Nonlinear Adaptive Control for Hypersonic Vehicle at Subsonic Speeds

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ABSTRACT

- Hypersonic vehicles are complex nonlinear systems with uncertain dynamics. This work presents a robust nonlinear adaptive (NA) control system for the operation of these vehicles at subsonic speeds. In this work, we only consider lateral dynamics with a fixed roll angle (five degrees of freedom, or 5-DOF).
- These dynamics are divided into subsystems for aircraft speed, flight-path angle, and yaw angle. A robust NA control design is implemented to provide asymptotic tracking regulation of these output quantities. Simulations of the design indicates that it successfully provides flight control.

CONTROL SYSTEM

- The design of the control system is considered under subsonic speed (where the GHI database goes up to $V_p < 320$ m/s, but our experiments are limited to the 0.2 Mach number range) and altitude (where $h < 4000$ m). The 5-DOF lateral dynamics are given by

$$\dot{V}_p = \frac{1}{m}\left(T\cos\alpha\cos\beta - D\cos\beta + F_{Y_s}\sin\beta\right) - g\cos\beta\sin\gamma$$

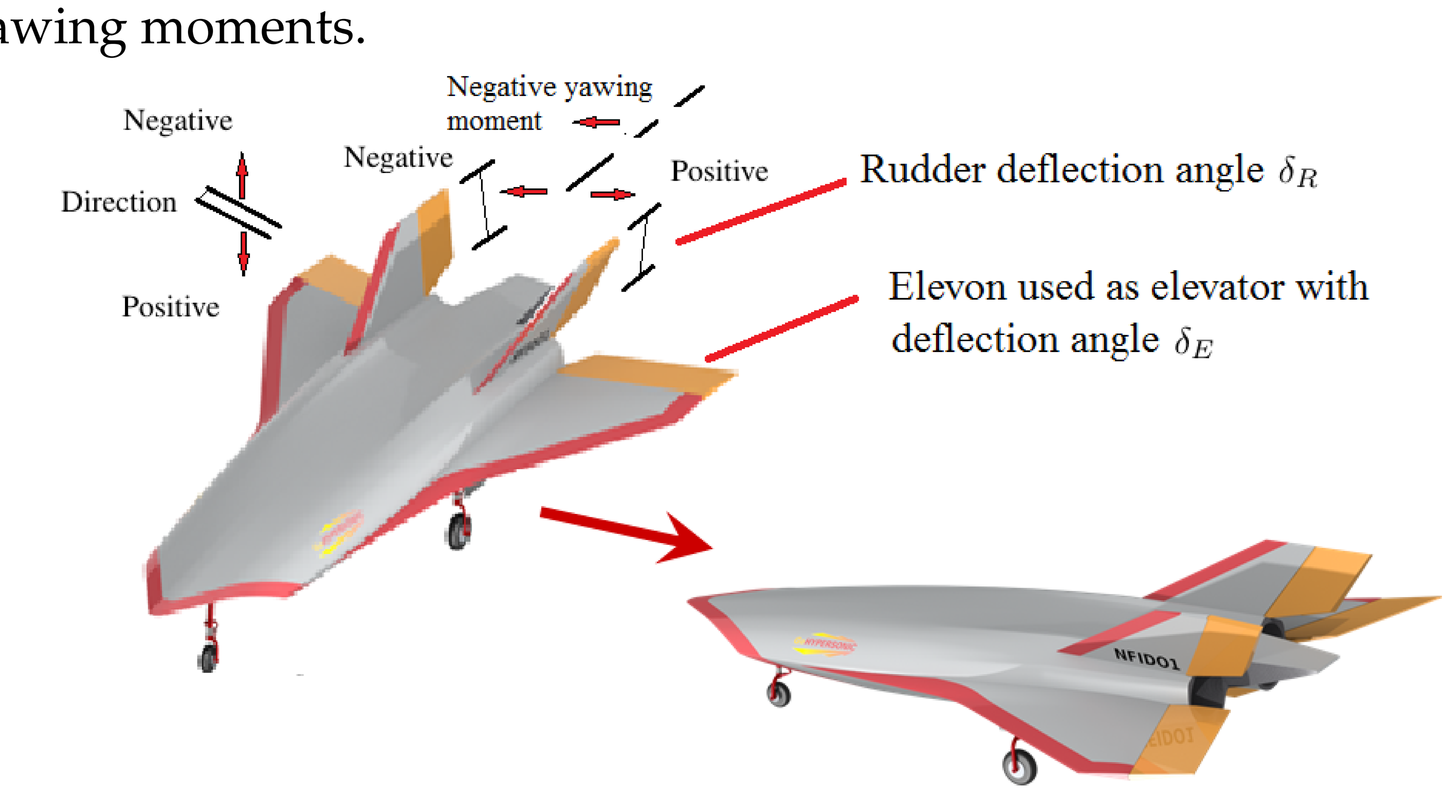
$$\dot{\alpha} = \frac{1}{mV_p\cos\beta}\left(-T\sin\alpha - L_i + mg\cos\gamma\right) + q - r\sin\alpha\tan\beta$$

