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Nonlinear disturbance observer based robust backstepping control for a flexible air-breathing hypersonic vehicle

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A R T I C L E I N F O

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A B S T R A C T

This paper presents a robust backstepping approach for a flexible air-breathing hypersonic vehicle in the longitudinal plane. The control design and stability analysis of the backstepping approach are based on a control-oriented model, which treats the flexible dynamics as dynamic perturbations. The backstepping method in this study utilizes a command filter to avoid the problem of "explosion of complexity" that occurs in the traditional backstepping method. To suppress the flexible dynamics and parameter uncertainties, a nonlinear disturbance observer is proposed to estimate these uncertainties during the tracking process. By introducing a group of virtual states, a Lyapunov-based stability analysis of the closed-loop system indicates that the tracking errors vanish asymptotically. A guideline for tuning the controller is given from a physical perspective to avoid exciting the flexible modes. This approach presents a good tracking performance with respect to both the flexible modes and parameter uncertainties. Simulation results of the full nonlinear model show the effectiveness of the proposed approach.

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1. Introduction

Air-breathing hypersonic vehicles (AHVs), which represent a cost-efficient and reliable way for access to space, have attracted much interest since the successful flight test of the X-43A aircraft in 2004. Differently from some conventional flight vehicles, the propulsion-airframe integration results in heavy coupling between propulsive and aerodynamic forces. Moreover, the strong coupling between rigid and flexible dynamics causes significant uncertainties, due to the slender geometries and light structures [1]. Consequently, the control design of AHVs is an important segment during the research process.

In the past few years, many effective models have been proposed for AHVs. The model developed by NASA Langley Research Center was presented in Wang and Stengel [2], and Xu et al. [3]. Chavez and Schmidt [4] utilized Newtonian theory to establish a two-dimensional analytical hypersonic aerodynamic model. Recently, Bolender and Doman [5] proposed a new model that applied oblique shock and Prandtl–Meyer expansion theory to determine the pressure distribution over the vehicle. In their work, Lagrange's Equations were used to derive the equations of motion for a flexible AHV (FAHV). Furthermore, piston theory [6,7] has been applied to improve the modeling of generic hypersonic vehicles, leading to a more accurate and complex model.

Generally speaking, the methods applied to AHVs are divided into two parts: linear methods and nonlinear methods. Justin et al. [8] investigated a H_∞ output feedback approach that achieved desirable properties. A linear parameter-varying control approach with gain scheduling was used to represent the structural dynamics of a FAHV in Lind [9]. The linear output feedback control proposed by Sigthorsson et al. [10] and the LQR control addressed by Kevin et al. [11] were shown to be effective to design controllers for a FAHV. Usually, the linear controllers are designed with gain scheduling to guarantee a desirable performance. However, extensive flight testing and offline analysis are required in this process. Advanced nonlinear control methods are presented to overcome the drawbacks remaining in linear methods and have received more attention these days. The feedback linearization method has been widely used in AHVs for its simplicity [2,12,13]. With the technique of the feedback linearization, a nonlinear system can be transformed into an equivalent linear system. Afterwards, the LQR control is applied to guarantee the stability of the closed-loop system. But this technique requires an accurate model because it's sensitive to uncertainties. Based on approximate feedback linearization, the elevator-to-lift coupling is ignored strategically, resulting in a significant mismatch between the control-oriented model and the full nonlinear model. To deal with the mismatch, Parker et al. [13] added an additional canard to cancel the lift from

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the elevator, rendering the system minimum phase. The backstepping method [14] is also an effective way to deal with nonlinear problems. But the traditional backstepping method suffers from the problem of "explosion of complexity", which can be eliminated by dynamic surface control and differentiator [15–18]. To deal with the flexible effects and parameter uncertainties, passive suppression ways and active suppression ways are pursued for AHVs. The H_∞ method [8,19] and integral augmented method [12,13,15] are passive suppression ways, while the adaptive control [14,18,20], the disturbance observer based control [12,19], and the neural network based control [16,17] are active suppression ways.

