deflection the angle of attack value is actualized that corresponds to the minimum allowable g-load factor.

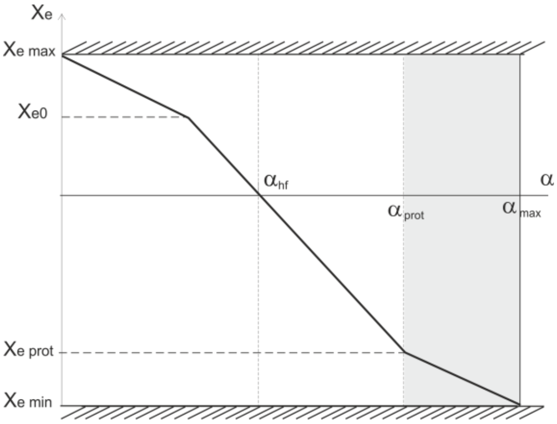

Figure 4 – the static characteristic of the longitudinal control lever deflection in re of the angle of attack

Figure 5 shows the angle of attack limitation. Under the full longitudinal control lever forward deflection the minimum angle of attack value is actualized that corresponds to $n_{y\ min}$ = 0. Under the full lever backward deflection the maximum angle of attack value is actualized. The α_{max} value in control system adjustment depends on the high-lift devices position, the M number and so on. Then at the transient one can see the angle of attack decreasing even under the full longitudinal control lever deflection. This is related to the activation of limiting the maximum pitch angle. The pitch angle limitation algorithm is by its structure analogous to the angle of attack limitation one and is composed of static and integral feedback links.

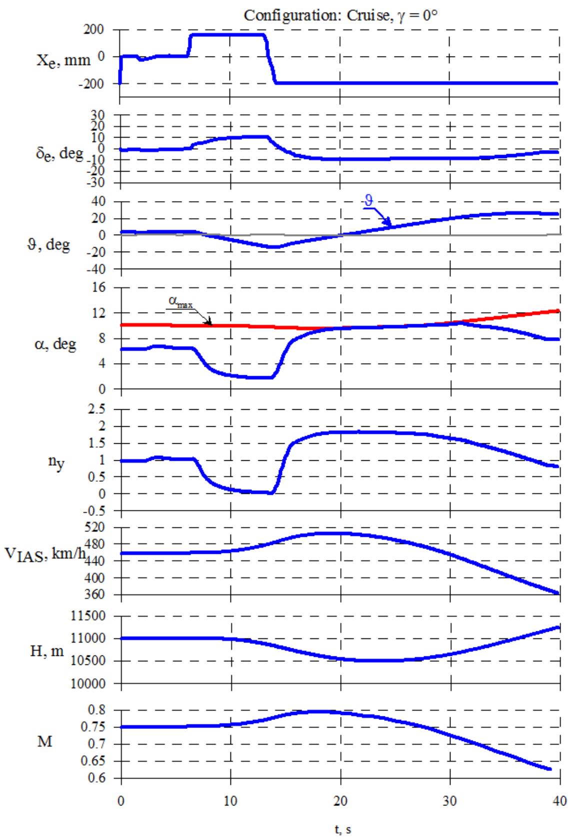

Figure 5 – the angle of attack limitation

The minimum indicated airspeed limiting function is provided by the limitation of the maximum angle of attack. The function of the maximum indicated airspeed limitation and of M number is provided by commutation of static and integral feedback links in reference to one of the parameters in dependence on which limitation is more urgent. As a result, the static characteristic of the longitudinal control lever deflection in re of the speed is actualized (See Figure 6). The static characteristic is composed of three portions. The central portion (V_{prot}<V<V_{MO}) corresponds to the X_e^V parameter zero value, where V_{prot} is a velocity that corresponds to the steady level flight under angle of attack that is equal to α_{prot}. Under low velocities (V_{min} ≤V≤ V_{prot}) the angle of attack protection function is activated. Under X_e=$X_{e\ prot}$ the steady velocity value is actualized that corresponds to the balancing angle of attack value that is equal to α_{prot}. Under the full longitudinal control lever backward deflection the maximum balancing angle of attack value is actualized that is equal to α_{max} and the V_{min} indicated airspeed value that corresponds to this angle of attack. Under high velocities (V_{MO} ≤V≤ V_D or M_{MO} ≤M≤ M_D) the maximum velocity protection function is activated. Under full forward lever deflection the velocity value is actualized that is equal to V_D or M number that is equal to M_D depending on the limitation that is more urgent.

