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THE EFFECT OF AUTOMATIC FLIGHT CONTROL SYSTEM STRUCTURE ON ATTENUATION OF THE SHORT – PERIOD AIRCRAFT VIBRATIONS DUE TO ATMOSPHERE TURBULENCE

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The influence of selected control laws representing autopilot structures on attenuation of the short-period vibrations due to atmosphere turbulence has been examined in the paper. A nonlinear model of the aircraft dynamics and a turbulence model representing stochastic enviromental conditions have been applied to computer simulation of the problem. Numerical calculations were made for three selscted control laws for their applicability to the I-22 Iryda automatic flight control system to be assessed.

Key words: aircraft, autopilot, atmosphere turbulence, simulation

1. Introduction

The process of control of a modern aircraft flight is a very complicated process to which contribute, of course besides a human-operator, also a number of on-board and ground systems. An autopilot is one of the on-board automatic control systems, main task of which is a program control of aircraft angular motions and a flight path in the way ensuring the applied control law to be fulfilled. The autopilot structures differ in complexity, depending on the aircraft mission to be performed, as well as the aerodynamic characteristics and the level of control automation assumed, respectively. The aircraft flight, being programmed or realised by a human pilot may be disturbed in many ways. Various factors may cause undesirable changes in the flight parameters. The co-ordinate systems applied to analysis of the aircraft motion and basic parameters of the motion are presented in Fig.1.

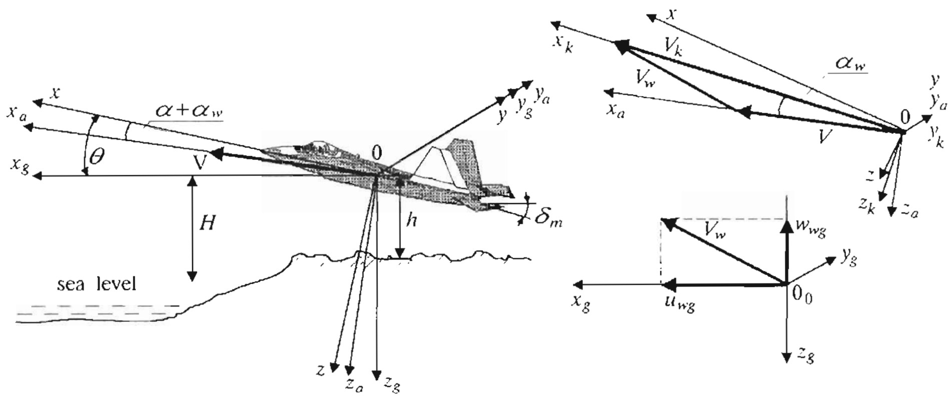

Fig. 1. Co-ordinate systems applied

In Fig.1. the following notation has been introduced:

V, V_w, V_k	–	air, wind, ground velocities, respectively
H	–	pressure altitude
h	–	radio altimeter altitude
θ	–	pitch angle
δ_m	–	pitch motivator deflection
α	–	angle of attack
α_w	–	turbulent component of the angle of attack
u_{wg}, v_{wg}, w_{wg}	–	gust velocity vector components
$0xyz$	–	body-fixed co-ordinate system
$0_0x_gy_gz_g$	–	normal earth – fixed axes
$0x_ay_az_a$	–	air-path axes
$0x_gy_gz_g$	–	aircraft-carrier earth axes
$0x_ky_kz_k$	–	flight-path axes.

Atmosphere turbulences create most serious disturbances affecting the aircraft flight.

Special systems designed for the effect of atmosphere turbulence to be minimised (e.g. aerodynamic forces active control) have been already known in aeronautics for years. These are, however, the automatic control systems of high complexity with which only the aircraft of special design supplied with additional steering surfaces, can be equipped. Application of such systems is therefore limited.

In the present contribution an attempt has been made to assess the usefulness of some well-known structures of the automatic flight control when flying in turbulent atmosphere.

2. Formulation of the problem

Systems of automatic flight control (autopilot) can be used for the effect of turbulence on the aircraft flight to be weakened. The efficiency of such systems depends upon the control law applied.

The influence of control law representing the autopilot structure on the disturbance mitigation in a flight in turbulent atmosphere has been simulated numerically. The scheme of computer simulation is given in Fig.2.

