

The use of the hierarchical structured dynamic inversion to the aircrafts longitudinal movement

Romulus Lungu, Saurabh Kwatra, Mihai Lungu, Lucian Grigorie

Abstract— The paper presents a methodology for the flight control law's design for the trajectory pursuit using hierarchical dynamic inversion; this is based on separation of multi-time-scale and multi-loop closing method. It greatly simplifies the flight control design compared with PID conventional approaches. The used dynamic equations are classified into 4 groups according to the stairs of time measuring from the physical point of view [1]; each group of variables is controlled by the group of faster neighboring variables. The authors made the analysis of the longitudinal movement of aircrafts and obtained graphic characteristics which demonstrate the effectiveness of the proposed method.

Keywords— aircraft, control law, hierarchical dynamic inversion, longitudinal movement.

I. INTRODUCTION

ONE knows that it is difficult to stabilize and control an aircraft using constant gain controllers because the aircraft's dynamics vary with the considerable modification of the dynamic pressure and Mach number. That's why a very good method for solve this problem is the determination of the gains of the control system. This is a simple and direct methodology for the design of flight control systems. The technique of the gains' determination is the most important thing today in the area of flight control's design [2], [3].

The technique of gains' determination depends on the designer's experience and on his engineering art. Variables' separation on two time scales combined with the theory of singular perturbation have been subject of research, the attitude being taken as slow variable while angular velocities as fast variables. The slow variables are controlled by the fast ones, which, in turn, are controlled by aerodynamic command

surfaces.

II. FORMULATION OF HIERARCHICAL DYNAMIC INVERSION

One considers the following nonlinear system [4], [5], [6]

$$\begin{aligned}\dot{x} &= f(x, u), \\ y &= h(x),\end{aligned}\quad (1)$$

where $x \in R^n$ is the state variable, $u \in R^m$ is the control input and $y \in R^m$ – the output which will be controlled by the control input u . From equations (1), one gets

$$\dot{y} = \frac{\partial h}{\partial x} f(x, u) = F(x, u) \quad (2)$$

or

$$u = F^{-1}(x, v), \quad (3)$$

where v is the auxiliary input of the system. From equations (2) and (3) one yields

$$\dot{y} = F(x, F^{-1}(x, v)) = v. \quad (4)$$

The auxiliary input may have the classical form

$$v = K(y_c - y), \quad (5)$$

where K is a gain matrix and y_c the imposed value of y .

The term that compensates the nonlinear dynamics also provides the linearization of the dynamic system and the exterior loop, expressed by equation (5); the system becomes linear and achieves the desired value of the output y_c (fig. 1).

Unfortunately, some input-output equations do not describe the aircraft dynamics with minimum phase because of the aerodynamic forces' derivatives in rapport with control surfaces' deflections. This fact has prevented the direct application of dynamic inversion to the automatic flight control systems. This problem can be avoided by system's separating on two time scales; thus, there are slow variables and fast variables. Fast state variables are used to control the slow state variables while the fast variables are controlled by the command variable. One considers the following two time scales nonlinear system

$$\dot{x}_1 = f_1(x_1, x_2, u), \dot{x}_2 = f_2(x_1, x_2, u), y = h(x_1), \quad (6)$$

where $x_1 \in R^n$ is the slow state, $x_2 \in R^n$ is the fast state, $u \in R^m$ – the control input and $y \in R^m$ – the controlled output. The input-output equations on the slow scale may be derived as follows

$$\dot{y} = \frac{\partial h}{\partial x_1} f_1(x_1, x_2, u) \equiv F(x_1, x_2, u), \quad (7)$$

where $F(x_1, x_2, u)$ is invertible in rapport with x_2 .

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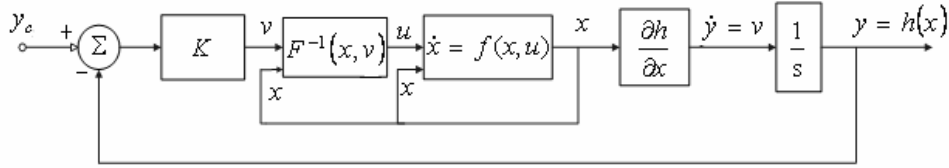


Fig.1 The linear system with dynamic inversion

One obtains x_{2c} from the previous equation using the dynamic inversion

$$x_{2c} = F^{-1}(x_1, v_1, u), v_1 = K_1(y_c - y), \quad (8)$$

where v_1 is the auxiliary input for the slow scale controller and K_1 – the feedback gain matrix. If $x_2 = x_{2c}$, the following equation is maintained

$$\dot{y} = F(x_1, F^{-1}(x_1, v_1, u)) = K_1(y_c - y) = v_1. \quad (9)$$

Finally, one obtains u_c in the fast scale so that $x_2 \rightarrow x_{2c}$

$$\begin{aligned} u_c &= f_2^{-1}(x_1, x_2, v_2), \\ v_2 &= K_2(x_{2c} - x_2), \end{aligned} \quad (10)$$

where v_2 is the auxiliary input for the fast scale controller K_2 – the feedback gain matrix.