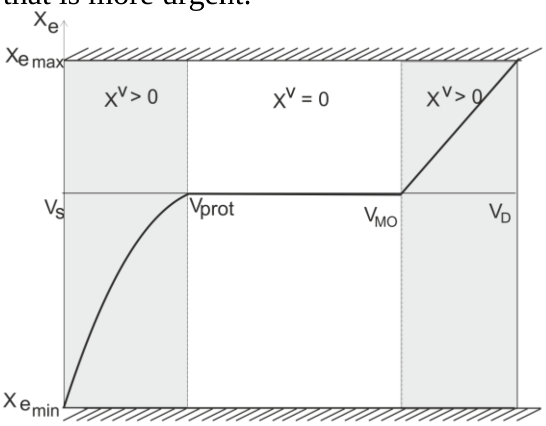

Figure 6 – the static characteristic of the longitudinal control lever deflection in re of the speed

Figure 7 represents the limitation of angle of attack and consequently of the velocities that takes place without pilot's participation in control. The aircraft while braking attains the angle of attack that is equal to α_{prot}. Hereby the limitation of the minimum velocity that corresponds to the given value of angle of attack is actualized.

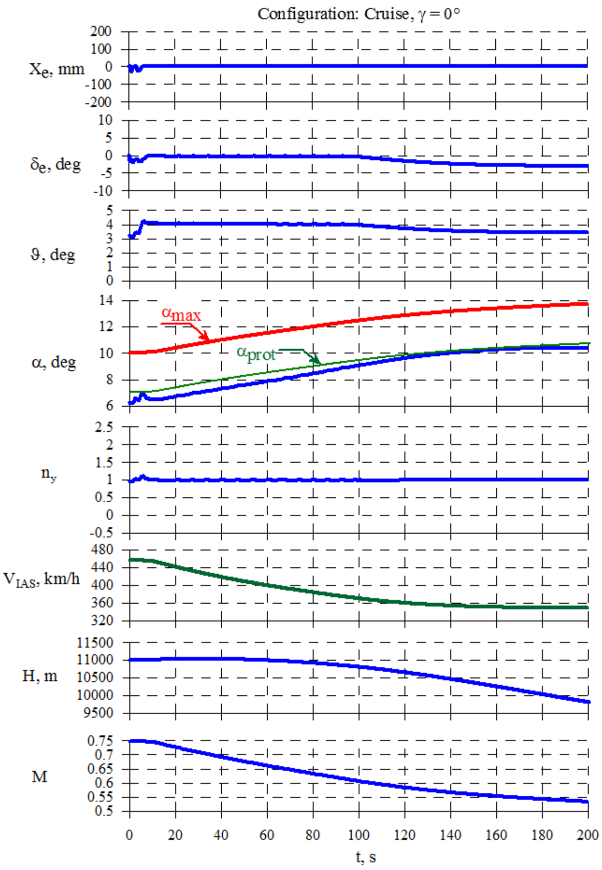

Figure 7 – the limitation of angle of attack and consequently of the velocities that takes place without pilot's participation in control

Figure 8 represents the limitation of the angle of attack and consequently of the velocities that takes place with pilot's participation in control (full backward longitudinal control lever deflection). The aircraft while braking attains the angle of attack that is equal to α_{max}. Hereby the limitation of the minimum velocity that corresponds to the given value of angle of attack is actualized.