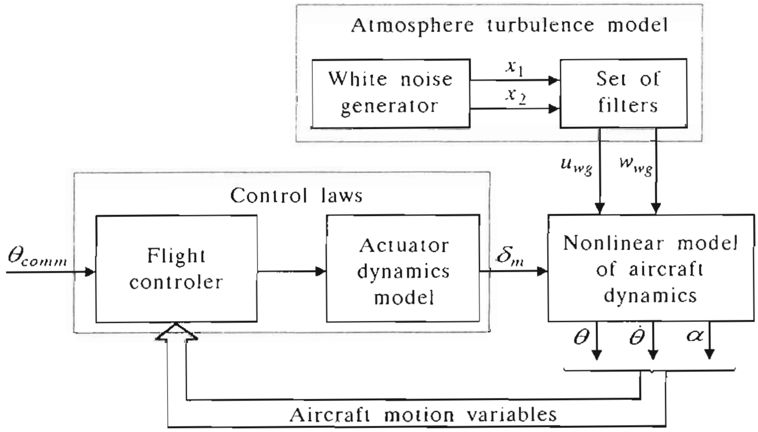

Fig. 2. Functional scheme of the aircraft dynamics simulation when flying in turbulent atmosphere

Each one of the three subsystems which can be easily seen from the scheme is assigned with a separate function:

- Non-linear model of the aircraft dynamics represents its properties when treated as the object of control
- Control law realising block comprises also the structure of automatic flight control and therefore its output signal should ensure that an effective control is realised
- Atmosphere turbulence model represents stochastic environmental conditions, in terms of disturbances occurring in flight. These disturbances

are represented by certain instantaneous values of the wind velocity vector components.

Short-period vibrations about the aircraft gravity centre appearing in flight due to the atmosphere turbulence disturb the control process of aircraft flight. Rapid changes in the values of angles of attack and pitch, respectively, appear when considering the aircraft motion in its plane of symmetry. One of the most important tasks the systems of semiautomatic and automatic flight control should perform is damping these vibrations until the values of parameters of motion enabling the effective control to be realised are reached.

The atmosphere turbulence realised in terms of wind velocity components variation, is assumed to be a quasi-stationary stochastic process of a given spectral density. The von Dryden turbulence model (cf Chalk et al., 1969; McLean, 1990; [6])

$$
\begin{aligned}
\Phi_{u_g} &= \sigma_u^2 \frac{2L_u}{\pi} \frac{1}{1+(L_u\Omega)^2} \\
\Phi_{w_g} &= \sigma_w^2 \frac{L_w}{\pi} \frac{1+3(L_u\Omega)^2}{\Big[1+(L_u\Omega)^2\Big]^2}
\end{aligned}
\tag{2.1}
$$

where

$\sigma_u(h), \sigma_2(h)$	–	mean square function representing the wind gust intensity [m/s]
$L_u(h), L_w(h)$	–	turbulence scales [m]
Ω	–	spatial frequency [rad/m].

has been applied to analysis of the aircraft flight in turbulent atmosphere.

The stochastic process described above is realised in terms of wind velocity components determined in the normal earth-fixed co-ordinate system (see Fig.1). However, on the assumption that the wind velocity field is time – independent (frozen) when crossing the turbulent region the process can be represented also in the aircraft- carried earth co-ordinate system. The stochastic process depends then upon the aircraft velocity and can be described with the following time dependent function of observed angular frequency ω [rad/s] (cf McLean, 1990) using

$$
\Phi_{u_g}(\omega) = \sigma_u^2 \frac{2L_u}{\pi V_k} \frac{1}{1+\omega^2 \frac{L_u^2}{V_k^2}} \qquad \Phi_{w_g}(\omega) = \sigma_w^2 \frac{L_w}{\pi V_k} \frac{1+3\omega^2 \frac{L_w^2}{V_k^2}}{\Big(1+\omega^2 \frac{L_w^2}{V_k^2}\Big)^2} \tag{2.2}
$$

where

$$\omega = \Omega V_k \qquad \Phi_{u_g}(\omega) = \frac{\Phi_{u_g}(\Omega)}{V_k} \qquad \Phi_{w_g}(\omega) = \frac{\Phi_{w_g}(\Omega)}{V_k}$$

By virtue of Eq (2.2) the transfer functions of the filters forming the stochastic processes can be written as follows

$$\begin{aligned} W_{u_g}(s) &= \frac{u_{wg}(s)}{x_1(s)} = \frac{\sigma_u\sqrt{\frac{2L_u}{\pi V_k}}}{1+\frac{L_u}{V_k}s} \\ W_{w_g}(s) &= \frac{w_{wg}(s)}{x_2(s)} = \frac{\sigma_w\sqrt{\frac{L_w}{\pi V_k}}\Big(1+\sqrt{3}\frac{L_w}{V_k}s\Big)}{\Big(1+\frac{L_w}{V_k}s\Big)^2} \end{aligned} \tag{2.3}$$

The recurrence algorithms emerging from discretization of the continuous forming filters, the transfer functions of which correspond to specified spectral densities have been used in computer simulation of the problem.