$$\dot{\beta} = \frac{1}{mV_p}\left(D\sin\beta + F_{Y_s}\cos\beta - T\cos\alpha\sin\beta + mg\sin\beta\sin\gamma\right) - r\cos\alpha$$

$$\begin{bmatrix}\dot{q}\\ \dot{r}\end{bmatrix} = M_1\begin{bmatrix}q^2\\ r^2\end{bmatrix} + M_0\begin{bmatrix}M\\ N\end{bmatrix}$$

$$\begin{bmatrix}\dot{\theta}\\ \dot{\psi}\end{bmatrix} = \begin{bmatrix}q\\ r\sec\theta\end{bmatrix}$$

where D, F_{Y_s}, L_i, M, N denote drag, lateral-force, lift, pitching , and yawing moments.



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ADAPTIVE CONTROL AND SIMULATIONS

- 1) The nonlinear adaptive control law for V_p subsystem is defined by

$$T = \frac{1}{g_A}\left(-f_A + \hat{F}_{A1}(z,\hat{\theta}_{A1}) - \hat{F}_{A2}(z,\hat{\theta}_{A2}) + v_A + u_{sA}\right)$$

where: $g_A = \frac{\cos\alpha\cos\beta}{m}$, $v_A = -k_A\tilde{e}_A + \dot{V}_{des}$, $\tilde{e}_A = V_p - V_{des}$, and u_{sA} is stabilizing controller.

- 2) The control law for the γ subsystem is

$$\delta_{E_{des}} = \frac{1}{\hat{g}_B}\left(-f_B - \hat{F}_B(z,\hat{\theta}_B) + v_B + u_{sB}\right)$$

where: $\hat{g}_B = \frac{\rho S V_p}{2m\cos\beta}\hat{\theta}_{L_{\delta_E}}$, $v_B = -k_B\tilde{e}_B + \dot{\gamma}_{des}$, and $\tilde{e}_B = \gamma - \gamma_{des}$

- 3) The control law for ψ subsystem is defined by

$$\delta_{R_{des}} = \frac{1}{g_c}\left(-f_c - \hat{F}_c(z,\hat{\theta}_c) + v_c + u_{sc}\right)$$

where: $g_c = M_o\bar{q}SbC_{n_{\delta R}}\sec\theta$, $v_c = -k_c\tilde{e}_c + \tilde{x}_c$, $\tilde{x}_c = -(\dot{\psi} - \dot{\psi}_{des}) + \ddot{\psi}_{des}$
$\tilde{e}_c = (\psi - \psi_{des}) + (\dot{\psi} - \dot{\psi}_{des})$

