Robust Nonlinear Adaptive Control For Longitudinal Dynamics of Hypersonic Aircraft Vehicle

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ABSTRACT

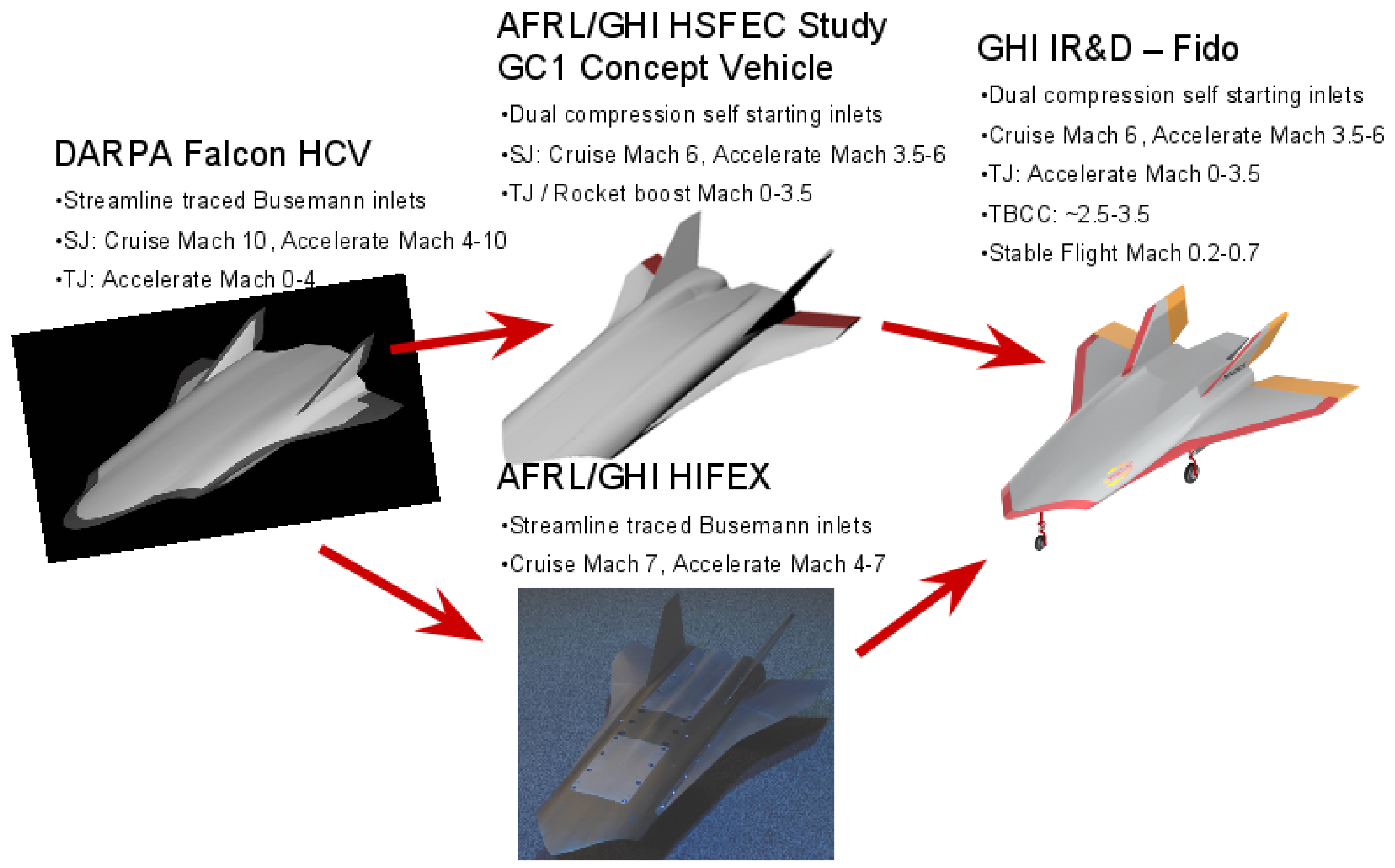
A hypersonic aircraft vehicle is a highly complex nonlinear system, which includes uncertainties in the dynamics. This paper presents the design of robust nonlinear adaptive control for a hypersonic aircraft vehicle. The complexity of the dynamic system is considered into the design structure of the control in order to address robustness issues. Design of a robust control system should decouple the longitudinal and lateral dynamics to handle the flight of hypersonic vehicle under certain specific conditions.

