

# Application of Two-Time Scale Method in Missile Autopilot Design

Payam Rezaie Moghaddam<sup>1</sup>, Hassan Zarabadipour<sup>2</sup>

<sup>1</sup> ME Department, Islamic Azad University, Takestan Branch, Qazvin, Iran

<sup>2</sup> ME Department, Islamic Azad University, Takestan Branch, Qazvin, Iran  
(<sup>1</sup>me@asis.ir, <sup>2</sup>h\_zarabadi@ikiu.ac.ir)

**Abstract-** In this paper two-time scale method is used to control an 8-DOF missile autopilot. The mathematical model is developed using the singular perturbation theory. Structural properties of the system in terms of the slow and fast subsystems are established. An asymptotically optimal two-time scale controller was developed for missile. The two-time scale controller was compared to the optimal controller, and it was demonstrated that there is negligible degradation in performance.

**Keywords-** Missile autopilot; Singular perturbation; Two-Time-Scale; Kalman filter; optimal control.

## I. INTRODUCTION

Over the years a number of authors have considered modeling, analysis and design of autopilots for atmospheric flight vehicles including guided missiles. In the majority of the published work on autopilot analysis and design, locally linearized versions of the model with decoupled airframe dynamics have been considered. This latter simplification arises out of the assumption that the airframe and its mass distribution are symmetrical about the body axes and that the yaw, pitch and roll motion about the equilibrium state, remain "small".

As a result, most of the autopilot analysis and design techniques, considered in open literature, use classical control approach, such as single input-single output transfer functions characterization of the system dynamics and bode, nyquist, root-locus and transient response analysis and synthesis techniques. These techniques are valid to cover a wider set of flight regimes and an airframe configuration requires autopilot design.

With the advent of fast processor it is now possible to take a more integrated approach to autopilot design. Modern optimal control techniques allow the designer to consider autopilots with high order dynamics (large number of states) with multiple inputs/outputs and to synthesis controllers such that the error between the demanded and the achieved output is minimized.

## II. GENERAL MISSILE 8-DOF MODEL

It is often the case in control systems design that while the concept are valid for any system order, their actual application is restricted to lower order system models. This is because higher order system model design may require excessive computation. Such prohibitively high system order can be caused by the presence of small "parasitic" parameters, typically small time constants, masses, etc.

Several approaches exist at present to reduce the system order, such as retaining dominant modes or neglecting fast modes. In singular perturbation method, both slow and fast system modes are retained while control system analysis and design may be solved in two separate parts, one for the slow modes and the other for the fast.

The objective is to approximate the performance of the original system through the analysis and design of the slow and fast mode subsystems with separate time-scales. By approximating the system with its slow and fast modes, both the high dimensionality and stiffness difficulties of the original singularly perturbed system are alleviated while retaining, in some sense, an approximation to the original system performance.

We can define three airframe axes for a missile like shown in Fig. 1.

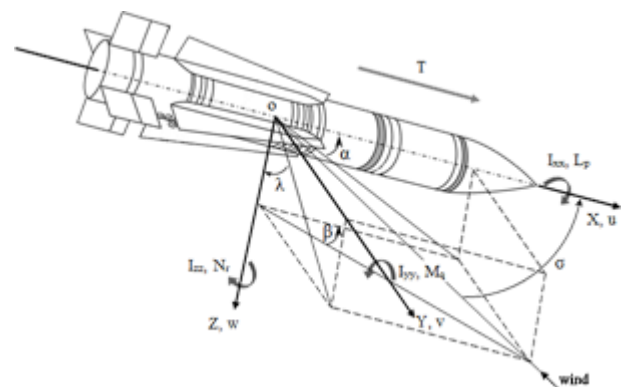


Fig. 1: Missile Body axes

If  $\alpha$  and  $\beta$  equals to angle of attack and slide slip angle of missile:

$$\tan \alpha = \frac{w}{u} \quad (1)$$

$$\sin \beta = \frac{u}{V} \quad (2)$$

And assume that they are small, by using Newton and Euler Equations in composition with (1) and (2), 8 DOF model of a missile can be written as:

$$\dot{\alpha} = -p\beta + q - \frac{q_d S}{mV} (C_{N\alpha} \alpha + C_{N\delta_e} \delta_e) \quad (3)$$

$$\dot{\beta} = p\alpha - r - \frac{q_d S}{mV} (C_{C\beta} \beta + C_{C\delta_r} \delta_r) \quad (4)$$