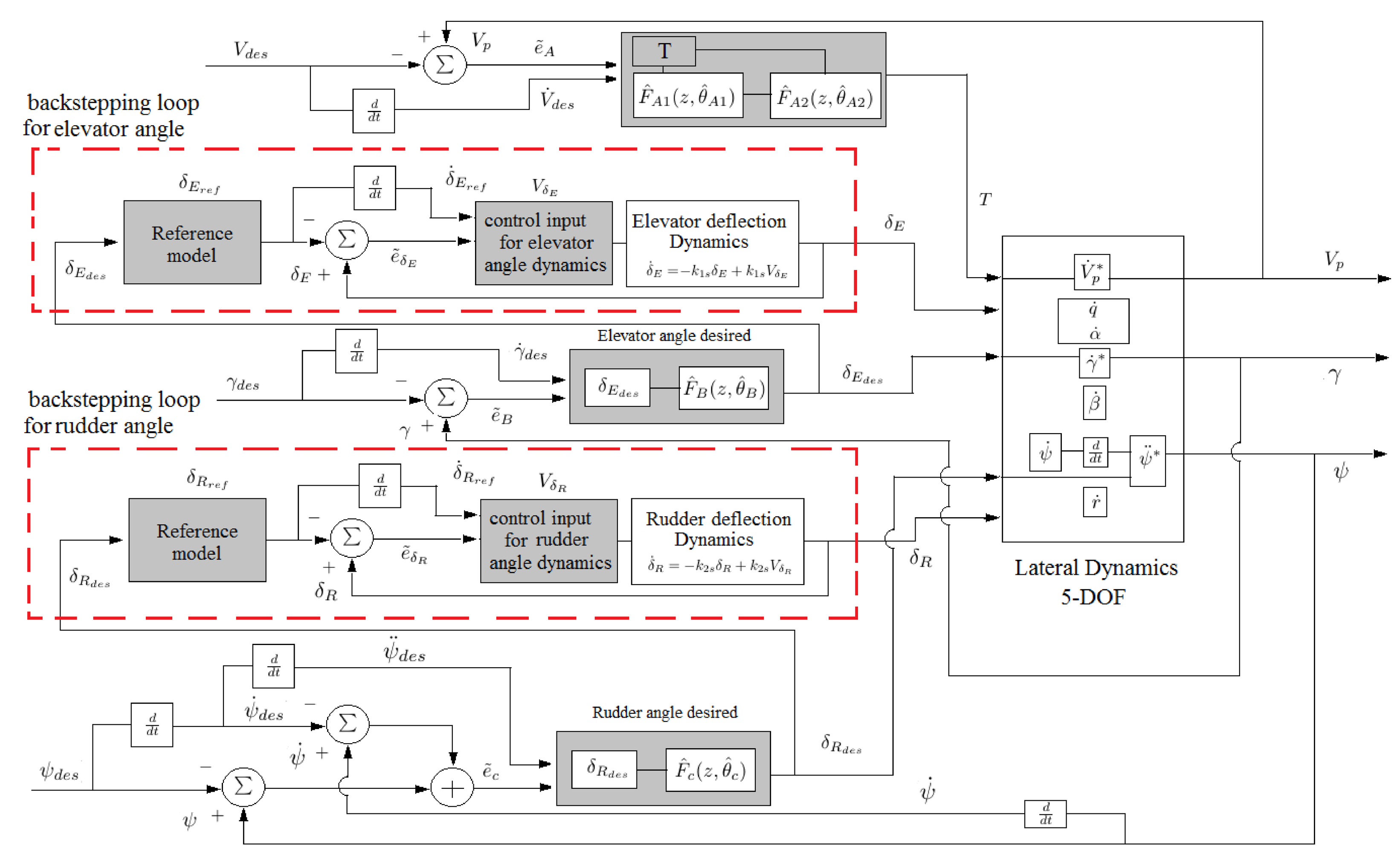

Figure 1: Block diagram of nonlinear adaptive control for 5-DOF lateral dynamics.