INTRODUCTION

- Studies of hypersonic aircraft vehicles have been made to be a consistent technologies for access to space.
- NASA and the U.S. Air Force in past years have conducted simulation studies, whereas success of experimental vehicles remains limited.
- We present here design of a control system for hypersonic vehicles in low speed and altitude (subsonic speed conditions, $V_p < 480$ m/s, and $h < 4000$ m), where the Mach number is less than 1.2.
- The control objectives are achieving robust tacking of the outputs $y_{LD} = [V_p, \gamma]^\top$, by using $u_{LD} = [T, \delta_E]^\top$ as the control inputs.
- The longitudinal aircraft dynamics are given by

$$\begin{aligned}\dot{V}_p &= \frac{1}{m}(T\cos\alpha - D) - g\sin\gamma, \quad \dot{\gamma} = q - \dot{\alpha}\\ \dot{\alpha} &= \frac{-1}{mV_p}(T\sin\alpha + L_i) + \frac{g}{V_p}\cos\gamma + q, \quad \dot{q} = \frac{1}{I_y}M, \end{aligned} \tag{1}$$

- where V_p, T, α, q, h, δ_E, D, L_i, and M denote forward speed, thrust, longitudinal angle of attack, pitch angular rate, altitude, elevator deflection angle, drag, lift, and aerodynamic pitching moment, respectively.



AFRL/GHI HSFEC Study GC1 Concept Vehicle
- Dual compression self starting inlets
- SJ: Cruise Mach 6, Accelerate Mach 3.5-6
- TJ / Rocket boost Mach 0-3.5

GHI IR&D – Fido
- Dual compression self starting inlets
- Cruise Mach 6, Accelerate Mach 3.5-6
- TJ: Accelerate Mach 0-3.5
- TBCC: ~2.5-3.5
- Stable Flight Mach 0.2-0.7

DARPA Falcon HCV
- Streamline traced Busemann inlets
- SJ: Cruise Mach 10, Accelerate Mach 4-10
- TJ: Accelerate Mach 0-4

AFRL/GHI HIFEX
- Streamline traced Busemann inlets
- Cruise Mach 7, Accelerate Mach 4-7

