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Disturbance observer based robust mixed H_2/H_∞ fuzzy tracking control for hypersonic vehicles

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Abstract

This paper introduces a disturbance observer (DO) based mixed H_2/H_∞ robust fuzzy tracking control design for the longitudinal dynamics of a generic hypersonic vehicle (HV) with modeled and unmodeled disturbances. A Takagi–Sugeno (T–S) fuzzy model is firstly employed to approximate the nonlinear dynamics of HV. Subsequently, based on the fuzzy model, a DO is constructed to estimate the modeled disturbance. Next, by integrating the HV dynamics, the tracking error integral and the disturbance estimation error dynamics, an augmented system is established for the control design. Then, a DO-based mixed H_2/H_∞ robust fuzzy control design is developed to ensure the asymptotic stability as well as the mixed H_2/H_∞ control performance of the augmented system. The proposed control scheme includes a fuzzy tracking controller with state feedback plus the tracking error integral, a robust nonlinear compensator for eliminating the matched part of the compound disturbance consisting of the unmodeled disturbance and fuzzy modeling error, and a DO-based compensator for the modeled disturbance cancellation. The outcome of the DO-based mixed H_2/H_∞ robust fuzzy control problem is formulated in terms of linear matrix inequalities (LMIs). Furthermore, by utilizing the existing LMI optimization technique, a suboptimal controller is obtained in the sense of minimizing an upper bound of H_2 performance. Finally, simulation results on an HV demonstrate the effectiveness of the proposed design method.

Keywords: Hypersonic vehicle; Fuzzy control; Disturbance observer; Mixed H_2/H_∞ optimization; Linear matrix inequality

1. Introduction

Hypersonic vehicles (HVs) are envisioned to be the promising technology for the reliable and affordable access to space. However, distinctive dynamic characteristics of HVs together with the aerodynamic effect of the hypersonic flight make this technology more challenging. Besides, a wide range of the flight envelope may lead to significant parameter variations and uncertainties of HVs, which will pose more difficulties to the control system design. As a

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result, a practical flight controller is required not only to stabilize the vehicles but also meet some control performances [1–5]. The existing works on the control design of HVs are mainly developed on the basis of the longitudinal dynamic model. In recent years, some classical linear control methods such as robust linear control and linear parameter-varying control have been studied for the flight control design of HVs in [6–9]. For example, Sigthorsson et al. [8] proposed a robust linear output feedback control method to track a desired trajectory in the presence of model uncertainties; in [9], a mixed real/complex μ-synthesis method was given for designing a flight control system of an HV. Moreover, many nonlinear control techniques have also been applied to the HVs, e.g., backstepping control [10], adaptive control [11,12], sliding mode control [13], and nonlinear dynamic inversion method [14].

On the other hand, external disturbances for HVs such as wind gust are inevitable in the flight control. It is well known that H_∞ control [15] is one of most efficient techniques to attenuate the effect of the uncertain external disturbances. Nevertheless, when dealing with a modeled disturbance in the same channel as the control input, H_∞ control may be too conservative because it can only achieve a good performance level of disturbance attenuation, not cancel the effect of the disturbance. In order to improve the ability of disturbance rejection, the disturbance observer based control (DOBC) scheme in [16] was proposed for a class of nonlinear systems to estimate and counteract the modeled disturbance. A composite control method was presented to cope with multiple disturbances for complex continuous systems by using DOBC and H_∞ control in [17]. Recently, the H_∞ control and DOBC techniques have been applied to handle the anti-disturbance control problems of HVs in [18–21]. For example, H_∞ and μ-synthesis were employed to deal with atmospheric disturbances and uncertainties for an HV in [18]. However, the results in [18] are developed based on the linearized model under a specific trim condition of the HV, which are only valid in the vicinity of the specific trim condition. Sun et al. [19] designed a nonlinear integral sliding mode DOBC law to track a desired trajectory in finite time for an HV with external disturbances. Yang et al. [20] provided a nonlinear robust flight DOBC design for an HV with mismatched disturbances and uncertainties. However, various problems have to be encountered in these nonlinear control schemes in [19–21], which limit the application of these control methods to HVs. For instance, the sliding control law in [19] may lead to chattering in practice; the feedback linearization in [19,20] requires that the nonlinear systems must be sufficiently smooth with exactly known parameters; the finite time control method in [21] is only applicable for specific structural nonlinear systems, to name a few.

In the past two decades, there has been a rapidly growing interest in the fuzzy control of nonlinear systems. Especially, the control technique based on the so-called Takagi–Sugeno (T–S) fuzzy model [22] has attracted lots of attention [23–25], since it is conceptually simple and effective for controlling complex nonlinear systems. Recently, this fuzzy control technique has been applied to the control design of HVs [26–28]. For examples, in [26], Shen et al. have investigated the fault-tolerant control problem of HVs with actuator faults based on the T–S fuzzy model. The guaranteed cost fuzzy tracking control for a flexible air-breathing HV was developed in [27]. However, the control schemes in [26] and [27] do not take the fuzzy approximation error between the original system and the fuzzy model into account, which may result in the control performance degradation and even instability of the system. In [28], by regarding the fuzzy approximation error as a part of a compound disturbance and constructing a disturbance observer (DO), a robust DO-based fuzzy stabilizing controller with adaptive bounding was developed for an HV to achieve the rejection of multiple disturbances. But the quadratic optimal tracking performance is not considered in [28]. In practice, for control engineers, it is usually desirable to design a fuzzy control system which has not only a satisfactory anti-disturbance performance, but also quadratic optimal performance. Although the mixed H_2/H_∞ methods have been proposed to address this issue of multi-objective control design for nonlinear systems in [29] and [30], they are still not enough to achieve an excellent anti-disturbance performance when a modeled disturbance exists in the control input channel. In this situation, it is more appealing to develop a DO-based mixed H_2/H_∞ method for the control design of nonlinear systems, where the modeled disturbance can be compensated via the DO and the other disturbance is attenuated by H_∞ control. To the best of our knowledge, such a multi-objective fuzzy control problem has not been addressed for HVs yet.

In this study, a DO-based mixed H_2/H_∞ fuzzy tracking control method is developed to track a desired trajectory with an excellent anti-disturbance performance as well as an optimized quadratic tracking performance for an HV with modeled and unmodeled disturbances. Initially, the T–S fuzzy model is utilized to approximate the nonlinear dynamics of HVs. Subsequently, a DO is constructed to estimate the modeled disturbances based on the T–S fuzzy model. Then, a DO-based mixed H_2/H_∞ robust fuzzy tracking control design is developed in terms of linear matrix inequalities (LMIs) to ensure the asymptotic stability as well as the mixed H_2/H_∞ control performance of the augmented system consisting of the HV dynamics, the tracking error integral and the disturbance estimation error dynamics. The