III. THE USE OF THE HIERARCHICAL DYNAMIC INVERSION TO THE AIRCRAFTS' DYNAMICS

For the conventional aircrafts with fixed wing the command surfaces' deflections has the slowest time scale [4], [5]. These deflections generate aerodynamic moments around aircrafts' axes. The aerodynamic moments generate angular velocities and the angular velocities are integrated in order to obtain the aircraft's attitude. The forces have the same time scale with the accelerations. The attitude is integrated to obtain the velocities and the velocities give the position of the flying object. The variables may be grouped in four layers (time scales): very slow scale (the position of the aircraft X, Y, Z), slow scale (none of the variables), fast scale (velocities U, V, W and angles φ, θ and ψ) and very fast scale (the angular velocities P, Q, R) [3]. The aircraft position is defined by the longitudinal error e_h , the lateral error e_y and the trajectory arc length s . The velocities are defined by the real velocity of the air currents V_{TAS} , the direction angle in rapport with the air currents ψ_a and the trajectory's angle in rapport with the air currents γ_a . V_{TAS} is directly controlled by the thrust force or by the aerodynamic braking. The attitude is defined by three angles: roll angle φ , pitch angle θ and sideslip angle β ; all these angles are controlled by angular velocities [1]. For the coordinated flight $\beta_c = 0$, the incidence angle α is not considered a state variable as it appears in [3]. This will improve the precision of control because the inertial attitude can be measured with less error than the aerodynamic angles like α . The three angular velocities P, Q, R are controlled by the three command surfaces: rudder, aileron and direction [7].

It is not enough to choose the state variables. This choice may be not optimal for some applications; that's why state transformations will be made.

The state variables are transformed from the initial ones $x \in R^{12}$ in the new state variables $\xi \in R^{12}$. One notes with $T(x)$ the nonlinear transformation which verifies equation $\xi = T(x)$, where ξ is selected so that T – invertible $x = T^{-1}(\xi)$.

$$\begin{aligned} x &= [X \ Y \ Z \ U \ V \ W \ \varphi \ \theta \ \psi \ P \ Q \ R]^T, \\ \xi &= [s \ e_y \ e_h \ V_{TAS} \ \psi_a \ \gamma_a \ \varphi \ \theta \ \beta \ P \ Q \ R]^T. \end{aligned} \quad (11)$$

The control vector u contains four variables representing the deflections of control surfaces

$$u = [\delta_p \ \delta_e \ \delta_d \ \delta_T]^T \quad (12)$$

where $\delta_p, \delta_e, \delta_d$ and δ_T are the deflections of the rudder, aileron, direction, respectively the gas lever's displacement. Taking into account the multi time scale separation from the previous section, ξ is separated as follows

$$\begin{aligned} \xi_1 &= [e_y \ e_h]^T, \xi_2 = [V_{TAS} \ \psi_a \ \gamma_a]^T, \\ \xi_3 &= [\varphi \ \theta \ \beta]^T, \xi_4 = [P \ Q \ R]^T. \end{aligned} \quad (13)$$

In layer i ($i = 1, 2, 3$) the equations of dynamic models of the subsystems can be defined as

$$\dot{\xi}_i = F_i(\xi_i, \xi_{i+1}, u, \tilde{\xi}_i), i = \overline{1, 3}, \quad (14)$$

where $\tilde{\xi}_i$ is a set of state variables other than ξ_i and ξ_{i+1} . On the other hand the dynamic equations of the inner layer ($i = 4$) and those for V_{TAS} are given as

$$\dot{\xi}_4 = F_4(\xi, \delta_T, \tilde{u}), \dot{V}_{TAS} = F_{21}(\xi, \delta_T, \tilde{u}), \quad (15)$$

where $\tilde{u}$ is the set of control variables. This case $\xi_{(i+1)c}, \tilde{u}_c$ and δ_{Tc} are determined from equations [1]

$$\begin{aligned} x_{(i+1)c} &= F^{-1}(x_i, v_i, u, \tilde{x}_i), \\ v_i &= K_i(x_{ic} - x_i), \\ u_c &= f_n^{-1}(x, v_n), \\ v_n &= K_n(x_{nc} - x_n). \end{aligned} \quad (16)$$

One obtains

$$\begin{aligned} \xi_{(i+1)c} &= F^{-1}(\xi_i, u, \tilde{\xi}_i, v_i), v_i = K_i(\xi_{ic} - \xi_i), \\ u_c &= F_4^{-1}(\xi, \delta_T, v_4), v_4 = K_4(\xi_{4c} - \xi_4), \\ \delta_{Tc} &= F_{21}^{-1}(\xi, v_{21}, \tilde{u}), v_{21} = K_{21}(V_{TASc} - V_{TAS}). \end{aligned} \quad (17)$$