$$\dot{p} = qr \frac{I_y - I_z}{I_x} + \frac{q_d S d}{I_x} (C_{l\beta} \beta + C_{l_p} \frac{d}{2V} p + C_{l\delta_a} \delta_a) \quad (5)$$

$$\dot{q} = pr \frac{I_z - I_x}{I_y} + \frac{q_d S d}{I_y} (C_{m\alpha} \alpha + C_{m|\beta|} |\beta| + C_{mq} \frac{d}{2V} q + C_{m\delta_e} \delta_e) \quad (6)$$

$$\dot{r} = pq \frac{I_x - I_y}{I_z} + \frac{q_d S d}{I_z} (C_{n\beta} \beta + C_{n\alpha\beta} \alpha\beta + C_{nr} \frac{d}{2V} r + C_{n\delta_a} \delta_a + C_{n\delta_r} \delta_r) \quad (7)$$

$$\dot{u} = -\frac{q_d S}{m} (a_{c_\alpha} + a_{c_\alpha} |\alpha| + a_{c_\beta} |\beta| + a_{c_\alpha} |\alpha\beta| + a_{c_\alpha} |\delta_q| + a_{c_\alpha} |\delta_r| + a_{c_\alpha} |\delta_p| + a_{c_\alpha} \delta_q^2 + a_{c_\alpha} \delta_r^2 + a_{c_\alpha} |\delta_r \delta_q|) - wq + vr + \frac{F_{xg}}{m} \quad (8)$$

$$\dot{v} = \frac{q_d S}{m} (a_{c_y} \alpha + a_{c_y} \beta + a_{c_y} \alpha^3 + a_{c_y} \beta^3 + a_{c_y} \delta_q + a_{c_y} \delta_r + a_{c_y} \delta_p) - ur + wp + \frac{F_{yq}}{m} \quad (9)$$

$$\dot{w} = -\frac{q_d S}{m} (a_{c_n} \alpha + a_{c_n} \beta + a_{c_n} \alpha^3 + a_{c_n} \beta^3 + a_{c_n} \delta_q + a_{c_n} \delta_r + a_{c_n} \delta_p) - vp + uq + \frac{F_{zg}}{m} \quad (10)$$

In these equations; U, V, W are the velocity components measured in the missile body axis. P, Q, R are the components of the body rotational rate.  $F_{xg}$ ,  $F_{yg}$ ,  $F_{zg}$  are the gravitational forces acting along the body axis and  $I_x$ ,  $I_y$ ,  $I_z$  are the missile moments of inertia. Also the aerodynamic force and moment coefficients are described in a polynomial form with respect to angle of attack  $\alpha$ , angle of slideslip  $\beta$ , pitch fin deflection  $\delta_Q$ , yaw fin deflection  $\delta_R$  and the roll fin deflection  $\delta_P$ . The coefficients of the polynomials describing the aerodynamic coefficients were derived by carrying out least squares fits on the aerodynamic data [4]. The variable S is the reference area and l is the reference length. For a regular missile  $V_T$ , Mach number M and dynamic pressure q are defined as:

$$V_T = \sqrt{U^2 + V^2 + W^2} \quad (11)$$

$$M = \frac{V_T}{a} \quad (12)$$

$$\bar{q} = \frac{1}{2} \rho V_T^2 \quad (13)$$

After linearizing these equations and adapting to state space form, the state vector and the control vector are chosen to be:

$$x = [\alpha \ \beta \ p \ q \ r \ u \ v \ w]^T \quad (14)$$

$$u = [\delta_Q \ \delta_R \ \delta_P]^T \quad (15)$$

### III. STANDARD LQG DESIGN

The Kalman filter gain matrix K is given by [13]:

$$K = P_e C^T V^{-1} \quad (16)$$

$$AP_e + P_e AP_e C^T V^{-1} CP_e + LWL^T = 0 \quad (17)$$

The optimal state-feedback gain matrix G is given by:

$$G = -R^{-1} B^T P_c \quad (18)$$

Where  $P_c$  satisfies the following algebraic Riccati equation:

$$PA + A^T P - (PB + N)R^{-1} (B^T P + N^T) = -Q \quad (19)$$

So optimal control of the system with the cost function will take the form:

$$U = G\hat{X} \quad (20)$$

Where the estimated states are obtained from Kalman filter.

