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Active robust control of uncertainty and flexibility suppression for air-breathing hypersonic vehicles

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ABSTRACT

Inevitable uncertainties and cross couplings between rigid and flexible modes pose huge challenges to control system design for flexible air-breathing hypersonic vehicles. This paper addresses an active robust control scheme that can simultaneously suppress diverse uncertainties and flexible modes using active approaches rather than inherent system robustness. Frequency-domain analysis is conducted to investigate the cross couplings. A novel conclusion lies in that the most significant cross couplings exist between the flexible modes and the rigid-body phugoid modes, followed by the altitude mode. Based on the analysis, a robust control scheme is proposed which consists of a stabilizing control frame and two active control techniques: a nonlinear extended state observer (ESO) and a notch filter. The ESO estimates diverse uncertainties to form a compensation law, and the notch filter is integrated to prevent the flexible modes from being excited by some specific high-frequency signals coming from the ESO estimated values. Thus, both uncertainties and flexible modes can be simultaneously suppressed. A Lyapunov-based stability analysis is conducted for the overall closed-loop system. At last, several representative simulations are conducted to demonstrate the advantages of the proposed active control scheme.

1. Introduction

Air-breathing hypersonic vehicles have been drawing lots of attention in recent decades because of their dramatic advantages such as fast flight speed, large payload, good cost-effectiveness, etc. Considerable design efforts since 1960s have brought encouraging achievements, including the successful flight tests of NASA X-43A [26] and, more recently, U.S. Air Force X-51A [10]. However, it is still a long way for practical and affordable vehicles to be used in real applications due to their peculiar dynamic behavior. These vehicles usually consist of long, slender configurations with light materials, causing noticeable flexible modes that own much slower frequencies than normal aircraft [29,17,18,3,1]. Significant couplings therefore exist between rigid and flexible modes, making control system design a challenging task. Particularly if the flexible modes get excited due to, for example, extreme aerodynamic heating, these coupling effects may cause instabilities and even potential structural damages. Besides the flexibility effects, uncertainties also exist inevitably in practical applications because of complex, even unknown vehicle behaviors and environment features during large flight envelopes [4,24,30,31,19]. In fact, the uncertainty effects are tightly connected with the flexibility effects: some specific high-frequency uncertainties could excite the flexible modes and, in return, the excited flexibility effects could generate larger uncertainties. This interconnection can further degrade control performances. Generally, for a flexible air-breathing hypersonic vehicle (FAHV), interactions of the rigid modes, flexible modes, controls, and uncertainties can be illustrated as in Fig. 1.

In view of the interactions mentioned above, it is quite required for FAHV to design a robust control scheme that can simultaneously achieve *active suppression* of both the flexible modes and diverse uncertainties. Here, "active" means special designs according to vehicle characteristics are included, which differs from other "passive" suppression ways roughly based on inherent system robustness. However, this simultaneous active control idea is, to the best of our knowledge, not available in current researches. In the literature, linear approaches [25,28,12,15] and nonlinear control design such as feedback linearization [21], robust adaptive inversion [6], and high-order sliding mode technique [33] were adopted. In these literatures, the flexibility effects were taken as uncertainties to the rigid-body model and were implicitly rejected by inherent system robustness. This *passive* idea is applicable only when flexible modes are not excited thus the coupling effects are not severe enough. As a rare exception, [16] utilized an active idea where a notch filter that acted on the control inputs was designed so as to actively suppress the flexible modes. Unfortunately, in this

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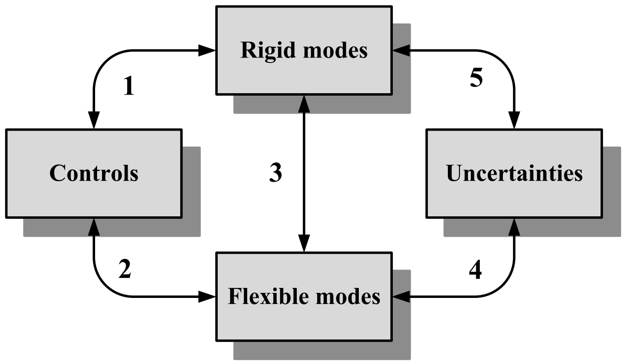

Fig. 1. Interactions of the rigid modes, flexible modes, controls, and uncertainties.

paper, uncertainties, as a tightly-connected factor with the flexibility, were not simultaneously considered. Similarly, although the uncertainty rejection problem was (passively) considered in many literatures [28,12,21], the flexibility rejection problem was not integrated there as a whole.

Building upon our recent work on uncertainty modeling and analysis [22], we present here an active robust control scheme for uncertainty and flexible modes suppression of the FAHV model by Bolender and Doman [3,1]. This scheme consists of a main stabilizing control frame and two active control techniques in the main frame: a nonlinear observer for uncertainty estimation and a notch filter for flexibility suppression. Based on Fig. 1, the control idea is addressed as follows. First, to reject diverse uncertainties existing in Paths 4 and 5, the nonlinear observer is designed to actively estimate and compensate the uncertainty effects. Therefore, information of the uncertainties is reflected in the controls through estimated signals. If the original uncertainties contain some components with frequencies closed to the flexible modes, the estimated signals may achieve an opposite result: they may excite the flexible modes and increase the couplings between rigid and flexible modes through Paths 1 and 2. To suppress this potential excitation effect, the notch filter is further designed subsequent to the uncertainty observers. In a sense, this control scheme makes a tradeoff between estimation performance and flexibility suppression. Therefore, both uncertainties and flexible excitations can be actively suppressed (not implicitly suppressed by inherent system robustness) simultaneously.