Using Taylor series expansions of F_i

$$F_i(\xi_i + \Delta\xi, u + \Delta u) \cong F_i(\xi, u) + \frac{\partial F_i}{\partial \xi} \Delta\xi + \frac{\partial F_i}{\partial u} \Delta u \quad (18)$$

and the first equation (17), one gets

$$\begin{aligned} F_i(\xi_i, \xi_{i+1}, u, \tilde{\xi}_i) + \frac{\partial F_i}{\partial \xi_{i+1}}(\xi_{(i+1)c} - \xi_{i+1}) &= K_i(\xi_{ic} - \xi_i), \\ F_4(\xi, \delta_T, \tilde{u}) + \frac{\partial F_4}{\partial \tilde{u}}(\tilde{u}_c - u) &= K_4(\xi_{4c} - \xi_4), \\ F_{21}(\xi, \delta_T, \tilde{u}) + \frac{\partial F_{21}}{\partial \delta_T}(\delta_{Tc} - \delta_T) &= K_{21}(V_{TASc} - V_{TAS}). \end{aligned} \quad (19)$$

In the above equation the superior order terms have been neglected and that is why the inversion is inexact. Solving equation (19) in rapport with $\xi_{(i+1)c}$, $\tilde{u}_c$ and δ_{Tc} , one gets

$$\begin{aligned} \xi_{(i+1)c} &= \xi_{i+1} - \left(\frac{\partial F_i}{\partial \xi_{i+1}} \right)^{-1} \{ F_i(\xi_i, \xi_{i+1}, u, \tilde{\xi}_i) - K_i(\xi_{ic} - \xi_i) \}, \\ \tilde{u}_c &= \tilde{u} - \left(\frac{\partial F_4}{\partial \tilde{u}} \right)^{-1} \{ F_4(\xi, \delta_T, \tilde{u}) - K_4(\xi_{4c} - \xi_4) \}, \\ \delta_{Tc} &= \delta_T - \left(\frac{\partial F_{21}}{\partial \delta_T} \right)^{-1} \{ F_{21}(\xi, \delta_T, \tilde{u}) - K_{21}(V_{TASc} - V_{TAS}) \}. \end{aligned} \quad (20)$$

IV. AIRCRAFT NUMERICAL APPLICATION OF THE HIERARCHICAL DYNAMIC INVERSION

One considers the longitudinal movement of an aircraft described by equations [1]

$$\begin{aligned} [F_1^{lon} \ F_{21}^{lon} \ F_3^{lon} \ F_4^{lon}]^T &= [\dot{e}_h \ \dot{V}_{TAS} \ \dot{\gamma}_a \ \dot{\theta} \ \dot{Q}]^T, \\ \begin{bmatrix} \dot{e}_h \\ \dot{V}_{TAS} \\ \dot{\gamma}_a \\ \dot{\theta} \\ \dot{Q} \end{bmatrix} &= \begin{bmatrix} a_{11}^{lon} & a_{12}^{lon} & a_{13}^{lon} & a_{14}^{lon} & a_{15}^{lon} \\ a_{21}^{lon} & a_{22}^{lon} & a_{23}^{lon} & a_{24}^{lon} & a_{25}^{lon} \\ a_{31}^{lon} & a_{32}^{lon} & a_{33}^{lon} & a_{34}^{lon} & a_{35}^{lon} \\ a_{41}^{lon} & a_{42}^{lon} & a_{43}^{lon} & a_{44}^{lon} & a_{45}^{lon} \\ a_{51}^{lon} & a_{52}^{lon} & a_{53}^{lon} & a_{54}^{lon} & a_{55}^{lon} \end{bmatrix} \begin{bmatrix} e_h \\ V_{TAS} \\ \gamma_a \\ \theta \\ Q \end{bmatrix} + \begin{bmatrix} b_{11}^{lon} & b_{12}^{lon} \\ b_{21}^{lon} & b_{22}^{lon} \\ b_{31}^{lon} & b_{32}^{lon} \\ b_{41}^{lon} & b_{42}^{lon} \\ b_{51}^{lon} & b_{52}^{lon} \end{bmatrix} \begin{bmatrix} \delta_p \\ \delta_T \end{bmatrix}, \\ \dot{\xi}_{lon} &= A^{lon} \xi_{lon} + B^{lon} u_{lon}. \end{aligned} \quad (21)$$

The matrices A^{lon} and B^{lon} are the ones from the second equation (21). One customizes the relations (20) for variables ξ_i ($i = \overline{1,4}$) defined by equation (13). Thus, for $i = 1$, ξ_{2c} has components ψ_{ac} , γ_{ac} and V_{TASc}

$$\xi_{2c}^{lon} = \gamma_{ac} = \gamma_a - \left(\frac{\partial F_1^{lon}}{\partial \gamma_a} \right)^{-1} [F_1^{lon}(\xi_1, \xi_2, u, \tilde{\xi}_1) - v_1^{lon}], \quad (22)$$

where F_1^{lon} verifies equation (14) for $i = 1$; using (21), one obtains

$$\begin{aligned} \dot{e}_h &= F_1^{lon}(V_{TAS}, \gamma_a) = a_{11}^{lon} e_h + a_{12}^{lon} V_{TAS} + \\ &+ a_{13}^{lon} \gamma_a + a_{14}^{lon} \theta + a_{15}^{lon} Q + b_{11}^{lon} \delta_p + b_{12}^{lon} \delta_T \end{aligned} \quad (23)$$

and

$$\begin{aligned} \gamma_{ac} &= -(a_{13}^{lon})^{-1} (a_{11}^{lon} e_h + a_{12}^{lon} V_{TAS} + a_{14}^{lon} \theta + a_{15}^{lon} Q) - \\ &- (a_{13}^{lon})^{-1} [b_{11}^{lon} \delta_p + b_{12}^{lon} \delta_T - K_1^{lon}(e_{hc} - e_h)]. \end{aligned} \quad (24)$$