In view of the control, dynamical properties of the aircraft can be represented by a set of implicit non-linear differential equations describing its decoupled longitudinal motion (cf McLean, 1990; Dobrolenskii, 1969). A simplified form of this set can be written as

— equation of forces in the flight-path co-ordinate system

$$\begin{aligned} m\frac{dV_k}{dt} &= F_S\cos(\alpha+\varphi_z) - \frac{1}{2}C_{Da}S_{SK}\rho V^2\cos\alpha_w - mg\sin(\theta-\alpha) + \\ &+\frac{1}{2}C_{Labu}S_{SK}\rho V^2\sin\alpha_w + \\ &+\frac{1}{2}S_H\rho k_H V^2\sin\alpha_w\Big[a_{H2}\delta_m + a_{H1}\Big(\alpha+\alpha_w-\varepsilon_0-\varepsilon^\alpha(\alpha+\alpha_w)+\chi_H\Big)\Big] \\ mV_k\Big(\frac{d\alpha}{dt}-\frac{d\theta}{dt}\Big) &= -F_S\sin(\alpha+\varphi_z) - \frac{1}{2}C_{Labu}S_{SK}\rho V^2\cos\alpha_w + \\ &-\frac{1}{2}S_H\rho k_H V^2\cos\alpha_w\Big[a_{H1}\Big(\alpha+\alpha_w-\varepsilon_0-\varepsilon^\alpha(\alpha+\alpha_w)+\chi_H\Big) + \\ &+a_{H2}\delta_m\Big] - \frac{1}{2}C_{Da}S_{SK}\rho V^2\sin\alpha_w + mg\cos(\theta-\alpha) \end{aligned} \tag{2.4}$$

— equation of moment in the body-fixed azes

$$
\begin{aligned}
I_y \frac{d\theta^2}{dt^2} &= \frac{1}{2} C_{mabu} b_A S_{SK} \rho V^2 + z_F F_S + C_m^q L_H^2 \rho V S_{SK} \frac{d\theta}{dt} + \\
&- \frac{1}{2} L_H S_H \rho k_H V^2 \Big[a_{H1} \Big(\alpha + \alpha_w - \varepsilon_0 - \varepsilon^\alpha (\alpha + \alpha_w) + \chi_H \Big) + \\
&+ a_{H2} \delta_m \Big] + C_m^{\dot{\alpha}} L_H^2 \rho S_{SK} \Big(\frac{d\alpha}{dt} + \frac{d\alpha_w}{dt} \Big)
\end{aligned}
\tag{2.5}
$$

where

α_w - turbulent component of the angle of attack

$$
\alpha_w = \arcsin \Big[- \frac{u_{wg} \sin(\theta - \alpha) + w_{wg} \cos(\theta - \alpha)}{V} \Big]
$$

$C_{Da}, C_{Labu}, C_{mabu}$ - drag, lift and pitching coeficients, respectively
F_S - thrust
χ_H - deflection for horizontal flight
ρ - density of air
g - acceleration of gravity
m - aircraft mass
$a_{H1}, a_{H2}, C_m^q, C_m^{\dot{\alpha}}, k_H, \varepsilon_0, \varepsilon^\alpha$ - coefficients of aerodynamic forces
$S_{SK}, L_H, z_F, \varphi_z$ - design parameters

— function describing the aircraft kinematics

$$
\frac{dH}{dt} = V_k \sin(\theta - \alpha) \tag{2.6}
$$

A structure of automatic control is represented by the control law. For simplifications purposes it has been assumed that the autopilot works within the "stabilisation" range (a commanded value of the pitch angle ensured). Three control laws represented in terms of the following equations have been applied.