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CONTROL OF SPEED SUBSYSTEM

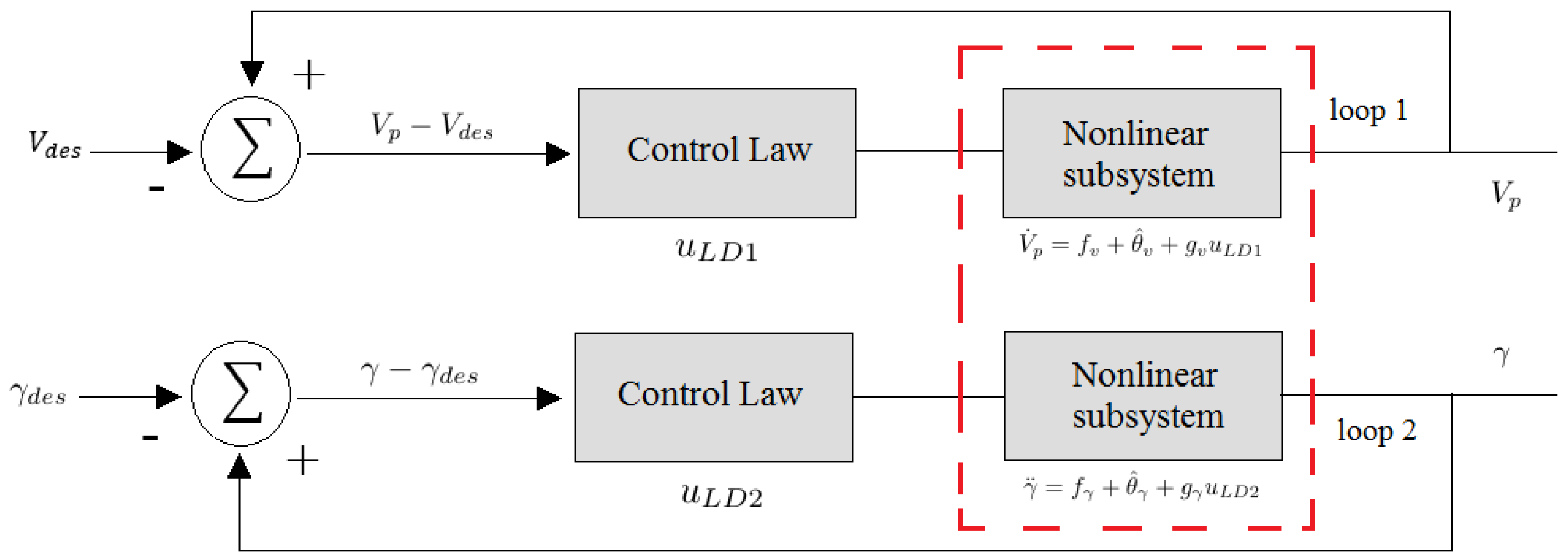

Figure 1: Block diagram of two SISO adaptive control.

- Based on longitudinal dynamic equations (1), the vehicle speed is presented as the output of V_p subsystem.
- Because the drag D contains uncertain parameters, a function approximator can be used instead, so that

$$\dot{V}_p = \frac{T}{m}\cos\alpha - \frac{\bar{q}S}{m}\Theta_A^{*\top}\xi_A - w_A(z) - g\sin\gamma, \tag{2}$$

- The adaptive control law T is defined by

$$T = \frac{1}{g_A(z)}(g\sin\gamma + \frac{\bar{q}S}{m}\hat{\Theta}_A^\top\xi_A + v_A + u_{sA}), \tag{3}$$

where

$$\hat{\Theta}_A = [\hat{\theta}_{A,C_{D0}}, \hat{\theta}_{A,\alpha}, \hat{\theta}_{A,\alpha^2}, \hat{\theta}_{A,\delta_E}, \hat{\theta}_{A,q}]^\top,\ g_A(z) = \frac{\cos\alpha}{m},\ v_A = -k_A\tilde{e}_A + \dot{V}_{des}.$$

CONTROL OF FLIGHT-PATH ANGLE SUBSYSTEM

- For control of flight-path angle, the second derivative is required to achieve asymptotic stability,

$$\begin{aligned}\ddot{\gamma} = {}&\frac{\dot{T}}{mV_p}\sin\alpha - \frac{T}{mV_p^2}\dot{V}_p\sin\alpha + \frac{T}{mV_p}\dot{\alpha}\cos\alpha + \frac{\rho S}{2m}\dot{V}_p\Theta_B^{*\top}\xi_B + w_B(z)\\ &+\frac{\rho S}{2m}V_p\Theta_c^{*\top}\xi_c + w_c(z) + \frac{g}{V_p^2}\dot{V}_p\cos\gamma + \frac{g}{V_p}\dot{\gamma}\sin\gamma,\end{aligned} \tag{4}$$

- We redefine the control law to be V_δ with the choice below

$$\begin{aligned}V_\delta = {}&\frac{1}{\hat{g}_c(z)}(\frac{-\dot{T}}{mV_p}\sin\alpha + \frac{T}{mV_p^2}\dot{V}_p\sin\alpha - \frac{T}{mV_p}\dot{\alpha}\cos\alpha - \frac{\rho S}{2m}\dot{V}_p\hat{\Theta}_B^\top\xi_B\\ &-\frac{\rho S}{2m}V_p\hat{\Theta}_c^\top\xi_c - \frac{g}{V_p^2}\dot{V}_p\cos\gamma - \frac{g}{V_p}\dot{\gamma}\sin\gamma + v_c + u_{sc}),\end{aligned} \tag{5}$$

