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Improved nonlinear dynamic inversion control for a flexible air-breathing hypersonic vehicle

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ABSTRACT

This paper presents an improved nonlinear dynamic inversion control approach for the longitudinal dynamics of a flexible air-breathing hypersonic vehicle. The control design of the approach is based on a control-oriented model that represents the nominal state. By establishing a three inputs and three outputs control system, the control-oriented model in this study has full relative degree, without dynamic extension. To maintain tracking performance in the presence of disturbances, a nonlinear disturbance observer is adopted to estimate the disturbances, and an adaptive damping term is proposed to the pitch dynamics. Based on approximate input–output linearization, linear control theory is applied to design a pole placement controller for the equivalent linear system. The damping ratio, natural frequency, and simple pole of the pole placement controller are optimized by the genetic algorithm along with the full nonlinear model of the vehicle. During the optimization, 11 uncertain parameters are introduced to the nonlinear model. Monte Carlo evaluation for the optimized pole placement controller shows that the controller provides robust tracking of reference trajectories. Simulation results indicate the effectiveness of the proposed control approach.

1. Introduction

With the development of scramjet technology, the flying of the air-breathing hypersonic vehicle (AHV) has become a reality [1–3]. The AHV presents a cost-efficient way for access to space, because the scramjet engine does not carry oxygen and has high specific impulse. In the past decade, the successful flight of X-43A, X-51A, and Hyshot2 has given a great number of test data on the aerodynamics, structure, guidance, and control of AHVs. However, the strong coupling among the propulsion, structure, and aerodynamics [4] makes the modeling and control of AHVs an open problem that attracts much interest.

In the literature, several papers have been proposed to discuss the modeling of AHVs [4–6]. Chavez and Schmidt [4] utilized Newtonian theory and shock expansion theory to establish a two dimensional analytical hypersonic aerodynamic model. In their work, the stability derivatives, derived from the longitudinal dynamics of an AHV, indicated an unstable pitch mode and a coupled aerodynamics/propulsion/structure mode. To extend the work done by Chavez and Schmidt, Bolender and Doman [5] applied oblique shock and Prandtl–Meyer expansion theory to calculate the location of the bow shock and to determine the forebody pressure distribution. Lagrange's equations were used to derive a first-order approximation of the flexible dynamics of the fuselage. The linearized system presented that the pitch and flexible dynamics are strongly coupled. Based on Bolender and Doman, the MASTrim (Michigan/Air force Research Laboratory scramjet trim) code [6] was proposed. The propulsion module of MASTrim was shown to agree with the experimental results.

The design of control systems for AHVs is a challenge due to the highly coupled dynamics. In the real flight of X-43A aircraft, a classical loop structure was adopted to design an angle of attack controller and a normal acceleration controller [3]. The classical controllers were gain scheduled as a function of Mach and angle of attack to acquire marginally stability. The adaptive control system shows more robustness than the classical control system [7]. To verify an adaptive control law of AHVs, HiFIRE6 [1] will evaluate the stability and performance of an adaptive control system. Due to the slender geometries and light structures of the AHV, the aerothermoelastic effects on structural dynamics were accounted in a linear parameter varying (LPV) frame [8]. Inherently, the LPV controller was gain scheduled with the time varying operating parameters. Sigthorsson et al. [9] designed a robust servomechanism controller that does not need full-state feedback. The zero dynamics of the pitch mode was stabilized by a simple dynamic compensator. These linear controllers are inherently gain scheduled to

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confirm the closed-loop stability. Advanced nonlinear methods that avoid gain scheduling are proposed. The main two nonlinear structures applied to hypersonic control are nonlinear dynamic inversion (NDI) control and backstepping (BS) control. Wang and Stengel [10] gave the condition of input–output linearization of an AHV system. The stochastic robustness theory was adopted to optimize the feedback parameters. In Parker et al. [11], a canard was interconnected with the elevator to cancel the elevator-to-lift coupling, rendering the system minimum phase. Afterward, the LQR control was applied to design feedback gains for the integral augmented NDI control. What's more, many other control strategies have been successfully combined with the NDI structure, such as the nonlinear disturbance observer based control [12], the adaptive sliding mode based control [13], and the neural network based control [14]. As for the BS method, the main problem remaining in conventional BS is "explosion of complexity". Although the problem of "explosion of complexity" can be avoided by dynamic surface control [15] and command filters [16], Fiorentini et al. [17] applied the canard deflection to control the outer-loop and utilized the elevator deflection to control the inner-loop, resulting in low-order subsystems that do not need command filters. Zhang and Xian [18] also proposed a BS strategy that considered a three inputs and three outputs system that avoids high-order time derivatives of the states.