— The control law No. 1

$$
\delta_m(s) = W_{SH}(s) \Big[\frac{k_{S1}}{T_{SZ}^2 s^2 + 2\xi T_{SZ} s + 1} + f(L_E) W_{TR}(s) \Big] [i_{\theta 1}(\theta_{comm} - \theta) - \mu_{\theta 1} s\theta] \tag{2.7}
$$

— The control law No. 2

$$
\delta_m(s) = W_{SH}(s) \Big[\frac{k_{S2}}{s(T_P s + 1)} + f(L_E) W_{TR}(s) \Big] [i_{\theta 2}(\theta_{comm} - \theta) - \mu_{\theta 2} s\theta - \nu_{\theta 2} s^2 \theta] \tag{2.8}
$$

— The control law No. 3

$$\delta_m(s) = W_{SH}(s)\Big[\frac{k_{S3}(T_i s+1)}{T_i s(T_i^* s+1)} + f(L_E)W_{TR}(s)\Big]\big[i_{\theta 3}(\theta_{comm} - \theta) - \mu_{\theta 3} s\theta\big] \qquad (2.9)$$

where

$W_{SH}(s)$	–	transfer function of the hydraulic servoactuator
$W_{TR}(s)$	–	transfer function of the trim actuator
$f(L_E)$	–	actuating function of the trim actuator
θ, θ_{comm}	–	current and commanded values, respectively, of the aircraft pitch angle
$k_{S1}, k_{S2}, k_{S3}, T_{SZ}, T_P, T_i, T_i^*, \xi$	–	dynamical parameters of the electic servoactuators
$i_{\theta i}, \mu_{\theta i}, \nu_{\theta i}$	–	variable parameters of the control law structure
s	–	complex variable of the Laplace tramsform

$$\delta_m(s) = \int\limits_0^\infty \delta_m(t)\mathrm{e}^{-st}\,dt$$

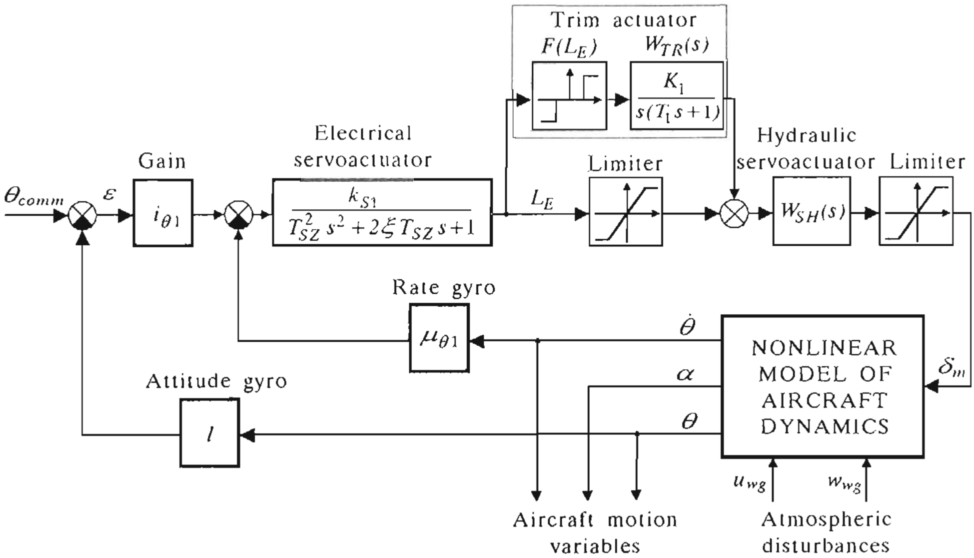

Fig. 3. Block diagram of the pitch attitude control system – the control law No. 1

Basing on the control laws given above one can simulate a flight in turbulent atmosphere using the structural schemes shown in Fig.3 ÷ Fig.5, (white blocks represent time-independent elements while the grey ones stand for time dependent substructures). Each subsystem should, no matter which one of the control laws has been applied, stabilise the aircraft pitch attitude during a flight in turbulent atmosphere. Fig.3 shows the structure of the angle of pitch autopilot represented by the control law No. 1. A similar structure can be found e.g. in MiG-21, MiG-21bis and MiG-23 aircraft, respectively. The angle of pitch stabilisation error ε has been registered as well as the angle of attack α increment (characteristic for short-period vibrations of the aircraft longitudinal motion) and the elevator displacement δ_m.