### IV. LQG DESIGN USING TWO-TIME SCALE METHOD

In Two-Time Scale method, the dynamics of a system is comprised of two separate sets of fluctuating modes. One set of

modes are the slow dynamics, denoted by  $\lambda_s$ , and another set is the fast dynamics that denoted by  $\lambda_f$ .

Without loss of generality, the ratio of:

$$\left| \lambda_s \right|_{\max} / \left| \lambda_f \right|_{\min}$$

is taken as the approximate value of the singular perturbation parameter  $\varepsilon$  given by:

$$\varepsilon \cong \left| \lambda_s \right|_{\max} / \left| \lambda_f \right|_{\min} \quad (21)$$

In order to use two-time scale property of the system, state space equations are partitioned as:

$$\dot{X} = A_{11}X + A_{12}Z + B_1U + L_1W \quad (22)$$

$$\dot{Z} = \hat{A}_{21}X + \hat{A}_{22}Z + \hat{B}_2U + \hat{L}_2W \quad (23)$$

$$Y = C_1X + C_2Z + v \quad (24)$$

Where

$$X = (x_1 \ x_2 \ x_3 \ x_4 \ x_5 \ x_6)^T \quad (25)$$

$$Z = (x_7 \ x_8)^T \quad (26)$$

The standard singular perturbation form of (22) and (23) is then given by:

$$\dot{X} = A_{11}X + A_{12}Z + B_1U + L_1W \quad (27)$$

$$\varepsilon \dot{Z} = A_{21}X + A_{22}Z + B_2U + L_2W \quad (28)$$

Where

$$\hat{A}_{21} = \frac{A_{21}}{\varepsilon}, \hat{A}_{22} = \frac{A_{22}}{\varepsilon}, \hat{B}_2 = \frac{B_2}{\varepsilon}, \hat{L}_2 = \frac{L_2}{\varepsilon} \quad (29)$$

And  $\varepsilon$  is the singular perturbation parameter. Applying the standard singular perturbation approach to decouple the slow-fast subsystems, the slow and the fast dynamics is obtained [1].

#### A. The Slow Subsystem

$$\dot{X}_s = A_s X_s + B_s U_s + L_s W \quad (30)$$

$$Y_s = C_s X_s + D_s U_s + E_s W + v \quad (31)$$

$$X_s(0) = X^0 \quad (32)$$

$$A_s = A_{11} - A_{12}A_{22}^{-1}A_{21} \quad (33)$$

$$B_s = B_1 - A_{12}A_{22}^{-1}B_2 \quad (34)$$

$$L_s = L_1 - A_{12}A_{22}^{-1}L_2 \quad (35)$$

$$C_s = C_1 - C_2A_{22}^{-1}A_{21} \quad (36)$$

$$D_s = -C_2A_{22}^{-1}B_2 \quad (37)$$

$$E_s = -C_2A_{22}^{-1}L_2 \quad (38)$$

The performance index  $J_s$  associated with slow subsystem is defined:

$$J_s = E \left\{ \frac{1}{2} \int_0^{\infty} \left\{ X_s^T Q_s X_s + X_s^T N U_s + U_s^T R_s U_s \right\} dt \right\} \quad (39)$$

The control signal for the slow subsystem is:

$$U_s = G_s \hat{X}_s \quad (40)$$

Where  $\hat{X}_s$  is the optimal estimated slow state  $X_s$  provided by the slow Kalman filter:

$$\dot{\hat{X}}_s = A_s \hat{X}_s + B_s U_s + L_s [Y - D_s U_s - C_s \hat{X}_s] \quad (41)$$

The filter gain  $L_s$  is:

$$L_s = (P_s C_s^T + L_s E_s^T) V_s^{-1} \quad (42)$$

And  $P_s$  is the stabilizing solution of the slow algebraic Riccati equation:

$$\begin{aligned} [A_s - L_s E_s^T V_s^{-1} C_s] P_s + P_s [A_s - L_s E_s^T V_s^{-1} C_s]^T \\ + L_s [I - E_s^T V_s^{-1} E_s] L_s^T - P_s C_s^T V_s^{-1} C_s P_s = 0 \end{aligned} \quad (43)$$

Where

$$V_s = V + E_s E_s^T \quad (44)$$

#### B. The Fast Subsystem

$$\varepsilon \dot{Z}_f = \hat{A}_{22} Z_f + \hat{B}_2 U_f + \hat{L}_2 W \quad (45)$$