For $i = 2$ one yields [1]

$$\begin{aligned} \theta_c &= -(a_{34}^{lon})^{-1} (a_{31}^{lon} e_h + a_{32}^{lon} V_{TAS} + a_{33}^{lon} \gamma_a + a_{35}^{lon} Q) - \\ &- (a_{34}^{lon})^{-1} [b_{31}^{lon} \delta_p + b_{32}^{lon} \delta_T - K_2^{lon}(\gamma_{ac} - \gamma_a)] \end{aligned} \quad (25)$$

and for $i = 3$ one gets

$$\begin{aligned} Q_c &= -(a_{45}^{lon})^{-1} (a_{41}^{lon} e_h + a_{42}^{lon} V_{TAS} + a_{43}^{lon} \gamma_a + a_{44}^{lon} \theta) - \\ &- (a_{45}^{lon})^{-1} [b_{41}^{lon} \delta_p + b_{42}^{lon} \delta_T - K_3^{lon}(\theta_c - \theta)] \end{aligned} \quad (26)$$

and

$$\begin{aligned} F_3^{lon} = \dot{\theta} &= a_{41}^{lon} e_h + a_{42}^{lon} V_{TAS} + a_{43}^{lon} \gamma_a + a_{44}^{lon} \theta + \\ &+ a_{45}^{lon} Q + b_{41}^{lon} \delta_p + b_{42}^{lon} \delta_T. \end{aligned} \quad (27)$$

To calculate $\tilde{u}_c$ the authors use second equation (20), taking into account that $\tilde{u} = [\delta_e \ \delta_p \ \delta_a]^T$. Thus, for the longitudinal movement of the aircrafts, one obtains

$$\begin{aligned} F_4^{lon} = \dot{Q} &= a_{51}^{lon} e_h + a_{52}^{lon} V_{TAS} + a_{53}^{lon} \gamma_a + a_{54}^{lon} \theta + \\ &+ a_{55}^{lon} Q + b_{51}^{lon} \delta_p + b_{52}^{lon} \delta_T, \end{aligned} \quad (28)$$

$$\begin{aligned} \tilde{u}_c^{lon} = \delta_{pc} &= \delta_p - (b_{51}^{lon})^{-1} (a_{51}^{lon} e_h + a_{52}^{lon} V_{TAS} + a_{53}^{lon} \gamma_a) - \\ &- (b_{51}^{lon})^{-1} (a_{54}^{lon} \theta + a_{55}^{lon} Q + b_{51}^{lon} \delta_p + b_{52}^{lon} \delta_T - v_4^{lon}), \end{aligned} \quad (29)$$

$$\begin{aligned} \delta_{pc} &= -(b_{51}^{lon})^{-1} (a_{51}^{lon} e_h + a_{52}^{lon} V_{TAS} + a_{53}^{lon} \gamma_a + a_{54}^{lon} \theta) - \\ &- (b_{51}^{lon})^{-1} [a_{55}^{lon} Q + b_{52}^{lon} \delta_T - K_4^{lon}(Q_c - Q)]. \end{aligned} \quad (30)$$

In order to calculate δ_{Tc} one uses the third relation (20). First, F_{21} from equation (21) must be determined

$$\begin{aligned} F_{21} = \dot{V}_{TAS} &= a_{21}^{lon} e_h + a_{22}^{lon} V_{TAS} + a_{23}^{lon} \gamma_a + \\ &+ a_{24}^{lon} \theta + a_{25}^{lon} Q + b_{21}^{lon} \delta_p + b_{22}^{lon} \delta_T, \end{aligned} \quad (31)$$

$$\begin{aligned} \delta_{Tc} &= -(b_{22}^{lon})^{-1} (a_{21}^{lon} e_h + a_{22}^{lon} V_{TAS} + a_{23}^{lon} \gamma_a + a_{24}^{lon} \theta) - \\ &- (b_{22}^{lon})^{-1} [a_{25}^{lon} Q + b_{21}^{lon} \delta_p - K_{21}^{lon}(V_{TASc} - V_{TAS})]. \end{aligned} \quad (32)$$

In general, feedback gains of exterior loop should be smaller than those in the inner loop. As the gains ratio between inner and outer loop is smaller, interference have less effect and stability is increased in expense of performance. Therefore the most efficient gain ratio between inner and outer loop is approximately 0.3 to 0.4 [1]. The authors of this paper have increased this ratio to 0.6. This way they increased the stability of the aircraft and its dynamic characteristics. Thus, the loop's gains are

$$\begin{aligned} K_1^{lon} &= (0.6^3) \cdot 1.3 \cdot \pi, \\ K_2^{lon} &= (0.6^2) \cdot 1.3 \cdot \pi, \\ K_3^{lon} &= (0.6^1) \cdot 1.3 \cdot \pi, \\ K_4^{lon} &= (0.6^0) \cdot 1.3 \cdot \pi. \end{aligned} \quad (33)$$

In order to apply the liniarised system obtained in the previous section, one uses an ALFLEX aircraft model presented in [1]. In fig. 2 the one presents the block diagram that models equations (21), (24), (25), (26), (29) and (32), associated to the longitudinal movement of aircrafts.