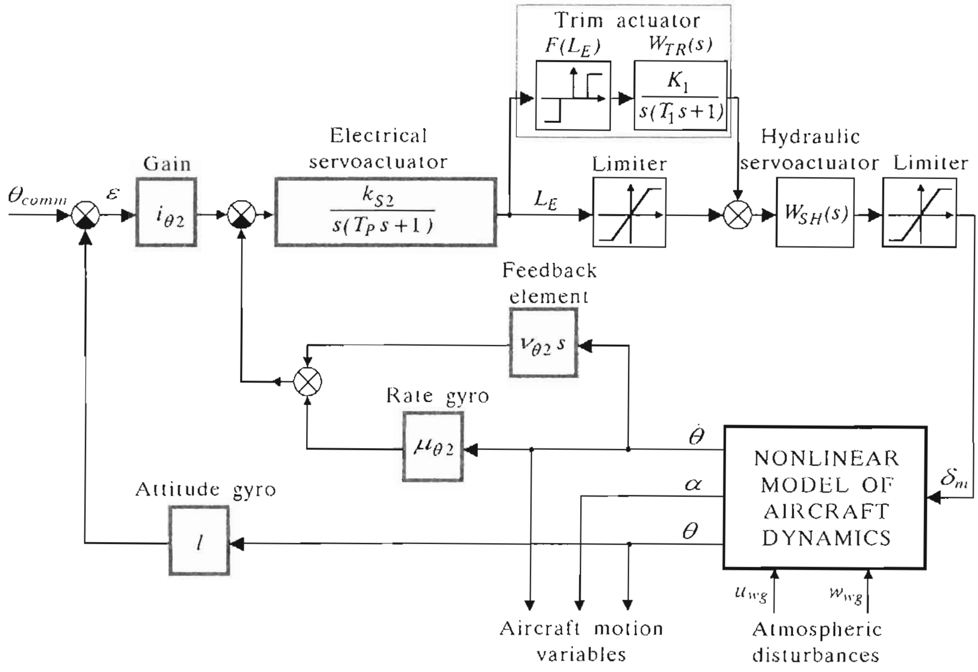

Fig. 4. Block diagram of the pitch attitude control system – the control law No. 2

Fig.4 shows the structure of the angle of pitch autopilot represented by the control law No. 2. A similar structure can be found in MiG-29.

The control law No. 3 has been applied to the autopilot structure presented in Fig.5. A similar structure can be found in SU-22.

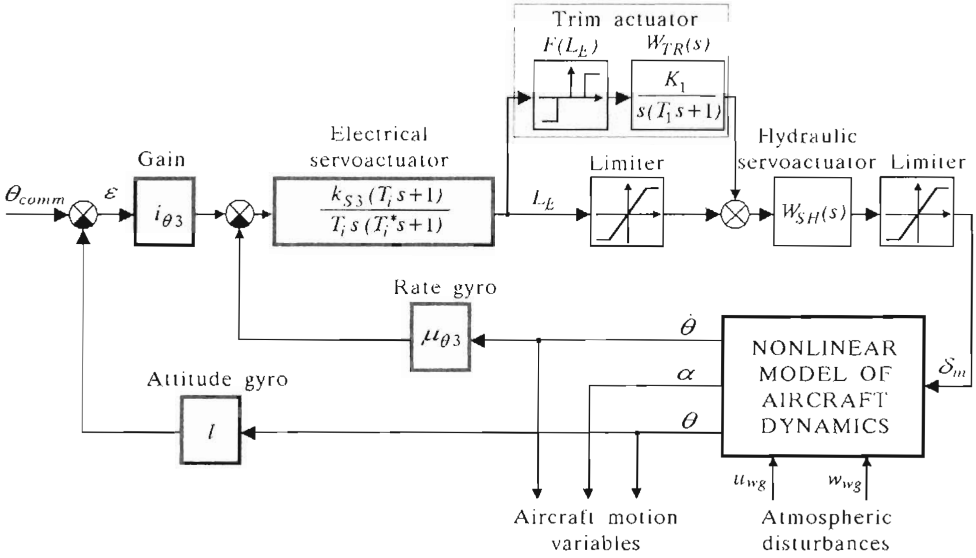

Fig. 5. Block diagram of the pitch attitude control system – the control law No. 3

3. Analysis of the results

The characteristics of I-22 Iryda have been introduced into the simulation models given above. The flight in turbulent atmosphere has been simulated for each structure. For the sake of simplicity it was assumed that before entering the turbulent region the aircraft was in a horizontal rectilinear uniform flight. The time taken for flying in the turbulent atmosphere was 5 s. Dynamical processes appearing due to disturbances have been registered for 10 s.