Based on previous work, the motivation in this study is to apply linear theory to design a reduced-order NDI (RNDI) controller for a flexible AHV (FAHV). The canard included configuration [11,19] was adopted to create low-order subsystems when applying the NDI control. With the feedback linearization, the nonlinear systems were transformed into low-order equivalent linear systems. We applied a pole placement technique [20] to design the feedback gains of the equivalent linear systems. Based on the pole placement technique, the genetic algorithm (GA) was used to optimize the feedback gains. To avoid exciting the flexible modes, the equivalent bandwidth of the pitch angle controller is limited by the flexible dynamics and actuator dynamics. A nonlinear disturbance observer (NDO) was adopted to compensate the disturbances for the equivalent linear systems, while an adaptive damping term was designed for the pitch angle subsystem to maintain tracking performance with respect to parameter uncertainties. For comparison, the conventional NDI (CNDI) [11] and the integral augmented RNDI are conducted and analyzed.

The main contributions of this paper are: (a) with an additional canard, the relative degree of the system is well defined without dynamic extension; (b) the pole placement technique is synthesized with the GA to design the feedback gains of the equivalent linear system; (c) a guideline from the frequency domain is proposed for tuning the controller based on the equivalent linear system. The remainder of this paper is organized as follows: In Sec. 2, a nonlinear model of the FAHV is presented and the control-oriented equations are obtained. The control design of the RNDI is proposed in Sec. 3. Section 4 discusses the pole placement technique and parameters optimization. Finally, simulation results and conclusions are presented in Sec. 5 and Sec. 6, respectively.

2. Model description

In this study, the longitudinal model of the FAHV is based on Bolender and Doman [5]. The model captures the structural, aerodynamic, and propulsion coupling. A free-beam model is adopted to represent the flexible dynamics. In the free-beam model, the coupling between rigid and flexible dynamics is through the aerodynamic forces. The Earth is assumed to be plat and the vehicle is normalized to unit depth. The longitudinal dynamic equations of a FAHV written in the stability axis coordinate system are

$$\dot{V} = (T\cos\alpha - D)/m - g\sin\gamma \tag{1}$$

$$\dot{h} = V\sin\gamma \tag{2}$$

$$\dot{\gamma} = (L + T\sin\alpha)/(mV) - g\cos\gamma/V \tag{3}$$

$$\dot{\theta} = Q \tag{4}$$

$$\dot{Q} = M/I_{yy} \tag{5}$$

$$\ddot{\eta}_i = -2\zeta_i\omega_i\dot{\eta}_i - \omega_i^2\eta_i + N_i, \quad i = 1, 2, 3 \tag{6}$$

The model comprises five rigid states $\boldsymbol{x} = [V, h, \gamma, \theta, Q]^T$ and six flexible states $\boldsymbol{\eta} = [\eta_1, \dot{\eta}_1, \eta_2, \dot{\eta}_2, \eta_3, \dot{\eta}_3]^T$, where V is the velocity, h is the altitude, γ is the flight path angle, θ is the pitch angle, and Q is the pitch rate. The angle of attack is given by $\alpha = \theta - \gamma$. Based on Lagrange's equations, $\boldsymbol{\eta}$ is derived from the first three bending modes of the free-beam model. The damping ratio of all flexible modes is $\zeta_i = 0.02$. The control inputs $[\phi, \delta_\mathrm{e}, \delta_\mathrm{c}]^T$ and the regulated outputs $[V, h, \theta]^T$ form a three inputs and three outputs system, where ϕ is the equivalent fuel-to-air ratio, δ_e is the elevator deflection, and δ_c is the canard deflection. The control object is to asymptotically track the reference trajectories of velocity, altitude, and pitch angel. The 50% fuel level [9] is defined as the nominal operating condition that has the parameters of vehicle mass $m = 147.9$ slug/ft, and modal frequencies $\omega_1 = 21.17$ rad/s, $\omega_2 = 53.92$ rad/s, and $\omega_3 = 109.1$ rad/s.

