Acta Astronautica 101 (2014) 16–32

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Uncertainty analysis and robust trajectory linearization control of a flexible air-breathing hypersonic vehicle

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ARTICLE INFO

Article history:
Received 23 May 2013
Received in revised form
20 November 2013
Accepted 27 January 2014
Available online 3 February 2014

Keywords:
Uncertainty
Flexible
Hypersonic vehicle
Trajectory linearization control
Extended state observer

ABSTRACT

Flexible air-breathing hypersonic vehicles feature significant uncertainties which pose huge challenges to robust controller designs. In this paper, four major categories of uncertainties are analyzed, that is, uncertainties associated with flexible effects, aerodynamic parameter variations, external environmental disturbances, and control-oriented modeling errors. A uniform nonlinear uncertainty model is explored for the first three uncertainties which lumps all uncertainties together and consequently is beneficial for controller synthesis. The fourth uncertainty is additionally considered in stability analysis. Based on these analyses, the starting point of the control design is to decompose the vehicle dynamics into five functional subsystems. Then a robust trajectory linearization control (TLC) scheme consisting of five robust subsystem controllers is proposed. In each subsystem controller, TLC is combined with the extended state observer (ESO) technique for uncertainty compensation. The stability of the overall closed-loop system with the four aforementioned uncertainties and additional singular perturbations is analyzed. Particularly, the stability of nonlinear ESO is also discussed from a Liénard system perspective. At last, simulations demonstrate the great control performance and the uncertainty rejection ability of the robust scheme.

1. Introduction

Air-breathing hypersonic vehicles are viewed as a reliable and cost-effective solution to access the space routine. Since the 1960s, considerable effort has been made to develop practical and affordable vehicles. Recent achievements include the successful flight tests of NASA X-43A [1] and U.S. Air Force X-51A [2]. However, the design of robust guidance and control systems is still a challenging task due to complex coupling effects and significant uncertainties [3–8]. Hypersonic flight usually covers a large flight envelope during which the environmental and aerodynamic characteristics undergo huge variations. The slender geometries and light structures required for these aircraft cause significant uncertain flexible effects. Strong interactions also exist among propulsion, structure, aerodynamics, and control. In addition, the lack of experimental data makes the vehicle model far less accurate [9–16].

In the recent literature, there are two dominant flexible air-breathing hypersonic vehicle (FAHV) models: one is the first-principle model developed by Bolender and Doman [3,4], the other is the computational fluid dynamics (CFD) based model of Mirmirani et al. [5]. Based on these models, diverse control systems are designed with varying levels of model fidelity. For the first model, linear approaches were applied for control design in [8–10] based on model linearization around trim conditions. In these cases, strategies in the frequency domain could be easily applied to evaluate the linear approaches. However, gain scheduling was needed

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http://dx.doi.org/10.1016/j.actaastro.2014.01.025
0094-5765

among the trim conditions for a large flight envelope, thus proof of the stability of the whole scheduled system became a challenging task. As for the nonlinear methods, feedback linearization [11], robust adaptive inversion-based design [12], and quasi-continuous high-order sliding mode approach [13] were proposed with less complex uncertainties than those considered in this paper. For the second model which is not discussed in this paper, Kuipers et al. [17] developed an adaptive linear quadratic controller, while Levin et al. [18] presented a control scheme that could suppress unknown or changing flexible modes online. Despite these research results, the design of robust control systems is still an open problem because of the peculiarity of the vehicle dynamics [12].