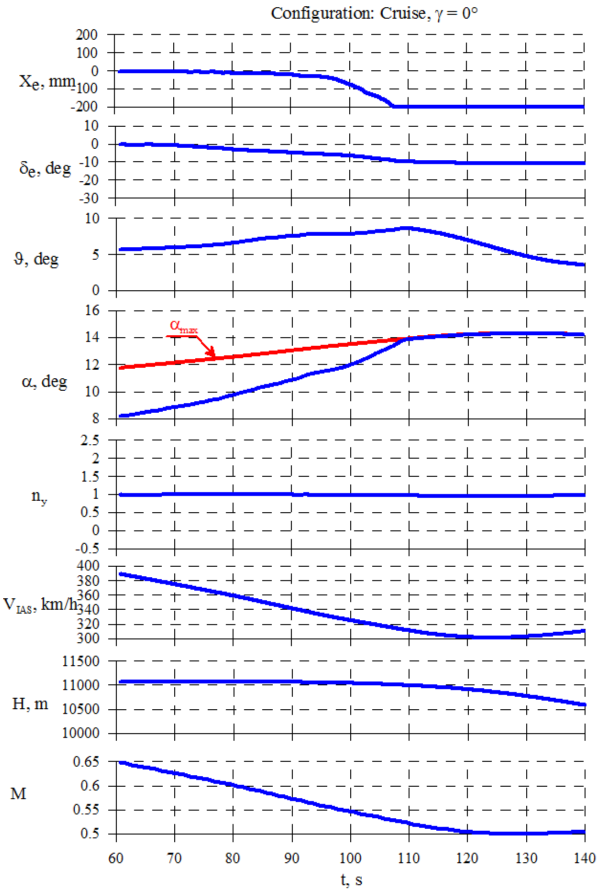

Figure 8 – the limitation of the angle of attack and consequently of the velocities that takes place with pilot's participation in control

The g-load factor limitation is provided by implementing the static characteristic of the g-load factor longitudinal control lever deflection in short-period moving (See Figure 9). The lever balancing position is equal to zero under the straight steady flight as the system is integrated. The static characteristic is composed of three linear portions. The central portion ($X_{e0}<X_e<X_{e\ prot}$) corresponds to the $X_e^{n_y}$ parameter optimal value. The maximum g-load factor value is actualized under the full longitudinal control lever backward deflection. By analogy, under the full lever forward deflection the minimum allowable g-load factor is actualized.

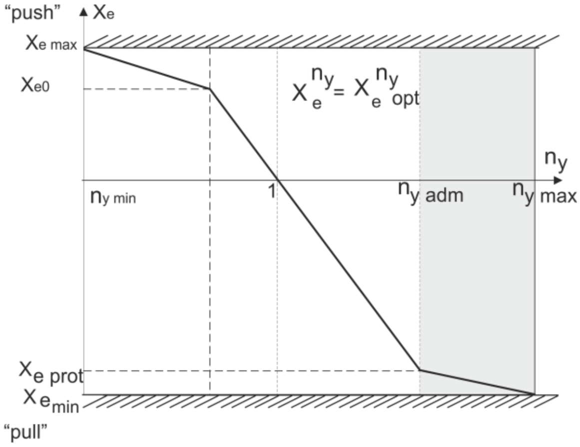

Figure 9 – the static characteristic of the longitudinal control lever deflection in re of the g-load factor

Figure 10 shows the g-load factor limitation. Under the full lever forward deflection the minimum allowable g-load factor that is equal to $n_{y\ min}$ (in the case under consideration $n_{y\ min}$=0.3) is actualized. Under the full lever backward deflection the maximum value that is equal to $n_{y\ max}$ (in the case under consideration $n_{y\ max}$=2) is actualized. The values of $n_{y\ min}$, n_{ymax} in system settings depend on high-lift devices position. Then at the transient one can see the angle of attack and g-load factor decreasing even under the full longitudinal control lever backward deflection. This is related to the activation of limiting the maximum pitch angle. By analogy, under the full longitudinal control lever forward deflection the function of limiting the minimum pitch angle is actualized.