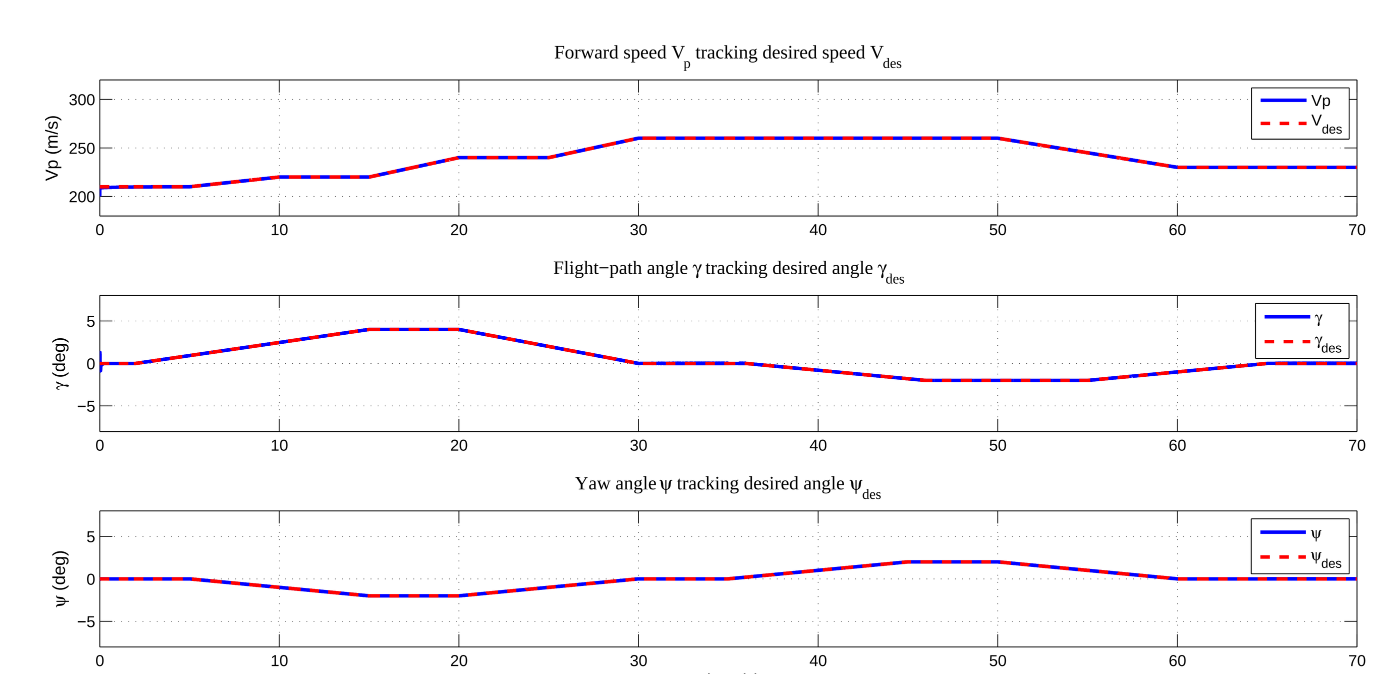

Figure 2: V_p, γ, and ψ tracking performance.