Based on this block diagram one obtains the Matlab/ Simulink model of longitudinal motion (fig. 3) and will obtains conclusions about the reliability and performance of the control method presented in this paper.

The Matlab/Simulink model from fig. 3 has three subsystems: Eq. (25), Eq. (29) and Eq. (32). In figures 4 - 6 one presents their Matlab/Simulink models.

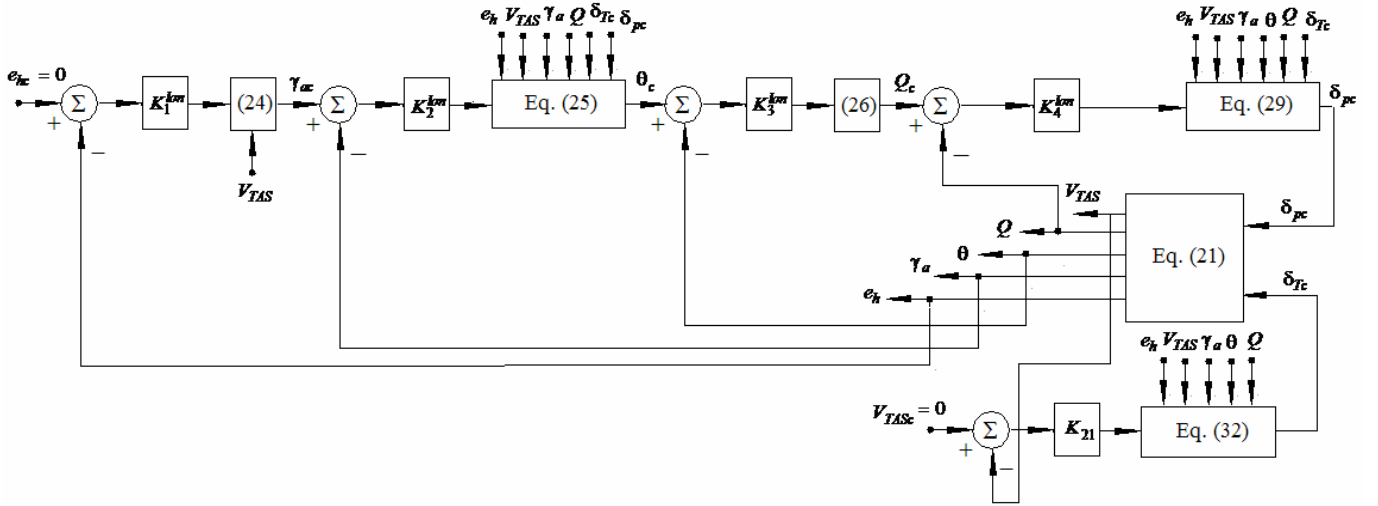


Fig. 2 Block diagram of the system

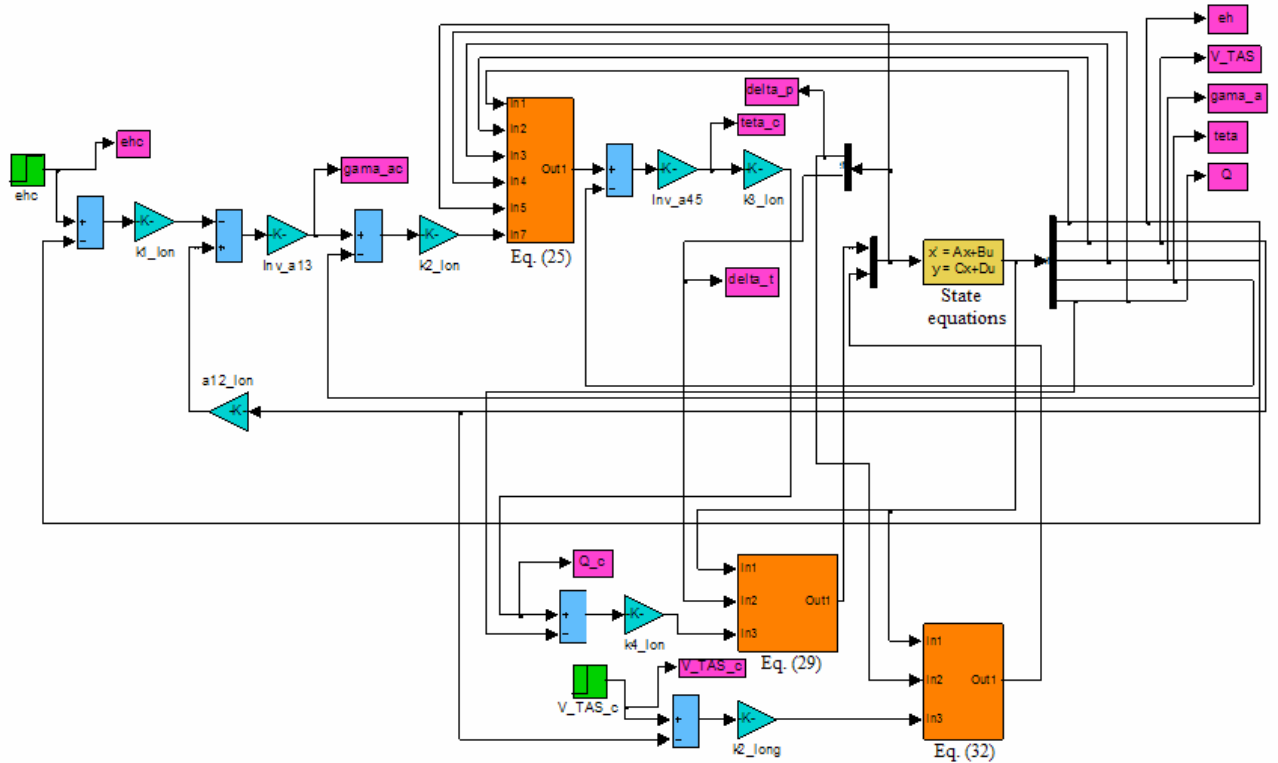


Fig. 3 Matlab/Simulink model of the block diagram from fig. 2

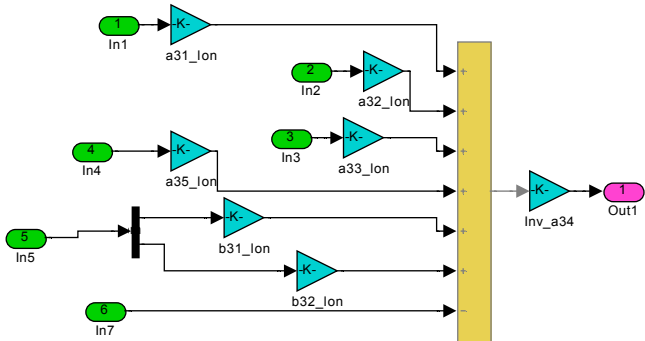


Fig. 4 Matlab/Simulink model of the subsystem Eq.(25)