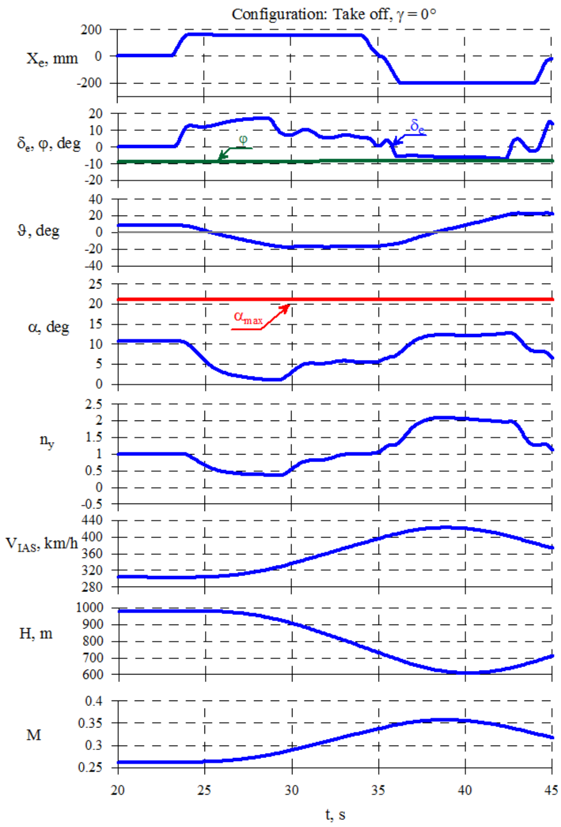

Figure 10 – the g-load factor limitation

The main inauspicious peculiarities of flight regimes that are close to stall are as follows:

- low g-load factor margin;
- low angle of attack margin;
- existence of aircraft intrinsic local longitudinal static instability;
- force instability under speed;
- degradation of aerodynamic controls efficiency;
- considerable roll and yaw moments may occur;
- deterioration of propulsion operational conditions.

By virtue of these reasons it is rational to use in line with the abovementioned functions the automatic thrust augmentation algorithm when reaching the regimes that are close to stall. Such a function is available at certain existing Russian and foreign airplanes.

The «αFLOOR» automatic augmentation thrust algorithm engaging usually is carried out by one of the following indications:

– when α >αFLOOR;

– when the control level pull-up angle deflection is more than 14° and the algorithms of angle of attack or pitch angle protection are activated.

The «αFLOOR» regime may be activated only after the take-off and at the altitude more than 100 футов (~30 m). Under the «αFLOOR» regime activating the engine thrust is commutated automatically to take-off regime regardless of the initial engine control lever position.

At TsAGI the up-graded algorithm is developed and proposed that is aimed at engine thrust augmentation in terms of predicted normal g-load factor margin value. This algorithm operates jointly with the limit behavior limiters including the angle of attack. When the algorithm has responded a command once-only is issued to retract the air brake-spoiler and to commutate the engines to maximum engine thrust regime. The engine thrust control algorithm is activated under the margin value of predicted normal g-load factor that is equal to threshold value. In order to prevent the algorithm operation within the envelope an additional commutation condition was introduced: the current normal g-load factor margin is not to surpass the specified threshold value.

The numeric and flight simulator comparative tests where the pilots took part were carried out. The TsAGI and the existing «αFLOOR» algorithms of automatic engine thrust augmentation were tested. The TsAGI's algorithm in general has a number of advantages. During researches, following results have been received:

– under hard maneuvering with attainment of high angles of attack the TsAGI algorithm has no unreasonable response under presence of sufficient g-load factor margin;

– under slow deceleration the both algorithms operate roughly equally. Under more intensive braking the TsAGI algorithm responds before as it takes into consideration the braking rate that allows on timely commuting the engines to maximum thrust regime under intensive braking even under relatively low angles of attack;

– under horizontal 30º roll braking the TsAGI algorithm in general responds slightly after but in this regime the algorithms behaviors are very similar.

3 Enhanced integrated control

The organization of integrated control that uses regimes that are realizable through ACS is further automation aircraft control to enhance the comfort of control and flight safety. When the control is integrated the airplane attitude hold modes are activated automatically without pilot's participation in control process. At that, the pilot is constantly within the control loop and the airplane control stereotypes do not differ from those ones normally accepted. The pilot's operation efficiency is improved due to this.