The results obtained; i.e., angle of attack increment $\Delta\alpha$, stabilisation error ε and elevator deflection δ_m under different flight conditions are presented in Fig.6 $\div$ Fig.10.

Fig.6. shows sample charts of parameters of the aircraft motion in turbulent atmosphere and just after leaving this region. In this example the automatic control system is represented by the control law No. 1. It can be easily seen from the diagrams that the atmosphere turbulence brings about substantial changes of the aircraft angle of attack. The elevator displacement δ_m corrects the stabilisation error ε. After leaving the atmospheric disturbance region the automatic control system corrects the system parameters until their input values, i.e. those before the turbulence appeared are reached. The transient states in this process take about 3 s.

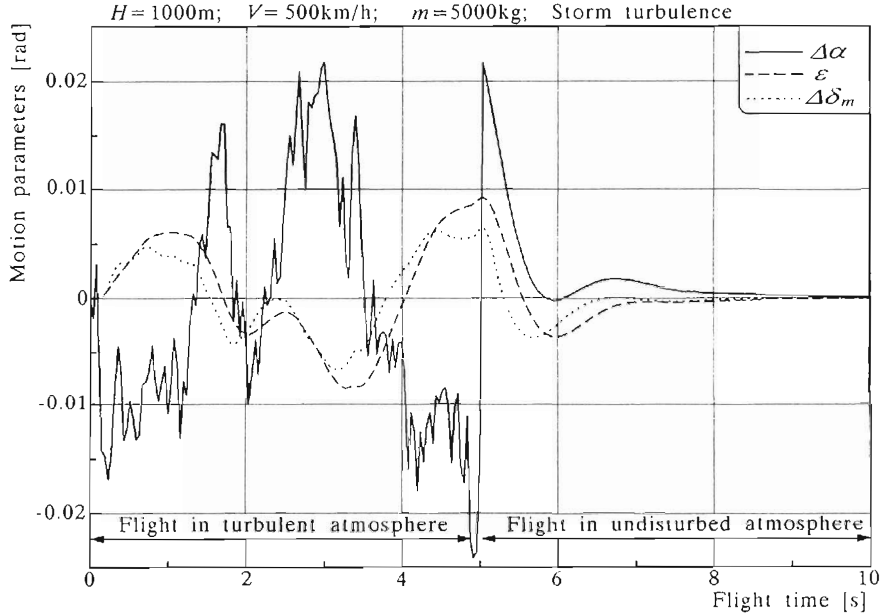

Fig. 6. Charts of the aircraft motion parameters in turbulent atmosphere and just after leaving this region (decaying of the transient processes visible)

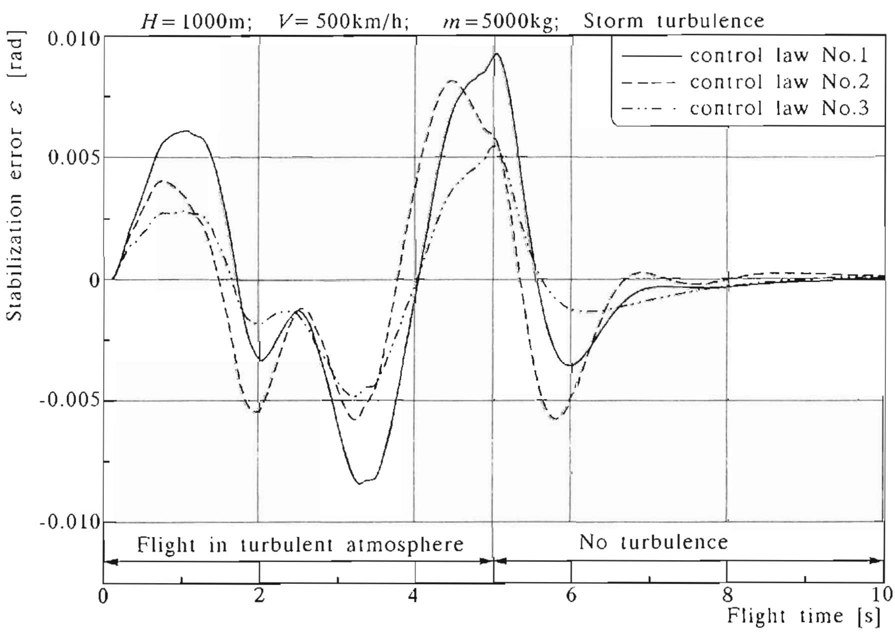

Fig. 7. Influence of the autopilot structure upon the angle of pitch stabilisation error in low-altitude flight