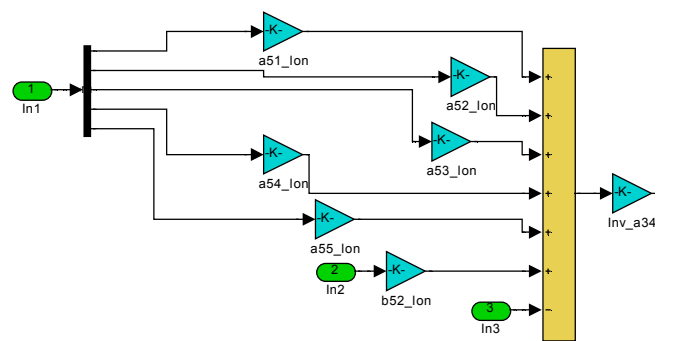


Fig. 5 Matlab/Simulink model of the subsystem Eq.(29)

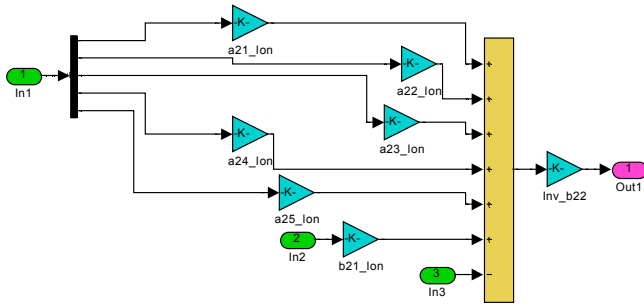


Fig. 6 Matlab/Simulink model of the subsystem Eq.(32)

Next, using data for the longitudinal motion, one obtains graphic characteristics representing time variations of the longitudinal error (fig. 7), air real speed (fig. 8), angle between trajectory and air current (fig. 9), pitch angle (fig. 10), pitch angular velocity (fig. 11), rudder deflection (fig. 12) and spoiler deflection (fig. 13). In figures 9, 10 and 11 the command variable is represented with red dashed line while the variable is represented with blue continuous line.