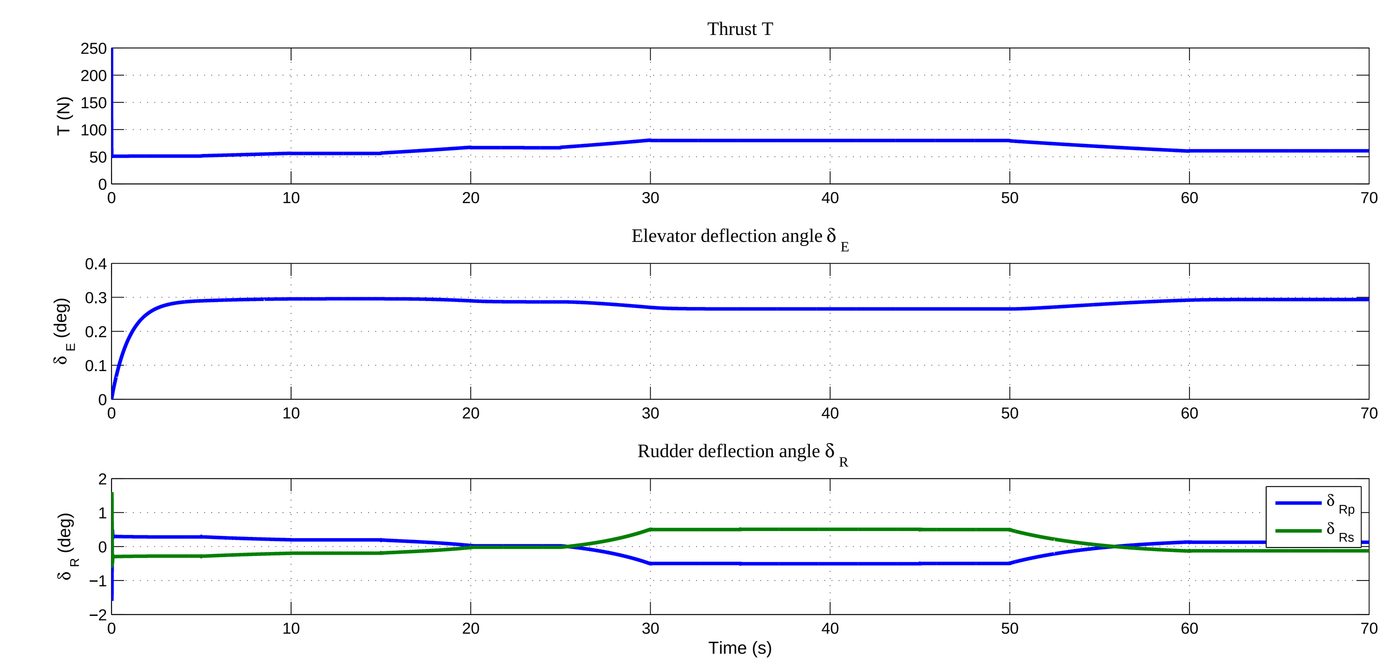

Figure 3: Control inputs T, δ_E, and δ_R.

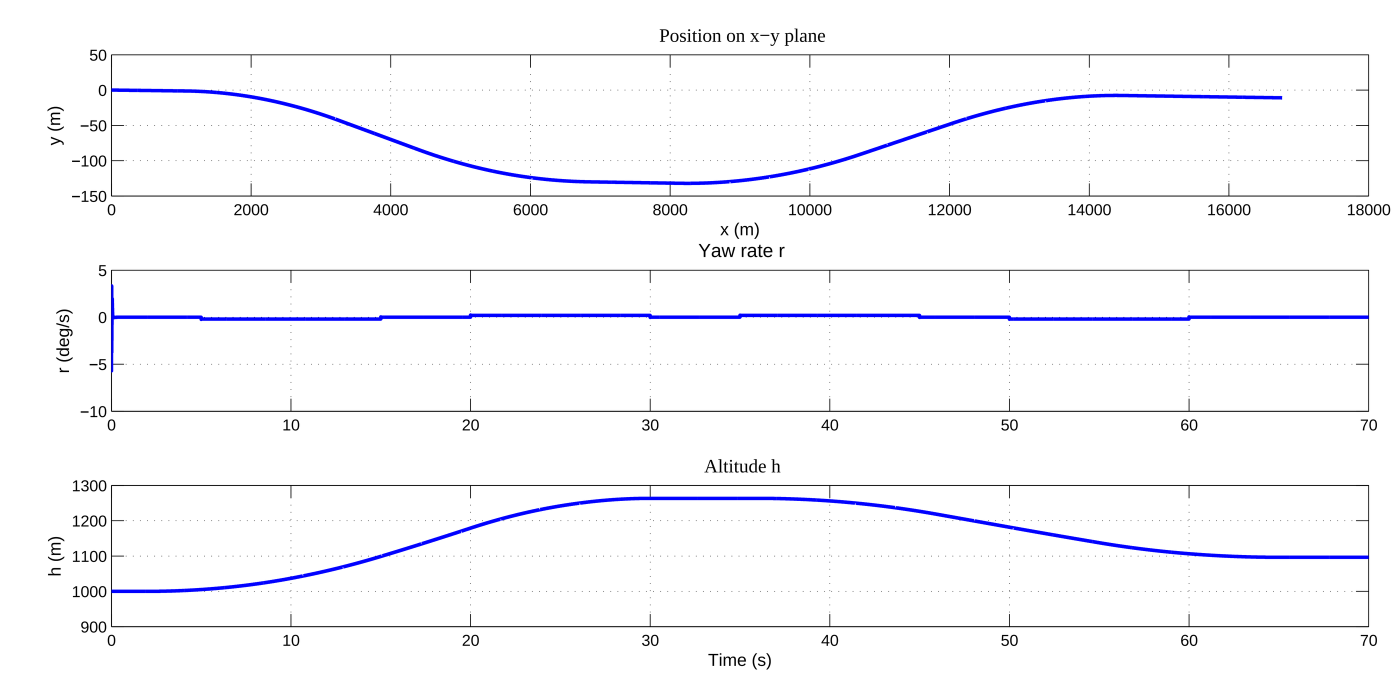

Figure 4: Position on x-y plane, yaw rate r, and altitude h.