As for relevant control methods in the proposed scheme, nonlinear dynamic inversion (NDI) [27,11] is adopted to design the main stabilizing control frame. Its inherent drawback of requiring exact knowledge of model dynamics is counteracted by uncertainty estimation and compensation. The uncertainty observer is implemented by an active disturbance rejection control (ADRC) [8,9,32,7,13] technique: the extended state observer (ESO) technique. ESO utilizes nonlinear structures which exhibit high efficiency of estimating both internal and external disturbances. Its great simplicity can significantly shorten online computing time and meet fast computation requirement in practical hypersonic missions, which is a great advantage over other time-consuming estimation techniques such as fuzzy logic and neural network. ESO also performs as a good low-pass filter, thus can be used to construct the notch filter. In this paper, both ESO and a traditional linear approach are utilized to design the notch filter, and their differences are also investigated.

The primary contributions of this paper lie in that: (a) model characteristics associated with uncertainties and cross flexibility couplings are analyzed; (b) based on the analysis, uncertainty rejection and flexibility suppression are treated as one interconnected problem; (c) for this interconnected problem, an active scheme is proposed that can achieve simultaneous suppression

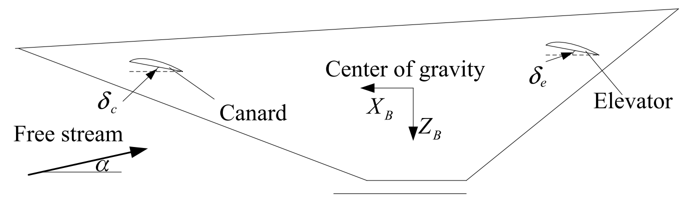

Fig. 2. Geometry of the FAHV model.

by ESO and notch filter, respectively. The paper is organized as follows. The FAHV motion equations, together with model analysis, are given in Section 2. Section 3 addresses the active control scheme. A main stabilizing control frame is firstly designed. Then uncertainty observers and flexible mode notch filters are developed. The frequency properties of the notch filters are also discussed in this section. Stability of the closed-loop system is derived based on Lyapunov theories in Section 4. Several representative simulations are conducted in Section 5. Section 6 concludes the paper and points out some future works.

2. Model description and analysis

2.1. Vehicle model

The vehicle studied in this paper is the model developed by Bolender and Doman [3,1] for the longitudinal dynamics of an FAHV with the sketch illustrated in Fig. 2. Flexibility effects are included by modeling the fuselage as a free–free beam so that the flexible modes are orthogonal to the rigid-body modes and the coupling effects between the flexible and rigid dynamics occur through the forces and moments [5]. Assume a flat Earth and normalize the vehicle to unit depth. Nominal motion equations of FAHV without extra disturbances are described as

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

$$\dot{\gamma} = (L + T\sin\alpha)/(mV) - g\cos\gamma/V \tag{2}$$

$$\dot{h} = V\sin\gamma \tag{3}$$

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

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

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

This model consists of eleven flight states: $\boldsymbol{x} = [V, \gamma, h, \alpha, Q]^T$ for the rigid-body with velocity V, flight-path angle (FPA) γ, altitude h, angle of attack (AOA) α, pitch rate Q, and $\boldsymbol{\eta} = [\eta_1, \dot{\eta}_1, \eta_2, \dot{\eta}_2, \eta_3, \dot{\eta}_3]^T$ for the first three flexible modes. Here m denotes mass, I_{yy} is moment of inertia, and g represents gravitational acceleration. The nominal modal frequencies are set as $\omega_1 = 21.17$ rad/s, $\omega_2 = 53.92$ rad/s, and $\omega_3 = 109.1$ rad/s [25], while for all flexible modes the damping ratio is constant: $\xi_i = 0.02$, indicating a severe mode vibration. As depicted in Fig. 2, a canard is included as an extra actuator to overcome the nonminimum phase feature of the flight-path dynamics reported in [2]. Its deflection δ_c is ganged with the elevator deflection δ_e with a negative gain $k_{ec} : \delta_c = k_{ec}\delta_e$. Therefore, the actual control input that needs control law design is $\boldsymbol{u} = [\delta_e, \phi]^T$, where ϕ is the fuel equivalence ratio. The output to be controlled is selected as $\boldsymbol{y} = [V, h]^T$. The lift L, drag D, thrust T, pitching moment M, and generalized forces N_i are complicated nonlinear functions of the flight states and control inputs. For the sake of control design and stability analysis, Fiorentini [5] developed a control design model (CDM) to approximate the forces and moment based on curve fitting. In the CDM, the forces and moment are described as