In the context of the aforementioned literature, the current research focus of FAHV is to design a controller that can achieve robust output tracking under diverse uncertainties. This problem is considered in many papers [9–16] with different kinds and varying levels of uncertainties. In [9–12], however, the uncertainties were only applied to test the system robustness. That means no particular technique was adopted to deal with uncertainties, and the uncertainty should be constrained within the stability domain of the closed-loop system. For a model based control method, in order to design a controller that owns the best uncertainty rejection ability, a valid uncertainty model is assumed to be available. Development of such a model, however, has received far less attention in the literature. Rehman et al. [14] developed an uncertainty model that considered 24 uncertain inertial and aerodynamic parameters. This model was chiefly based on mathematical computation to make feedback linearization applicable, but physical genesis of the uncertainties was not discussed. Buschek et al. [15] and Chavez et al. [16] presented another two uncertainty models which were only applicable to linear control law synthesis. In this paper, based on different physical and/or mathematical geneses, uncertainties are characterized by four types: flexibility effects, aerodynamic parameter uncertainties, external environmental disturbances, and control-oriented modeling errors. The first three uncertainties physically exist in vehicle dynamics, thus open-loop behaviors of FAHV with these uncertainties are analyzed, offering insights on the vehicle features and guidelines for control design. Based on the analysis, we develop a uniform nonlinear uncertainty model that is more realistic for FAHV. This model lumps all these three uncertainties together and is therefore beneficial for compensation design. This model also features two “disturbance-matching matrices” which clearly describe the physics of typical aerodynamic parameter uncertainties such as propulsive perturbations and variations in control effectiveness. The fourth uncertainty results from mathematical derivation of the control law design and is not included in the uncertainty model. However, it is considered in closed-loop stability analysis.

Based on the uncertainty analysis and modeling, we propose a robust control scheme that combines trajectory linearization control (TLC) [19–25] and extended state observer (ESO) [26–28]. As a novel nonlinear control approach, TLC can inherently guarantee the exponential stability of the closed-loop system along nominal trajectories using linear time-varying (LTV) system PD-spectral theory [29]. Moreover, TLC provides a unique time-varying bandwidth (TVB) technique to feasibly improve control performance and system robustness. Because of its simplicity and inherent robustness, TLC has been applied to hypersonic vehicles [19–21], unmanned aircraft [24], and mobile robots [25]. In this paper, TLC is integrated with ESO for uncertainty estimation, forming a robust TLC scheme. By adopting simple nonlinear structures, ESO shows high estimation efficiency while maintaining good flexibility as the control scheme can be easily redesigned to determine whether ESO is used in one specific control channel or in all channels. In addition, its great simplicity can significantly shorten the computing time and meet the 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.

To sum up, the objective of this paper is to design a robust TLC scheme for FAHV in the presence of multiple uncertainties. The paper is organized as follows. The FAHV motion equations, together with force/moment expressions, are given in Section 2. Uncertainty analysis and modeling are discussed in Section 3. Section 4 addresses the control scheme design. The vehicle dynamics are decomposed into five functional subsystems. In each subsystem, a basic TLC configuration, together with an adaptive TVB algorithm, is integrated with ESO for uncertainty estimation. Section 5 presents stability analysis of the perturbed closed-loop system, where the aforementioned uncertainties and additional singular perturbations are considered. The stability of nonlinear ESO is also analyzed in this section from a Liénard system perspective. Section 6 contains multiple simulations to show the effectiveness of the robust scheme. Finally conclusions are drawn in Section 7.

2. Vehicle model

The vehicle studied in this paper is the model developed by Bolender and Doman [3,4] for the longitudinal dynamics of a FAHV. Its sketch is illustrated in Fig. 1. Flexibility effects are included by modeling the fuselage as two cantilever beams clamped at the center of gravity, rather than a single free–free beam as done in [7–9]. This vibrational model captures the inertial coupling between the rigid-body states and the flexible states, resulting in a system that is more complex to control [4]. Assuming a flat Earth and normalizing the vehicle to unit depth, the equations of motion are written in the stability axes as [11]

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

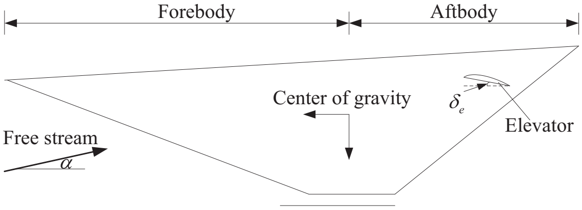

Fig. 1. Geometry of the hypersonic vehicle model.