The performance index  $J_f$  is:

$$J_f = E \left\{ \frac{1}{2} \int_0^{\infty} \left\{ Z_f^T Q Z_f + Z_f^T N U_f + U_f^T R U_f \right\} dt \right\} \quad (46)$$

The feedback control signal for fast sub-system is given by:

$$U_f = G_f \hat{Z}_f \quad (47)$$

Where  $\hat{Z}_f$  is the optimal estimated fast state ( $Z_f$ ), provided by the fast Kalman filter:

$$\varepsilon \dot{\hat{Z}}_f = \hat{A}_{22} \hat{Z}_f + \hat{B}_2 U_f + L_f [Y_f - C_2 \hat{Z}_f] \quad (48)$$

The filter gain  $L_f$  is:

$$L_f = P_f C_2^T V^{-1} \quad (49)$$

And  $P_f$  is the stabilizing solution of the fast algebraic Riccati equation

$$A_{22} P_f + P_f A_{22}^T + L_2 W L_2^T - P_f C_2^T V^{-1} C_2 P_f = 0 \quad (50)$$

The composite control signal is the sum of the slow and fast control signals

$$U_c = U_s + U_f = G_s \hat{X}_s + G_f \hat{Z}_f \quad (51)$$

If  $U_c$  applied to the system the resulting performance index  $J_c$  is near optimal in the sense

$$J_c = J_s + J_f = J_o \quad (52)$$

Where  $J_o$  is the optimal value of the performance index.

## V. APPLICATION ON A MISSILE AUTOPILOT

The slow-fast controller design presented in section 4 is now applied to the missile autopilot model in section 2. The A, B and C matrices of missile state space model and consonant matrices Q and R of cost function are given bellow.

$$Q = \text{diag}([100, 100, 100, 0, 1e-8, 1e-8, 2e1, 2e16]) \quad (52)$$

$$R = 1e10 \times \text{diag}([1, 1, 1]) \quad (53)$$

$$A = \begin{bmatrix} -1.3220 & 0.0640 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & -1.89 & 0 & 0 & 0 & 0 & 0 & -1 \\ 0 & 0 & -2.6784 & 0.6646 & -0.7333 & 0.1315 & 0 & 0 \\ 0 & 0 & -0.0254 & -2.4764 & -0.0319 & -0.0620 & 0 & 0 \\ 0 & 0 & 0 & -1.2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -20.2257 & 0 & 0 & 0 \\ 0 & 0 & 0 & 57.2958 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -20.2256 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & -1.758 & 0 \\ 0 & 0 & -0.6 \\ 1 & 1 & 0 \\ 0 & -5 & 0 \\ -10 & 2 & 0 \\ 0 & -10 & 2 \\ -1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \quad C = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & -2.457 & 0 & 0 & 8 & 0 \\ 0 & 0 & 0 & 1.5795 & 0 & -1.5 & -2.4 & 0 \\ 1 & 0 & 0 & 0.3787 & 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & -0.11 & 0 & 0 & 6.89 & 0 \\ 0 & 0 & 1 & 4.78 & 0 & 0 & -2.3688 & 0 \end{bmatrix}$$

In order to observe the performance of each of the above controllers in the presence of external disturbances, a command is considered. Such a particular disturbance simulates both the slow and the fast modes in the system. In addition, a white noise signal with a power spectral density has been selected as a disturbance signal to model the missile motor vibrations.

The outputs are important in LQG controller design, since in such a design, by using the optimal estimator, the measurable output must provide a good and proper estimate for the modes (x1, x2, x3, x4). Computing the controller gain matrix (20) for the standard LQG design, we get:

$$L_k = [4.2354, 0.1553, 0, 0, -1.2186, 11.2196; \\ 0, -0.7523, 0, -21.1891, 0, 0; \\ 0, 10.1584, 0, 0, 0.9421, 2.8854; \\ -15.1457, 4.4423, 0, 4.7126, 0.0814, -8.7309; \\ -9.0842, 0.1823, 0, 6.5025, 17.5508, -8.1795; \\ 7.5104, 0, 3.6033, 0, 0, -1.1214; \\ 0, 0, 0.2865, -17.6435, 5.9048, 0.7746; \\ 14.3092, 18.4517, 0, 0.4906, -7.8261, 9.3928]$$