In the curve-fitted model, the lift L, drag D, thrust T, pitching moment M, and generalized forces N_i are given by

$$\begin{aligned}
&T \approx \bar{q}S\left[C_{T,\phi}(\alpha)\phi + C_T(\alpha) + \boldsymbol{C}_T^{\eta}\boldsymbol{\eta}\right]\\
&L \approx \bar{q}SC_L(\alpha, \boldsymbol{\delta}, \boldsymbol{\eta})\\
&D \approx \bar{q}SC_D(\alpha, \boldsymbol{\delta}, \boldsymbol{\eta})\\
&M \approx z_T T + \bar{q}S\bar{c}C_M(\alpha, \boldsymbol{\delta}, \boldsymbol{\eta})\\
&N_i \approx \bar{q}S\left[N_i^{\alpha^2}\alpha^2 + N_i^{\alpha}\alpha + N_i^{\delta_e}\delta_e + N_i^{\delta_c}\delta_c + N_i^0 + \boldsymbol{N}_i^{\eta}\boldsymbol{\eta}\right],\\
&\quad i = 1, 2, 3
\end{aligned} \tag{7}$$

where $\bar{q}$, S, $\bar{c}$, and z_T are the dynamic pressure, reference area, mean aerodynamic chord, and thrust moment arm, respectively. The dynamic pressure is expressed as $\bar{q} = 1/2\rho V^2$, while the air density is given by $\rho = \rho_0\exp[-(h - h_0)/h_s]$. The curve fitted approximations in Eq. (7) show that the coupling between the rigid and flexible dynamics is through the forces and moments. The aerodynamic coefficients are present by

$$\begin{aligned}
&\boldsymbol{\delta} = [\delta_e, \delta_c]^T\\
&C_{T,\phi}(\alpha) = C_T^{\phi\alpha^3}\alpha^3 + C_T^{\phi\alpha^2}\alpha^2 + C_T^{\phi\alpha}\alpha + C_T^{\phi}\\
&C_T(\alpha) = C_T^3\alpha^3 + C_T^2\alpha^2 + C_T^1\alpha + C_T^0\\
&C_M(\alpha, \boldsymbol{\delta}, \boldsymbol{\eta}) = C_M(\alpha, \boldsymbol{\delta}) + \boldsymbol{C}_M^{\eta}\boldsymbol{\eta}\\
&\qquad = C_M^{\alpha^2}\alpha^2 + C_M^{\alpha}\alpha + C_M^{\delta_e}\delta_e + C_M^{\delta_c}\delta_c + C_M^0 + \boldsymbol{C}_M^{\eta}\boldsymbol{\eta}\\
&C_L(\alpha, \boldsymbol{\delta}, \boldsymbol{\eta}) = C_L(\alpha, \boldsymbol{\delta}) + \boldsymbol{C}_L^{\eta}\boldsymbol{\eta}\\
&\qquad = C_L^{\alpha}\alpha + C_L^{\delta_e}\delta_e + C_L^{\delta_c}\delta_c + C_L^0 + \boldsymbol{C}_L^{\eta}\boldsymbol{\eta}\\
&C_D(\alpha, \boldsymbol{\delta}, \boldsymbol{\eta}) = C_D(\alpha, \boldsymbol{\delta}) + \boldsymbol{C}_D^{\eta}\boldsymbol{\eta}\\
&\qquad = C_D^{\alpha^2}\alpha^2 + C_D^{\alpha}\alpha + C_D^{\delta_e^2}\delta_e^2 + C_D^{\delta_e}\delta_e + C_D^{\delta_c^2}\delta_c^2\\
&\qquad\quad + C_D^{\delta_c}\delta_c + C_D^0 + \boldsymbol{C}_D^{\eta}\boldsymbol{\eta}\\
&\boldsymbol{C}_j^{\eta} = [\,C_j^{\eta_1} \quad 0 \quad C_j^{\eta_2} \quad 0 \quad C_j^{\eta_3} \quad 0\,], \quad j = T, M, L, D\\
&\boldsymbol{N}_i^{\eta} = [\,N_i^{\eta_1} \quad 0 \quad N_i^{\eta_2} \quad 0 \quad N_i^{\eta_3} \quad 0\,], \quad i = 1, 2, 3
\end{aligned} \tag{8}$$

where the numerical values of the curve-fitted coefficients and vehicle parameters can be found in Fiorentini [21].

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