In dependence of the situation been created after pilot's participation in control through control levers the follow regimes are automatically activated:

- Pitch angle hold – ϑ hold AP;
- Flight path angle hold –θ hold AP;
- Altitude hold–H hold AP;
- Indicated airspeed hold or M number hold by engines thrust (autothrottle);– V_{IAS} hold AT or M hold AT;
- Indicated airspeed hold or M number hold by elevator –V_{IAS} hold AP or M hold AP;
- Bank angle hold –γ hold AP;
- Heading angle hold –ψ hold AP.

Let us consider the hold regimes activation logic. The block-diagram of airplane hold regimes activation logic for longitudinal channel is given in the Figure 11.

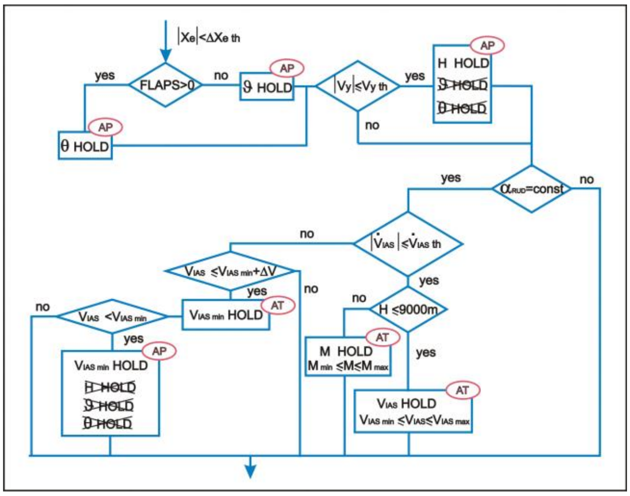

Figure 11 – the block-diagram of airplane hold regimes activation logic for longitudinal channel

The absence of the pitch control lever movement $|X_e| < \Delta X_{e\,th}$, ($\Delta X_{e\,th}$ – threshold value) during some time delay indicates that the pilot takes no part in pitch control and the hold mode in longitudinal channel is activated. Firstly, the *pitch angle hold ϑ hold AP or the flight path angle hold θ hold AP* is activated through elevator. Further by results of the path motion analysis the regimes may be automatically activated as follows:

– *Flight altitude hold H hold AP* by elevator when $|V_y| \le V_{y\,th}$ ($V_{y\,th}$– threshold value) during some time delay. The pitch angle hold or the flight path angle hold in this case is deactivated.

In *flight altitude hold* by elevator and at the absence of throttle motion performed by pilot i.e. when the engines running regime is constant and when the time delay is expired, the following regime is automatically activated:

– *The indicated airspeed hold V_{IAS} hold AT or M-number M hold AT* by autothrottle if $|\dot{V}_{IAS}| \le \dot{V}_{IAS\,th}$ ($\dot{V}_{IAS\,th}$– threshold value). The activation of indicated airspeed hold regime or the M-number through autothrottle is defined by the flight altitude. The altitude hold through elevator remains operating.

The minimum indicated airspeed hold ($1.3V_s$) is activated through autothrottle in order to limit the minimum flight speed if the speed is approaching the minimum specified value. In the case if minimum indicated airspeed is not maintained through autothrottle (autothrottle achieves limiting modes) *limitation of indicated airspeed V_{IAS} hold AP* through elevator is activated.

The *flight path angle hold θ hold AP* is proposed to be used instead of the pitch angle hold when high-lift devices are extracted. The use of flight path angle hold is reasonable at those flight stages where the aircraft is required to hold the straight flight. The glideslope flight is the most representative one when the straight descent trajectory hold under speed variation is required.

The numeric and flight simulator researches were carried out to evaluate the efficiency of given integrated control extended version for advanced civil airplane.

The mathematical simulation results are given in the Figure 12.