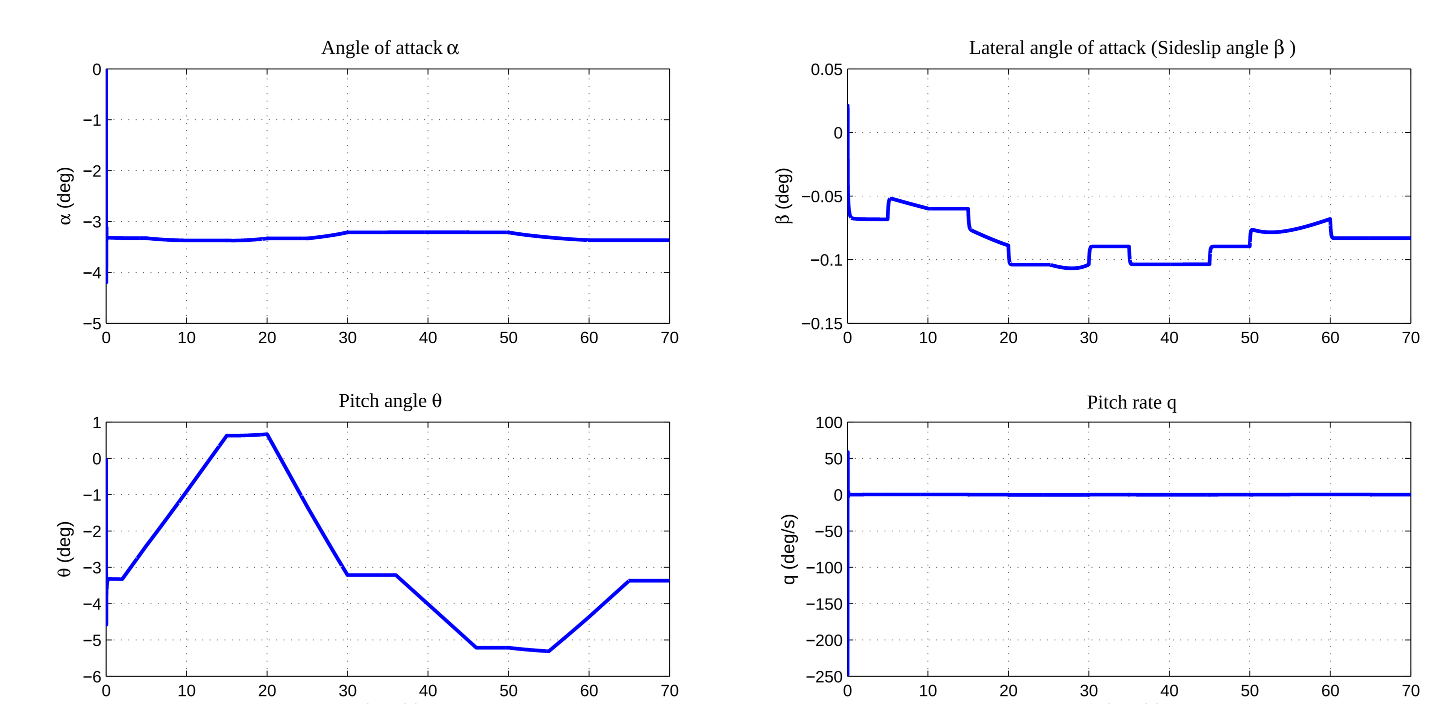

Figure 5: Flight states α, β, θ,, and q behaviors.

CONCLUSION

- The adaptive control is a robust becuase the tracking of the outputs require less than 2.5 s.
- The control inputs also reach the stability condition in short time, without oscillation.