In order to apply the singular perturbation theory, first, let's check the two-time-scale property of the system. The singular perturbation parameter  $\varepsilon$  is computed:

$$|\lambda_s|_{\max} / |\lambda_f|_{\min} \cong 0.1365 \quad (54)$$

The calculations of the controller gains matrices using the singular perturbation theory for both the slow and the fast subsystems result in the following:

$$L_{k_s} = [-12.2616, 5.2442, 1.2827, -3.9372, 0.4383, 7.3291; \\ 8.6779, 3.5593, 14.4463, -8.2021, 0, 0.4739; \\ 0.3609, -10.1870, -1.9327, 5.5115, 19.8197, -0.0885; \\ 1.5661, 13.2775, 0, 1.4807, 3.9281, 15.0304; \\ 10.9428, 2.0483, 1.6014, 9.8064, 0.4126, -11.6858; \\ -5.0124, 4.4812, 2.9671, 0.4581, 11.1611, 0.5003]$$

$$L_{k_f} = [-6.7189, 12.6661, 0.0322, 1.2769, 8.0741, 2.5609; \\ 3.3590, 0.4014, 17.8586, 2.3510, -13.7015, 0.9777] \quad (56)$$

Design of the controller using the two-time scale method entails cost increase that is negligible, and clearly justifies the utilization of this approach. The simulation results of both design approaches are compared graphically. Fig. 2 shows the real and estimated states of full order missile autopilot, and fig. 3 shows the real and estimated states of reduced order system using two-time scale method, also fig. 4 to fig. 11 shows response of both systems that is too close to each other separately and shows the efficiency of this work.

Although we use an 8 degree of freedom missile model in this work, but using two-time scale method for expanded problem with further dimensions can give better and greater advantages.

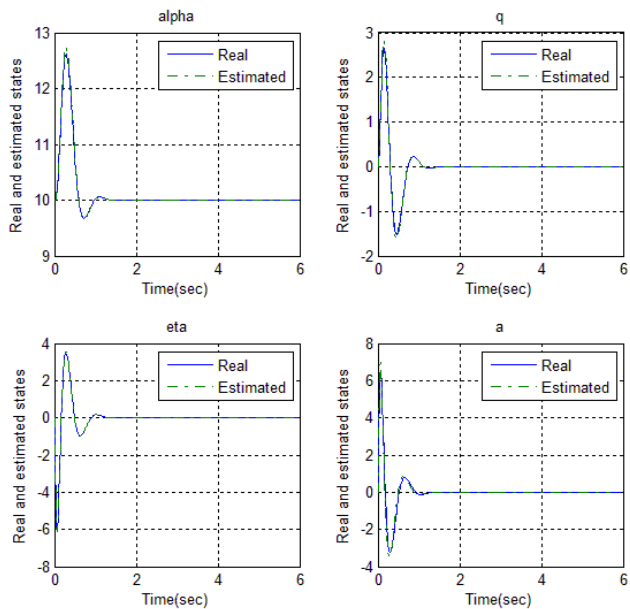


Fig. 2: Real and estimated (full order)

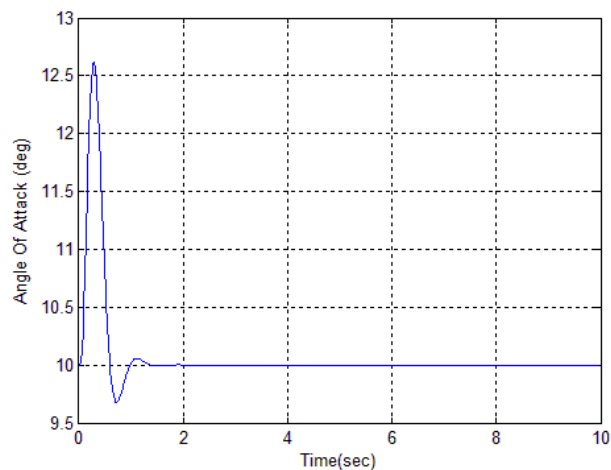


Fig 4: Angle of attack response (full order)