Motivated by previous works, the backstepping method is adopted in this study to relax the accuracy requirements of the flight dynamics model. In the backstepping control, a command filter is proposed to create virtual signals and their first derivatives, while providing magnitude, bandwidth and rate limit constraints [21,22]. The command filter is utilized to deal with the problem of "explosion of complexity". To enhance the robustness of the controller with respect to the flexible modes and parameter uncertainties, a nonlinear disturbance observer (NDO) [23] is proposed to estimate these uncertainties. The command filter also acts as a low-pass filter to the estimates. We found that the NDO is a bounded-input and bounded-output (BIBO) system with proper selection of the control functions. Therefore, the bandwidths of the NDO are obtained for parameters design to avoid exciting the flexible modes. At the end, a comparison among the NDO based backstepping control, an extended state observer (ESO) [24,25] based backstepping control, and the NDO based nonlinear dynamic inversion (NDI) is performed.

The primary contributions of this paper lie in that: (a) the bandwidths of the NDO are obtained for parameters design; (b) a guideline is proposed for tuning the controller to avoid exciting the flexible modes based on the analysis of the first order vibration frequency and the bandwidths of the actuators and command filters; (c) a group of new virtual states are introduced to analyze the stability of the controller in the sense of Lyapunov. The remainder of this paper is organized as follows: In Sec. 2, a nonlinear model for the FAHV is proposed and a strict feedback form for the backstepping control design is obtained. The control design of the NDO and backstepping method is presented in Sec. 3. Section 4 discusses the Lyapunov stability of the rigid-body states. A guideline for tuning the controller is given in Sec. 5. Finally, simulation results and conclusions are presented in Sec. 6 and Sec. 7, respectively.

2. Model description

The model adopted in this study is on the basis of Bolender and Doman [5], and Trevor et al. [26]. For simplicity, only longitudinal dynamics are considered. The fuselage is modeled as a free-beam instead of a couple of cantilever beams. In the free-beam model, the coupling between rigid and flexible dynamics is through the aerodynamic forces. Assuming that the Earth is flat and the vehicle is normalized to unit depth. The general longitudinal dynamics of a FAHV are [20]

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

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

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

$$\dot{\alpha} = Q - \dot{\gamma} \tag{4}$$

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

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

Table 1
Vehicle mass and modal frequencies at different fuel levels [10].

Fuel level	0%	30%	50%	70%	100%
m, slug/ft	93.57	126.1	147.9	169.6	202.2
ω_1, rad/s	22.78	21.71	21.17	20.73	20.17
ω_2, rad/s	68.94	57.77	53.92	51.24	48.4
ω_3, rad/s	140	117.8	109.1	102.7	95.6

Five rigid-body states are included in this model $\boldsymbol{x} = [V, h, \gamma, \alpha, Q]^T$, which represent velocity, altitude, flight path angle (FPA), angle of attack (AOA), and pitch rate, respectively. Six flexible states $\boldsymbol{\eta} = [\eta_1, \dot{\eta}_1, \eta_2, \dot{\eta}_2, \eta_3, \dot{\eta}_3]^T$ are derived from the first three bending modes of the free-beam model. The damping ratio of all flexible modes is $\zeta_i = 0.02$. To suppress the non-minimum phase behavior, a canard is added in conjunction with the elevator by choosing $\delta_c = k_{ec}\delta_e$, $k_{ec} = -C_L^{\delta_e}/C_L^{\delta_c}$ strategically, where δ_e is the elevator deflection, δ_c represents the canard deflection, and k_{ec} is defined as the interconnection gain between the elevator deflection and the canard deflection. The interconnection gain means that when the elevator deflects trailing edge up, the canard deflects trailing edge down at the same time so that the lift due to the elevator is canceled. Therefore, the non-minimum phase behavior of the rigid dynamics is alleviated. The control inputs become $\boldsymbol{u} = [\phi, \delta_e]^T$, where ϕ is the equivalent fuel-to-air ratio. The outputs are selected as $\boldsymbol{y} = [V, h]^T$. The 50% fuel level is defined as the nominal operating condition. The vehicle mass and modal frequencies at different fuel levels are given in Table 1.

For control design, lift L, drag D, thrust T, pitching moment M, and generalized forces N_i are presented by curve fitted approximations.

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

where $\bar{q}$, S, $\bar{c}$, and z_T are dynamic pressure, reference area, mean aerodynamic chord, and thrust moment arm, respectively. The detailed expressions of aerodynamic coefficients are given by

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

The dynamic pressure is expressed as $\bar{q} = 0.5\rho V^2$, while the air density is given by $\rho = \rho_0\exp[-(h - h_0)/h_s]$. We refer the in-

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