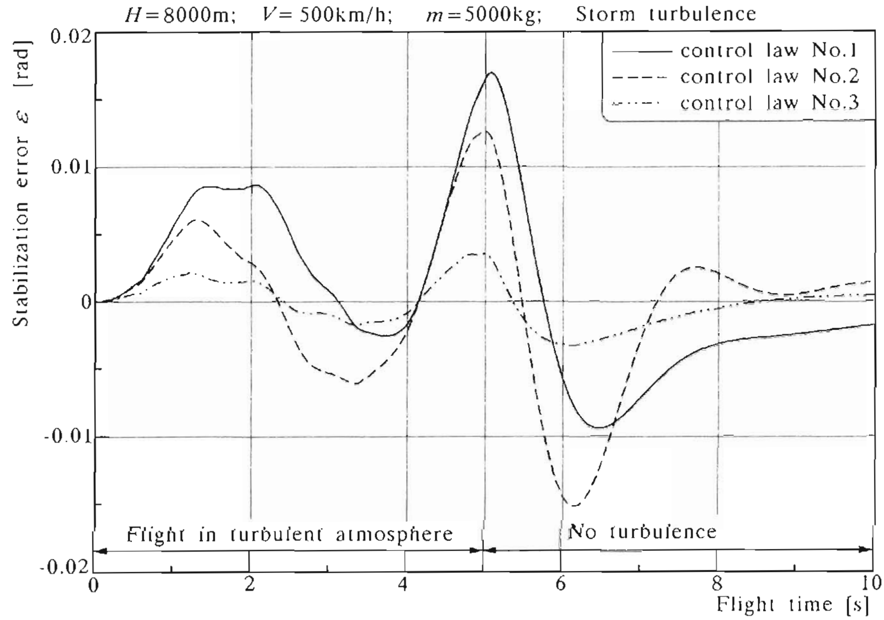

Fig. 8. Influence of the autopilot structure upon the angle of pitch stabilisation error in high-altitude flight

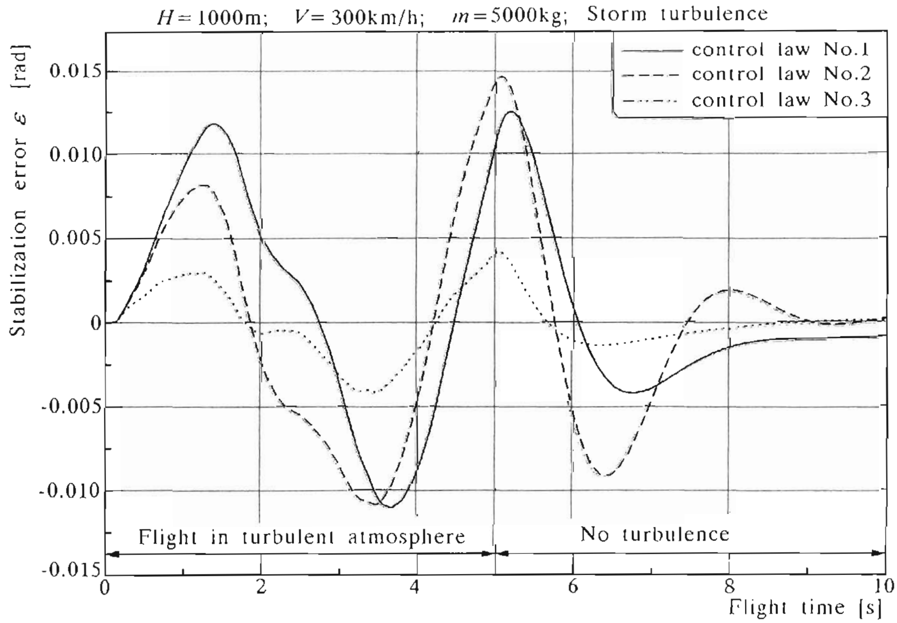

Fig. 9. Influence of the autopilot structure upon the angle of pitch stabilisation error in landing approach

From the charts shown in Fig.7 it follows that when applying the structure represented by the control law No. 1 the stabilisation quality of the angle of pitch deteriorates substantially. Only slight improvement in the performance quality is observable with the control law No. 2 applied, while the autopilot structure represented by the control law No. 3 enables the best results to be obtained. This structure ensures a very good performance in flight in turbulent atmosphere and just after leaving this region.