$$\hat{\Theta}_B = [\hat{\theta}_{B,C_{L0}}, \hat{\theta}_{B,\alpha}, \hat{\theta}_{B,\delta_E}, \hat{\theta}_{B,q}]^\top, \hat{\Theta}_c = [\hat{\theta}_{c,\dot{\alpha}}, \hat{\theta}_{c,\Gamma_1}, \hat{\theta}_{c,\dot{q}}]^\top,$$
$$\hat{g}_c(z) = \frac{\rho S}{2m}V_p\Gamma_2\,\hat{\theta}_{V_\delta},\ v_c = -\chi_c - k_c\tilde{e}_c.$$

NUMERICAL SIMULATIONS

- The adaptive control design has been tested using MATLAB for the simulation model.

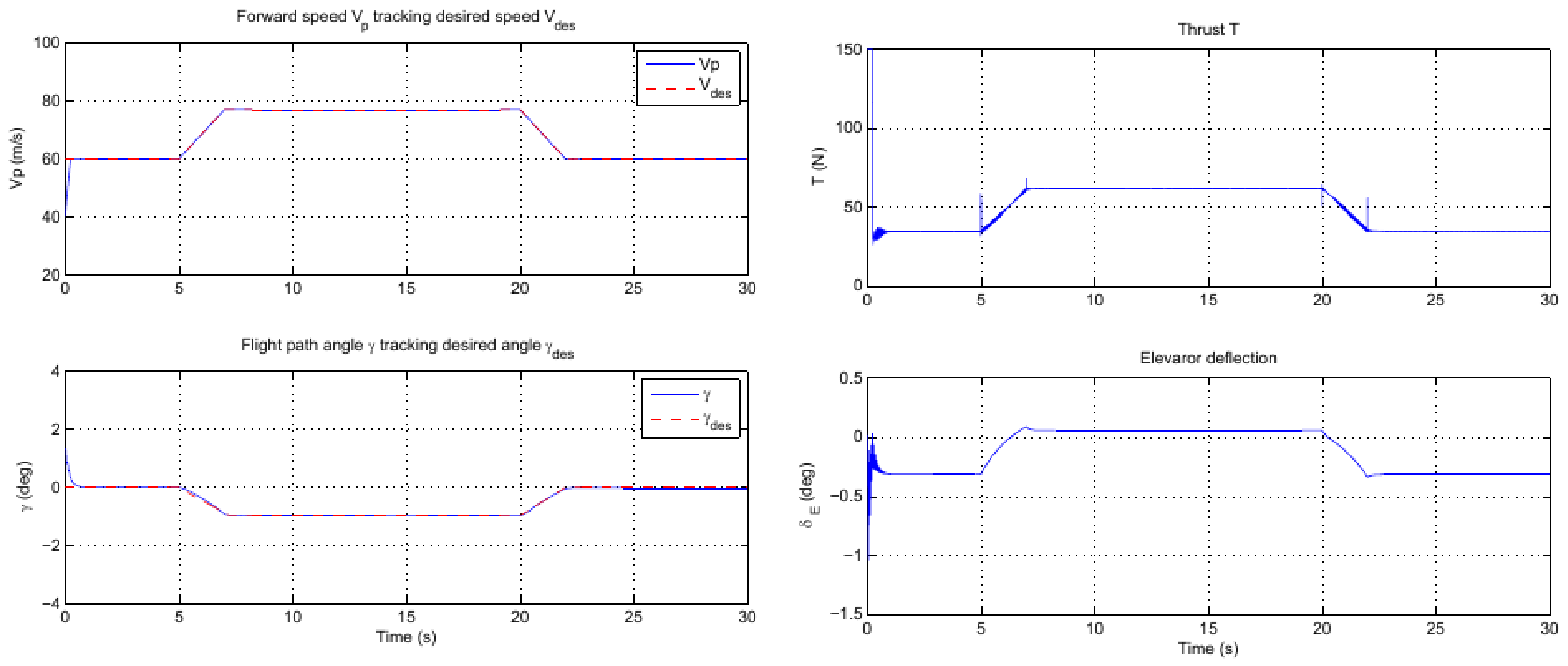

Figure 2: V_p and γ tracking performance, and control inputs T,δ_E.