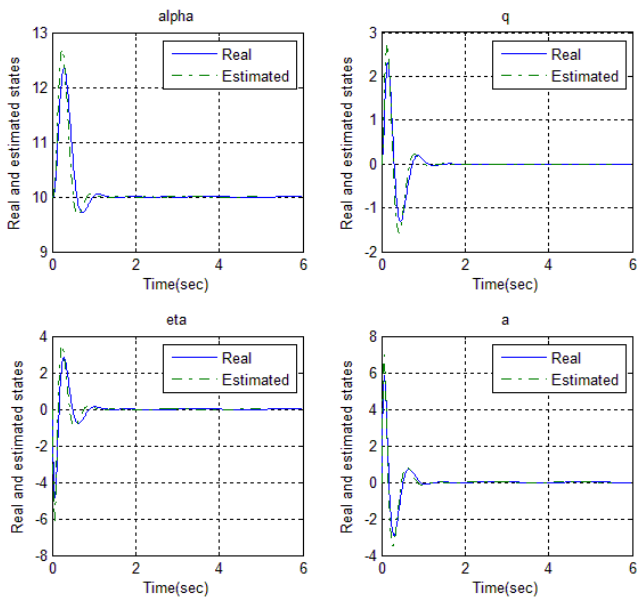


Fig 3: Real and estimated (reduced order)

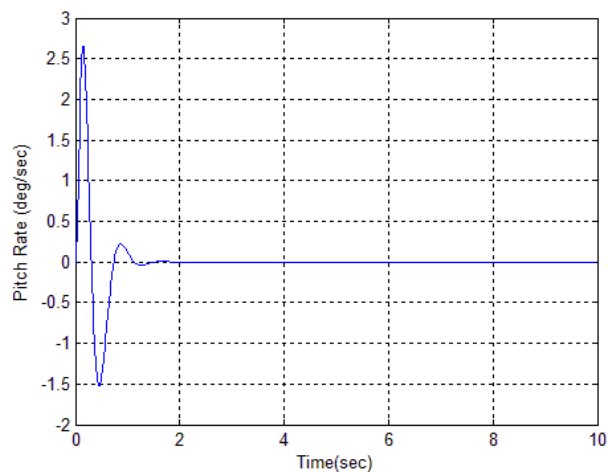


Fig 5: Pitch rate (full order)

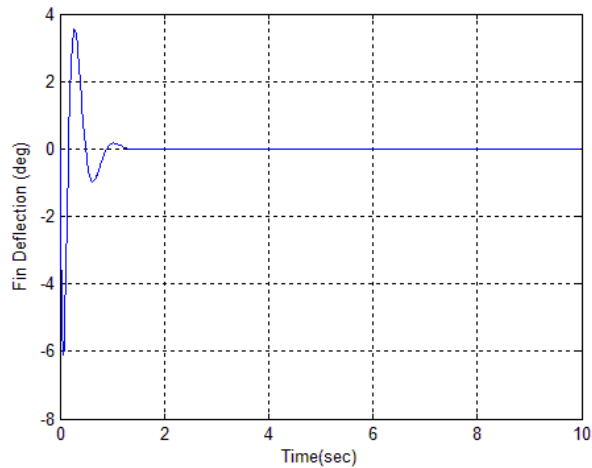


Fig 6: Fin deflection (full order)

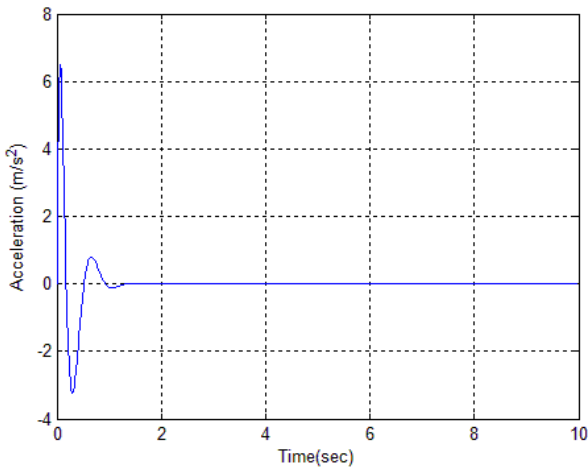


Fig 7: Acceleration (full order)

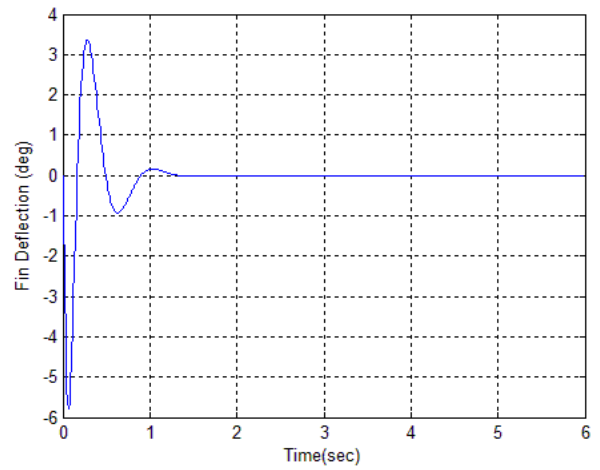


Fig 10: Fin deflection (reduced order)