Similar results have been obtained in the high-altitude flight at large angles of attack (see Fig.8). It should be noted that in this case the transient processes after leaving the disturbance zone decay much more slowly.

It can be easily seen from Fig.9. that the automatic control structure represented by the control law No. 3 ensures the best performance also in the landing approach.

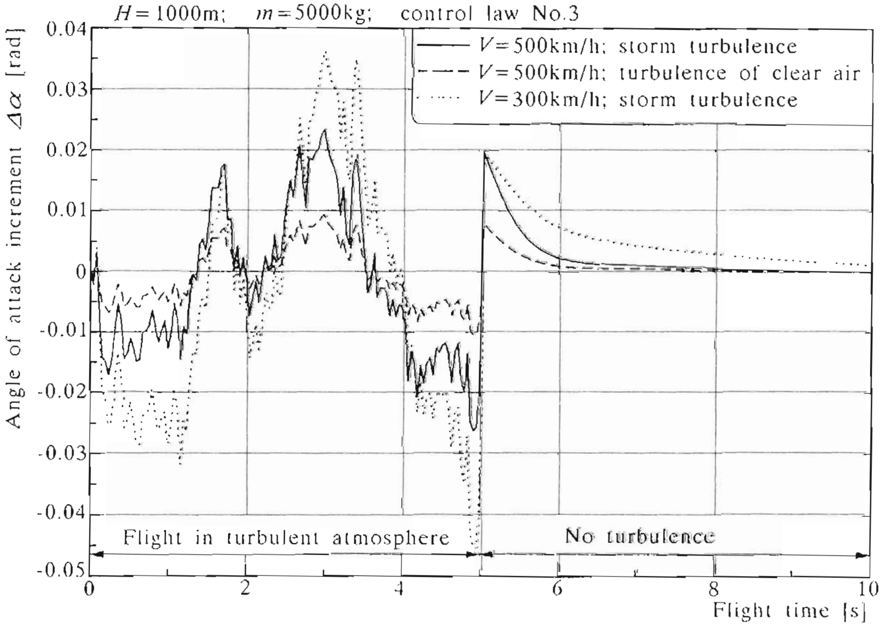

Fig. 10. Transient processes appearing in the angle of attack variation under different flight conditions when applying the autopilot structure represented by the control law No. 3

Two different aircraft velocities as well as storm and clear-air turbulence, respectively, have been also considered (see Fig.10). It can be easily seen that in the course of flight simulation, i.e. in turbulent atmosphere and clear-air, respectively, the values of angle of attack oscillate about several different levels. In low-altitude flight in the storm turbulence there appears a possibility of exceeding the critical value of angle of attack and, therefore, a hazard to the aircraft manoeuvrability arises. In low-speed flight the transient processes of the angle of attack increment damping decay much more slowly, when compared with those appearing in high-speed flight. As can be expected, in a flight across the clear-air turbulence region the transient processes decay faster.

4. Conclusions

From the results presented above it can be easily seen that a proper choice autopilot structure can make unnecessary to use complex specialised and very expensive anti-turbulence systems. Satisfactory results can be obtained also by the proper choice of a control law structure and its parameters.

Summing up it can be stated that the automatic control structure represented by the control law No. 3. works best in a flight across the turbulent atmosphere region for the fighter-training "Iryda" aircraft tested.

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Wpływ struktury układu automatycznego sterowania lotem na tłumienie krótkookresowych drgań samolotu spowodowanych turbulencją atmosfery

Streszczenie

W pracy przedstawiono badania wplywu wybranych praw sterowania pilotów automatycznych na tlumienie krótkookresowych drgań samolotu wywołanych turbulencją atmosfery. Do komputerowej symulacji lotu wykorzystano nieliniowy model dynamiki samolotu oraz model turbulencji atmosfery odzwierciedlający stochastyczne właściwości środowiska ruchu. Przeprowadzono obliczenia dla trzech praw sterowania, oceniając ich przydatność w ukladzie automatycznego sterowania lotem na przykładzie samolotu I-22 Iryda.

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