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Finite-time fault-tolerant control for flutter of wing

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ABSTRACT

In this paper, we use the radial basis function neural network and the finite-time H_∞ adaptive fault-tolerant control technique to deal with the flutter problem of wings with propulsion system, which is affected by input saturation, time delay, time-varying parameter uncertainties and external disturbances. Then sensor and actuator faults are both considered in the control design. The theory content of this article includes the trajectory optimization, modeling of wing flutter and fault-tolerant controller design. The stability of the finite-time H_∞ adaptive fault-tolerant controller is theoretically proved. Finally, simulation results are given to demonstrate the effectiveness of the scheme.

1. Introduction

During the reentry process of the reentry vehicle, extremely high flight speed leads to serious aerodynamic heating on the surface of the vehicle. Due to high temperature in the flow field, various surface phenomena, such as catalysis and pyrolysis, start to occur, particularly on the place near the stagnation region (Edwards, 1992). To avoid serious surface ablation during the reentry process, temperature protection is necessary. One of the possible solutions to reduce the heating rate on the body surface is using ablative materials (Antonnio & Mario, 2010). However, due to the complicated behavior of ablative materials, studies on these materials are still at an empirical level and the theoretical system for such materials is not perfect. Therefore, optimizing the reentry trajectory of reentry vehicle to reduce the heating rate is of greater importance.

Although the optimized reentry trajectory can decrease the heating rate and temperature on the surface of reentry vehicle, aerodynamic load on the surface of reentry vehicle is still very high. Besides, when the propulsion system becomes the follower force on the wing structure, it will increase vibration of the wing. The coupling of aerodynamic load and propulsion system will give rise to more serious wing flutter. Flutter instability of elastic systems subjected to non-conservative forces have been studied by many authors (Amoozgar, 2013; Mardanpour, Richards, Nabipour, & Hodges, 2014; Mazidi, Kalantari, & Fazelzadeh, 2013). Amoozgar (2013) investigated the aeroelastic instability of a wing model, which behaves as an orthotropic composite beam with a concentrated mass subjected to the engine thrust; Wagner function is used to model the unsteady aerodynamic loads, while the engine thrust is modeled as a follower force and a concentrated mass is used to model the engine mass. Mardanpour et al. (2014) using the code NATASHA (Nonlinear Aeroelastic Trim And Stability of HALE Aircraft) investigated the effects of multiple engine placement on flutter characteristics of a backswept flying wing. Mazidi et al. (2013) presented the aeroelastic response of a wing containing an engine subjected to different types of time-dependent thrust excitations. However, few would consider building a connection between the propulsion system and the wing flutter, such as the inlet ramp angle speed of turbine and compressor, fuel flow of the combustor and after-burner, and the variable nozzle area, etc.

Flutter instability may decrease aircraft performance or even lead to the catastrophic failure of the structure (Zhao, 2009). The technique of active flutter suppression has drawn much attention over the past decade (Cassaro & Battipede, 2015; Wang, Behal, & Marzocca, 2012; Zhang, Wang, Behal, & Marzocca, 2013). For example, Wang et al. (2012) considered a class of aeroelastic systems with an unmodeled nonlinearity and external disturbance and proposed a full-state feedforward/feedback controller with a high-

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gain observer; they also designed a continuous robust controller to suppress the aeroelastic vibrations of a nonlinear wing-section model. Zhang et al. (2013) designed a partial state feedback continuous adaptive controller in order to suppress the aeroelastic vibrations of the wing section model. Cassaro and Battipede (2015) considered a class of aeroelastic systems with parameter uncertainties and designed an adaptive control architectures for flutter suppression; they also designed an adaptive controller involves signal filtering in order to improve system performance. Although a number of flutter controller design approaches, most of the research assume that there exists no actuator fault or failure during the entire flutter suppression. This assumption is rarely satisfied in practice because malfunction of actuators may cause some catastrophic faults. As a result, if the flutter controller is designed without any fault tolerance capability, an abrupt occurrence of an actuator fault could ultimately cause failure of the flutter control. Therefore, we must give priority to considering the faults of actuators and sensors in the design of the flutter controller. Therefore, the fault tolerant control should be taken into consideration for the flutter control.