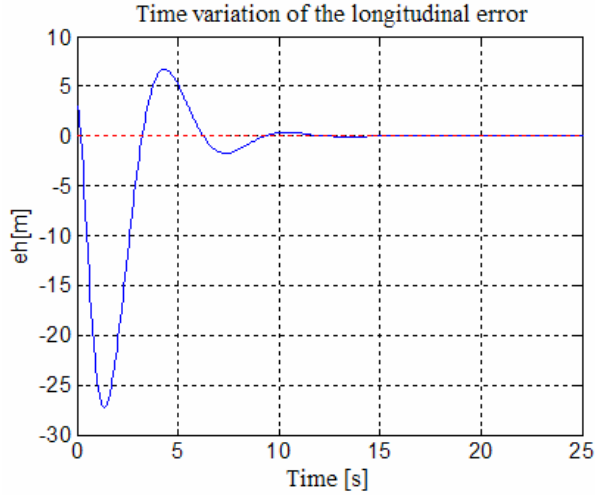


Fig. 7 Time variation of the longitudinal error

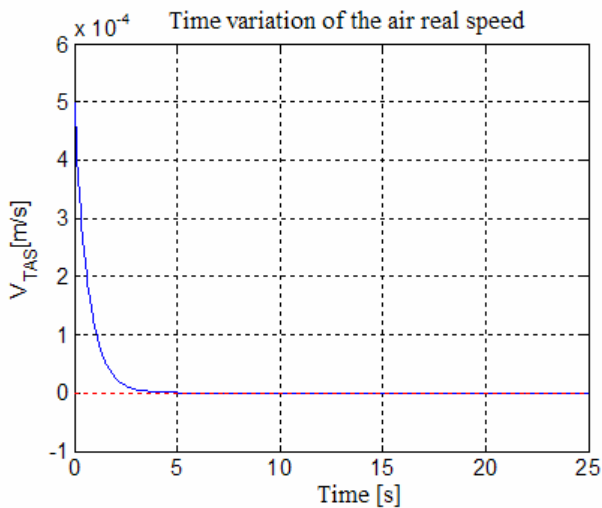


Fig. 8 Time variation of the air real speed

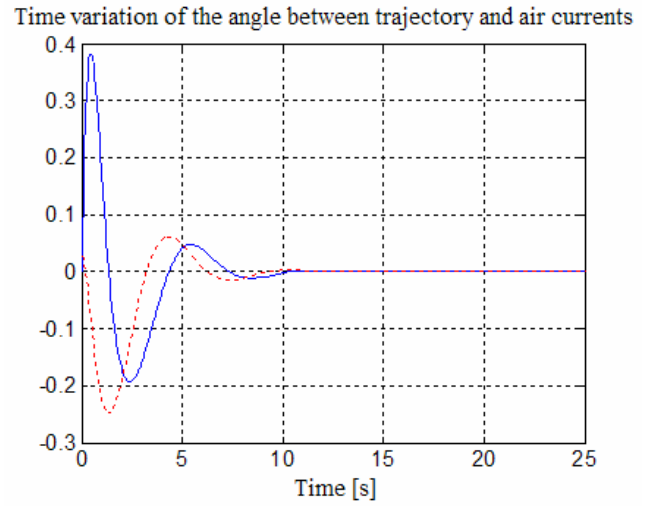


Fig. 9 Time variation of the angle between trajectory and air currents

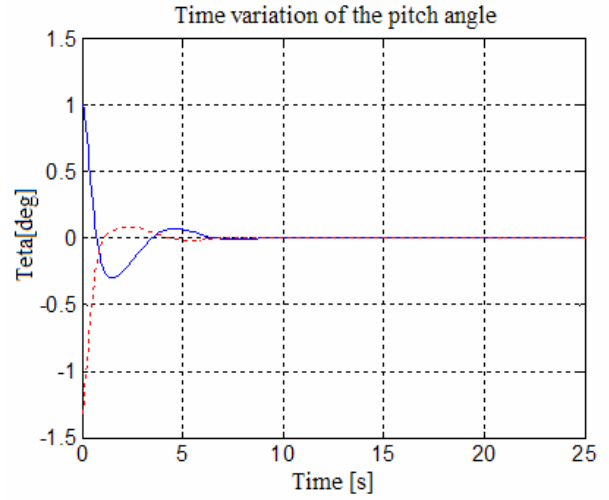


Fig. 10 Time variation of the pitch angle

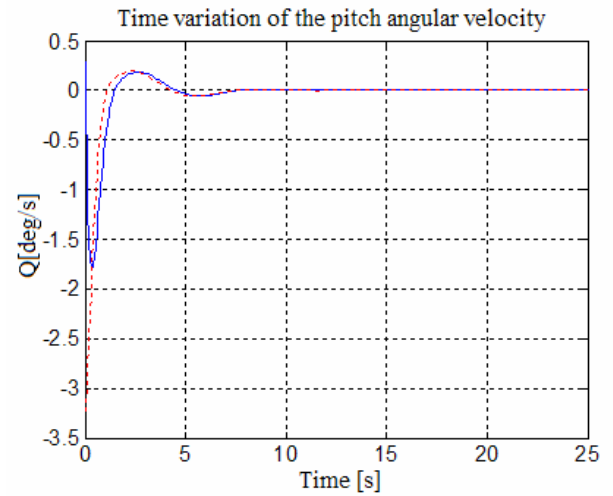


Fig. 11 Time variation of the pitch angular velocity

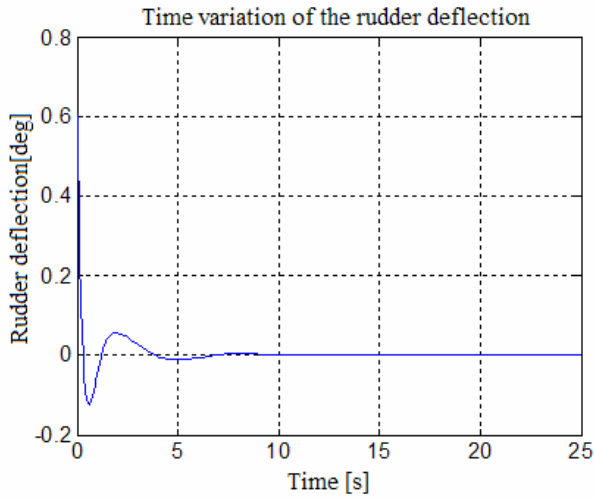


Fig. 12 Time variation of the rudder deflection

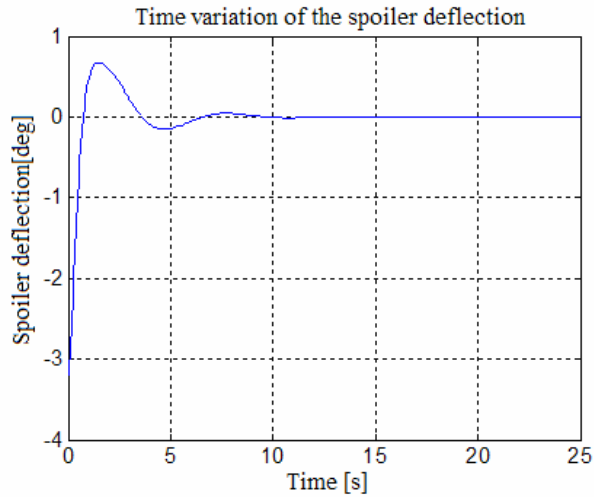


Fig. 13 Time variation of the spoiler deflection

For the simulation one has used the following matrices

$$A^{lon} = \begin{bmatrix} 0 & -0.0392 & -96.907 & 0 & 0 \\ -4.491 \cdot 10^{-5} & -1.0941 & -1.130 & -7.525 & -7.212 \cdot 10^{-6} \\ 9.838 \cdot 10^{-6} & 0.00243 & -1.323 & 1.268 & 4.174 \cdot 10^{-7} \\ 0 & 0 & 0 & 0 & 1 \\ -1.912 \cdot 10^{-7} & -1.037 \cdot 10^{-4} & -1.459 & 1.459 & -1.130 \end{bmatrix},$$

$$B^{lon} = \begin{bmatrix} 0 & 0 \\ -4.596 & -3.216 \\ 0.376 & -0.068 \\ 0 & 0 \\ -14.536 & 2.106 \end{bmatrix}.$$

V. CONCLUSION

The paper presents a methodology for the flight control law's design for the trajectory pursuit using hierarchical dynamic inversion; this is based on separation of multi-time-scale and multi-loop closing method. The authors made the analysis of the longitudinal movement of aircrafts and obtained graphic characteristics which demonstrate the effectiveness of the proposed method.