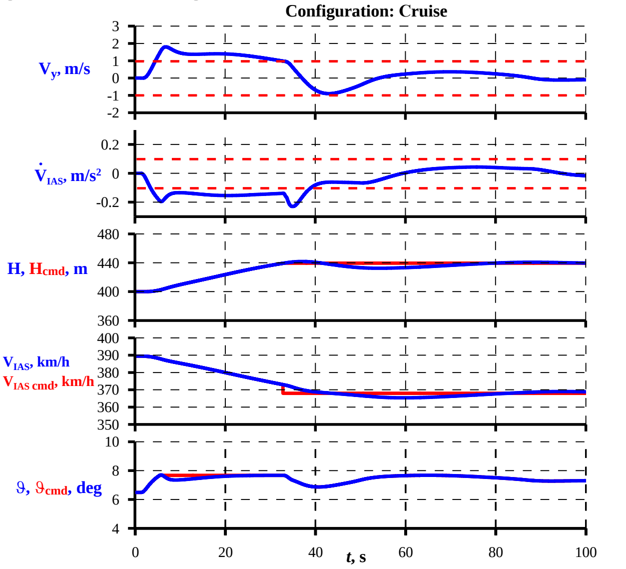

Figure 12 – activation of *H hold AP* and *V_{IAS} hold AT*

The operation of logic is given for involving the flight altitude hold through elevator and the stabilization of indicated airspeed through autothrottle in order to limit the minimum flight speed. The regime of climbing and decelerating is under consideration. It is evident that firstly, the pitch hold is involved and then when after the vertical speed value becomes less than the specified one, the altitude hold is activated. At the same, the indicated speed hold through autothrottle is involved as the speed is approaching the minimum specified value.

In order to make a comparison the Figures 13-14 show the results of simulation for the following versions: the airplane control system without (Fig.13) and with (Fig.14-15) enhanced integrated control. The following maneuver was considered: to nose-up deflection of control level and then the pilot did not participate in control neither by the (X_e=0) control lever nor by the (α_{RUD}=const) throttle.

The Figure 13 (version of control system without enhanced integrated control) evidently shows that after pilot's exit of control process the pitch angle hold mode is activated. The airplane starts climbing followed by deceleration and angle of attack increase. When approaching the α_{PROT} protection angle of attack, the pitch angle hold mode is deactivated and the airplane starts to stabilize the α_{PROT} protection angle of attack. The airplane decreases dramatically the pitch angle and starts the intensive descent. The flight speed is utmost low.

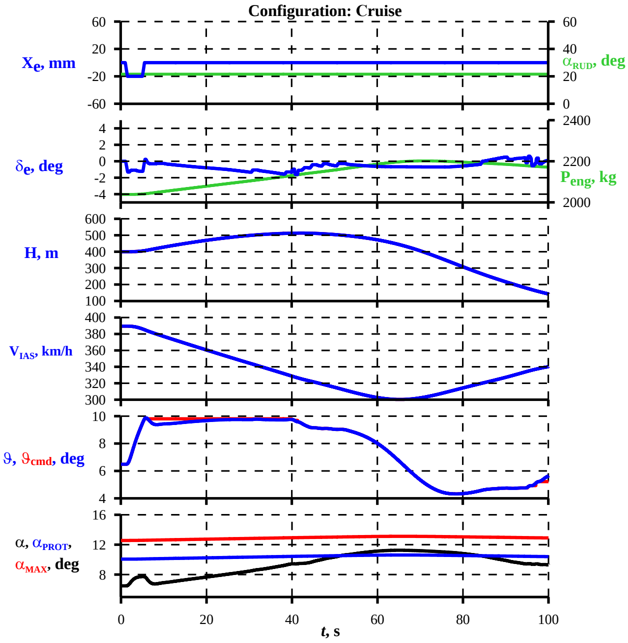

Figure 13 – version of control system without enhanced integrated control

The Figure 14 (version of control system with enhanced integrated control) shows the activation of indicated airspeed hold through elevator for the maneuver under consideration. It is evident that in this case the airplane flying-trajectory is safe by both the angle of attack and the flight speed and altitude. The losses in speed and height are significantly lower. Consequently the flight safety is higher that is particularly important when flying at low altitudes.