Fault-tolerant control (FTC) is a control design strategy that guarantees system stability and acceptable performance (Shen, Wang, Zhu, & Poh, 2015). In general, FTC methods are classified into two types: passive fault tolerant control (PFTC) and active fault tolerant control (AFTC) schemes (Allerhand & Shaked, 2015; Cao, Chen, & Misra, 2014; Castaldi, Mimmo, & Simani, 2014; Fonod et al., 2015; Hu, Xiao, & Friswell, 2011; Jia, Chen, Zhang, & Li, 2015; Li & Yang, 2012; Liu, Qiu, Cui, & Sun, 2016; Marino, Scalzi, Tomei, & Verrelli, 2013; Mekki, Benzineb, Boukhetala, Tadjine & Benbouzid, 2015; Wang, Jing, Karimi, & Chen, 2015; Xiao, Hu, & Zhang, 2012). The similarities and differences between these two FTC design methodologies can be found in Jiang and Yu (2012). Shen et al. (2015) designed a fault-tolerant attitude tracking control for an over-actuated spacecraft in the presence of actuator faults/failures and external disturbances; the time-varying dead-zone modification technique is employed to improve the robustness of the adaptive law. Li and Yang (2012) developed a robust adaptive fault-tolerant compensation control schemes for linear systems with parameter uncertainty, disturbance and actuator faults including outage, loss of effectiveness and stuck. Liu et al. (2016) designed a novel fault-tolerant H_∞ control for a class of networked control systems with randomly occurring missing measurements; moreover, network-induced time-varying delay is considered in the network model. Allerhand and Shaked (2015) considered as switching in the system dynamics and proposed a fault tolerant control approach to model multiplicative faults. Jia et al. (2015) constructed a novel fuzzy descriptor learning observer to achieve simultaneous reconstruction of system states and actuator faults; utilizing the reconstructed fault information, a reconfigurable fuzzy fault-tolerant controller is designed to compensate for the impact of actuator faults. In the active flutter suppression of reentry vehicle, multiple control surfaces and sensors arranged on the surface of the wing are under adverse aerodynamic heating and constantly changing flight condition, and there exist unpredictability and diversity to the faults. The passive fault-tolerant control designed by limited faults and fixed controller will not be able to guarantee the performance of the system. Therefore, the active fault-tolerant control has proposed in this paper. It is worth mentioning that the above researches (Cassaro & Battipede, 2015; Wang et al., 2012; Zhang et al., 2013) are derived from the assumption that the controllers are able to provide any requested outputs. However, in the reentry process, hypersonic vehicles demand large control forces and signal magnitude, the control actions are usually limited, which means the controller is under actuator saturation. So we must take actuator saturation into account in the design of controller; in the previous active flutter control researches, there are two common methods to deal with actuator saturation; please see reference Applebaum and Ben-Asher (2007) for more details. However, both the above methods require validation of controllability and stability for specific initial conditions and control constraints through an iterative process of parameter selection and numerical simulations. At the beginning of controller design, Applebaum and Ben-Asher (2007) considered the saturation nonlinearity, and thus designed an anti-saturation flutter controller. However, this method needs firstly to compute a conservative estimate of the domain of attraction for the closed-loop antistable subsystem. In addition, these references (Cassaro & Battipede, 2015; Wang et al., 2012; Zhang et al., 2013) are mainly focusing on the problems of linear and nonlinear systems over an infinite-time interval. However, in the actual reentry process of vehicle, the flutter will destroy the vehicle in a short time, we must control the flutter within a certain range in a finite time. To the best of our knowledge, the studies on finite-time H_∞ adaptive fault-tolerant control of wing flutter subject to actuator saturation and parameter uncertainties are very limited in the published literature.

On the other hand, the state of the hypersonic reentry vehicle changes fast in a short time. Therefore, time delay exists inevitably in active control system, which mainly results from the following: (1) the time taken in the online data acquisition from sensors at different locations of the system; (2) the time taken in the filtering and processing of the sensory data for the required control force calculation and the transmission of the control force to the actuator; and (3) the time taken by the actuator to produce the required control force. Due to the time delay, when unsynchronized control force is applied to a structure, it may result in degradation in the control efficiency and instability of the control system. Among the studies on active flutter suppression, only few of them have addressed the effect of time delays on the stability of controlled aeroelastic systems (Huang, Qian, Hu, & Zhao, 2015; Singh, 2015; Zhao, 2011). Huang et al. (2015) presented a new optimal control law to suppress the flutter with an input time delay in the control loop and the delayed controller was digitally implemented and tested for the three-dimensional wing model in NH-2 subsonic wind-tunnel. Singh (2015) considered a single time delay in the control loop and presented flutter boundary extension by partial pole placement in an aeroelastic system to suppress airfoil flutter. Zhao (2011) investigated the effect of time delay on the flutter instability of an actively controlled airfoil in an incompressible flow field. However, these studies are based on the controller which is designed when the actuator is with no fault to deal with control delay of flutter. When the actuator is in faults, these control methods will be not applicable for control delay problem of flutter.

In order to reveal the negative effect of the conventional control on the stability of aeroelastic system and considering the influence of faults, control delay, actuator saturation, parameter uncertainties and external disturbances, this paper focuses on the design of H_∞ adaptive fault-tolerant controller for flutter of wing. Main contribution: comparing with the existing researches, we think that our study has two innovation points: (i) we optimize the reentry trajectory of the vehicle so as to decrease the temperature and the aerodynamic heating of the vehicle surface. Furthermore, based on the trajectory optimization, we ignores the influence of temperature and establish the equation of wing flutter carrying with the propulsion system. Therefore, compared with (Amoozgar, 2013; Mardanpour et al., 2014; Mazidi et al., 2013) previous studies, our research is of great significance. (ii) In order to reveal the negative effect of the conventional control on the stability of aeroelastic system (Cassaro & Battipede, 2015; Huang et al., 2015; Singh, 2015; Wang et al., 2012; Zhang et al., 2013; Zhao, 2009, 2011) and consider the influence of faults, time delay,