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REFERENCES

- [1] A. Fujimori, F. Terui, P. Nikiforuk, "Flight Control Design of an Unmanned Space Vehicle using Gain Scheduling", *Journal of Guidance, Control and Dynamics*, January 2005.
- [2] D. Enns, D. Bugajski, R. Hendrick, G. Stein, "Dynamic inversion: an evolving methodology for flight control design", *International Journal of control*, Vol. 59, No. 1, 1994, pp. 71-91.
- [3] A. Nagash, D. Enns, "Precision Approach With Curved Flight Path and Accurate Time of Arrival", *Proceedings of the AIAA Guidance, Navigation and Control Conference*, AIAA Paper 98-4207, Boston, August, 1998, pp. 1217-1223.
- [4] D. J. Bugajski, D. Enns, "Nonlinear Control Law with Application to High Angle-of-Attack Flight", *Journal of Guidance, Control and Dynamics*, Vol. 15, No. 3, 1992, pp. 761-777.
- [5] R. Da Costa, Q. P. Chu, J. A. Mulder, "Re-entry Flight Controller Design Using Nonlinear Dynamic Inversion Controller", *Journal of Guidance and Rockets*, Vol. 40, No. 1, 2003, pp. 29-37.
- [6] G. Looye, H. D. Joos, "Design of Robust Dynamic Inversion Control Laws using Multi-Objective Optimization", *Proceedings of the AIAA Guidance, Navigation and Control Conference*, AIAA-2001-4285, May 5, 2001.
- [7] C. Teisanu, M. Calbureanu, "Sintering parameters influences on the iron base self-lubricating bearing porosity", *International Conference on Materials Science and Engineering Bramat 2003, Brasov*, vol. I, pp. 158-163.