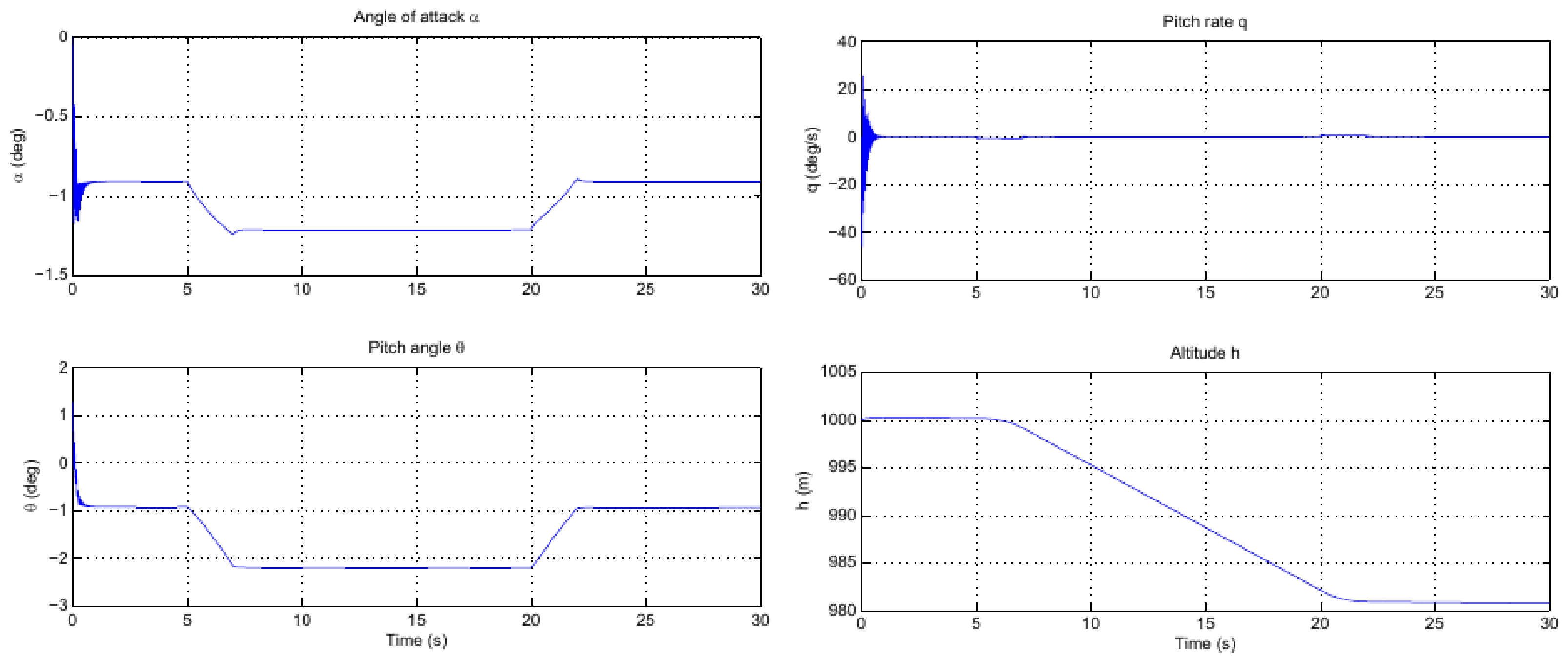

Figure 3: α, θ, q, and h behaviors.

CONCLUSION

- Adaptive control design achieves the stability conditions of control inputs with different combinations of forward speed and flight-path angle.
- The simulations and validations for adaptive control indicate that these perform well for flight control.
- Additionally, the longitudinal dynamics showed the control inputs behavior, and correct tracking conditions for V_p and γ were confirmed.
- The adaptive control is a robust because the tracking of the outputs require less than 2 s.
- The control inputs also reach the stability condition in short time, without significant oscillation.