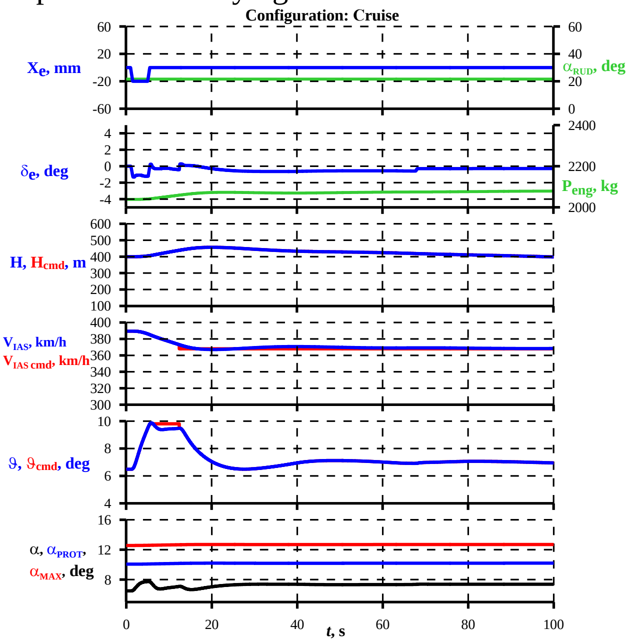

Figure 14 – version of control system with enhanced integrated control, activation of *V_{IAS} hold AP*

The Figure 15 (version of control system with enhanced integrated control) shows the activation of indicated airspeed hold through autothrottle for the maneuver under consideration as well. It is clear that when the specified speed is obtained the stabilization mode of this speed through autothrottle starts followed by climb. At that, the conditions of safe flying continuation are satisfied.

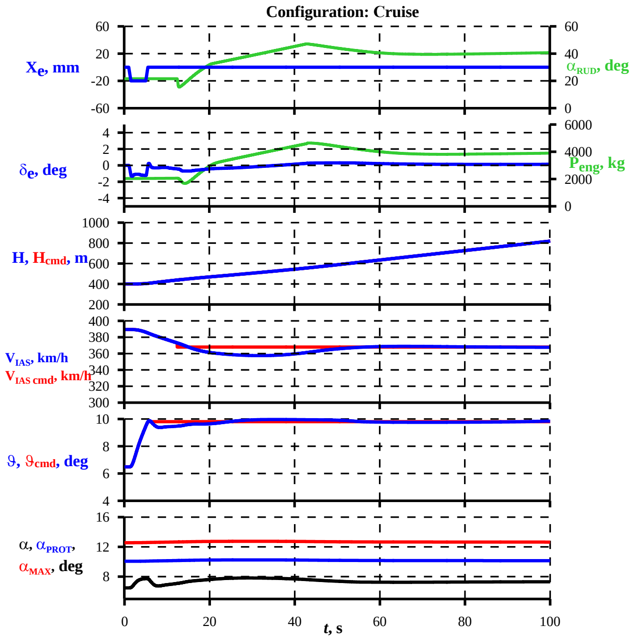

Figure 15 – version of control system with enhanced integrated control, activation of *V_{IAS} hold AT*

4 Conclusions

Numeric computations, flight simulator tests and flight tests have shown the high efficiency of the aircraft motion parameters limitation control laws developed. These control laws significantly enhance the flight safety during all flight stages (from take-off to landing), and some of them have been already successfully implemented on a number of aircraft generated in Russia.

References

[1] Alyoshin B.S., Bazhenov S.G., Didenko Yu.I., Shelyukhin Yu.F., *Fly-By-Wire Control Systems for civil aircraft*, Moscow: Science, 2013 (in Russian).

[2] Byushgens G.S., Studnev R.V., *Longitudinal and lateral aircraft motion dynamics*, Moscow: Mechanical Engineering, 1978 (in Russian).

[3] Mihalyov I.A., Okoyomov B.N., Chikulaev M.S., *Automatic Control System of aircraft*, Moscow: Mechanical Engineering, 1987 (in Russian).

[4] Didenko Yu.I., Kosmachyov V.N., Kuzmin P.V., Automatic limitation of pitch angle at takeoff-landing regimes, Moscow: *Air Fleet Egineering*, №6, 2000 (in Russian).

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