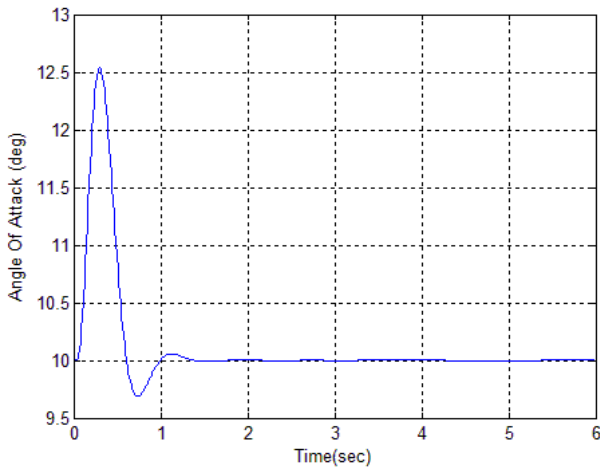


Fig 8: Angle of attack (reduced order)

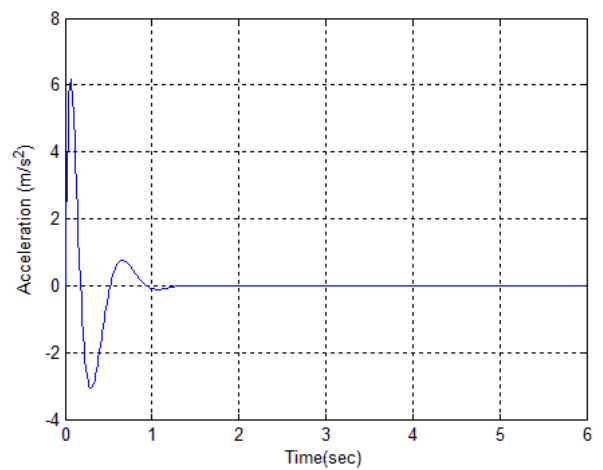


Fig 11: Acceleration (reduced order)

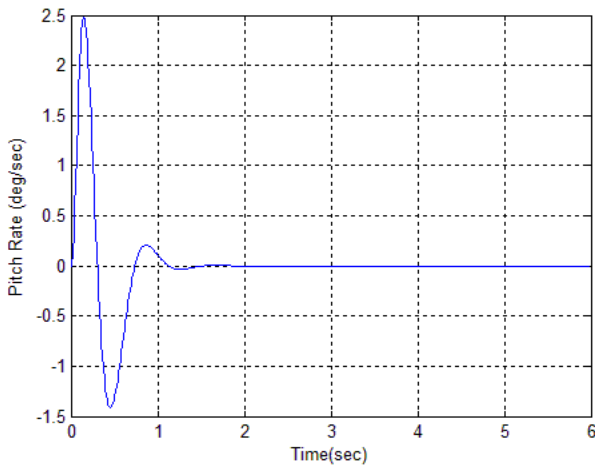


Fig 9: Pitch rate (reduced order)

## VI. CONCLUSION

The model of a missile autopilot can be put in two-time scale form to design LQG controller. The responses were concluding by using observer with good match between full and reduced systems. In spite of the simplified structure of these strategies, the resulting missile autopilot performance is comparable to the performance with the full order feedback design.

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**Payam Rezaie Moghaddam**

He received B.Sc. degree in Mechanical Eng. from Azad University of Tabriz, Iran in 2009 and his M.Sc. degree of Mechanical Eng. from Azad University of Takestan, Qazvin, Iran. His research interests are in the areas of Dynamical Systems, Control and Robotics, Aeronautics and Military Robots. He is currently research and development

administrator at Cybernet Security Systems.



**Hassan Zarabadipour**

Ph.D., from Wichita State University, Wichita, Kansas, USA. His research interests include Optimal Control, Singular Perturbation, Large Scale Systems, Stochastic Control and Game Theory. Now he is Assistant Professor at Electrical Engineering Department of Imam Khomeini International University.