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Robust fault-tolerant control for wing flutter under actuator failure

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Observer

Abstract Many control laws, such as optimal controller and classical controller, have seen their applications to suppressing the aeroelastic vibrations of the aeroelastic system. However, those control laws may not work effectively if the aeroelastic system involves actuator faults. In the current study for wing flutter of reentry vehicle, the effect of actuator faults on wing flutter system is rarely considered and few of the fault-tolerant control problems are taken into account. 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, which is affected by actuator faults, actuator saturation, parameter uncertainties and external disturbances. The theory of this article includes the modeling of wing flutter and fault-tolerant controller design. The stability of the finite-time adaptive fault-tolerant controller is theoretically proved. Simulation results indicate that the designed fault-tolerant flutter controller can effectively deal with the faults in the flutter system and can promptly suppress the wing flutter as well.

1. Introduction

With the rapid development of aerospace technology, modern aircraft perform their characteristics such as high velocity, lightweight structures, flexible and low damping, which makes the aeroelasticity phenomenon more and more prominent. Flutter is one of such problems. Flutter instability may decrease aircraft performance or even lead to the catastrophic failure of the structure.[1] The traditional passive techniques are usually inefficient (because they add weight to the structure), and they do not always succeed. In order to overcome the inadequacy of passive techniques, the active flutter suppression techniques were developed in early 1970s. In active flutter suppression, we carry it out by utilizing multiple steerable control surfaces laid out on the surface of the wing.

The technique of active flutter suppression has drawn much attention over the past decade.[2–6] For example, Yu et al.[2] designed a μ controller to suppress airfoil flutter, and wind tunnel experiments were carried out to verify the effectiveness

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of the designed controllers. Prime et al.[3] synthesized a state-feedback controller using linear matrix inequalities (LMIs) to control the vibration of an improved three-degree-of-freedom aeroelastic model and this controller could effectively suppress limit-cycle oscillations over a range of airspeeds. Wang et al.[4,5] considered a class of aeroelastic systems with an unmodeled nonlinearity and external disturbance and proposed a full-state feedforward/feedback controller with a high-gain observer; they also designed a continuous robust controller to suppress the aeroelastic vibrations of a nonlinear wing-section model. Zhang et al.[6] designed a partial state feedback continuous adaptive controller in order to suppress the aeroelastic vibrations of the wing section model.

Although a number of flutter controller design approaches,[2–6] most of the researches assume that there exists no actuator fault or failure during the entire flutter suppression. This assumption is rarely satisfied in practice because some catastrophic faults may occur due to the malfunction of actuators. As a result, if the flutter controller is designed without any fault tolerance capability, an abrupt occurrence of an actuator fault could ultimately fail 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 (FTC)[7] should be taken into consideration for the flutter control. In general, FTC methods are classified into two types: passive fault-tolerant control (PFTC) and active fault-tolerant control (AFTC) schemes.[7] The PFTC designed by limited faults and fixed controller will not be able to guarantee the performance of the system.[8–10] Correspondingly, active method[11–13] may provide more powerful fault-tolerant capability for compensating for faults of the systems in terms of reconfiguring control strategies online or switching to a more suitable control law based on the fault information. Therefore, in this paper, the investigation of an active fault-tolerant controller for a flutter control system with the occurrence of unexpected faults or failures. It is worth mentioning that the above results[2–6] are derived from the assumption that the actuators are able to provide any requested outputs. However, in almost every physical application, the actuator has bounds on its input. Therefore, the phenomenon of actuator saturation has to be considered when the controller is designed in practical industrial process control field. In addition, the flutter will destroy the vehicle in a short time, we must control the flutter within a certain range in a finite time. However, to the best of our knowledge, the studies on finite-time adaptive fault-tolerant control of wing flutter are very limited in the published literature.

In order to reveal the negative effect of the conventional control on the stability of aeroelastic system and considering the influence of faults, time-varying parameter uncertainties and external disturbances, this paper focuses on the design of finite-time H_∞ adaptive fault-tolerant controller for flutter of wing. A 2D cubic structure nonlinearity wing system is adopted as structure model. The actuator fault is considered in the controller design. This paper is organized as follows. The dynamic equation of wing flutter and the control problem of flutter system with faults are established in Section 2. Section 3 presents a finite-time adaptive fault-tolerant flutter controller based on observer. Numerical simulations are given in Section 4. Section 5 briefs the conclusions of the research.

2. Flutter model of 2D wing and fault-tolerant control problem

In this section, we briefly recall the mathematical model for the flutter of a reentry vehicle with actuators fault-free. Based on this nominal flutter system, the state equation with actuator faults and saturation, parameter uncertainties and external disturbances are established.

2.1. Wing flutter model under actuators fault-free

In this section, flutter problem for a 2D wing including cubic hard spring nonlinearity is analyzed. As shown in Fig. 1, a two degree-of-freedom (2-DOF) wing system model is considered herein. The plunge deflection is denoted by h, positive in the downward direction; θ is the pitch angle about the elastic axis, positive nose up; V denotes the air speed; the chord length is c; Q, p and C are the aerodynamic center, elastic axis and center of mass, respectively; the distance from the leading edge to the elastic axis is x_p, and that from the leading edge to the mass center is x_C; δ_{LEout} and δ_{LEin} (or δ_{REout} and δ_{REin}) are the control surface angles.

From Fig. 1, the velocity of mass center of wing can be expressed as

$$\dot{z} = \dot{h} + (x_C - x_p)\dot{\theta} \tag{1}$$

The kinetic energy, potential energy and dissipation of the system can be given by

$$\begin{cases} T = \frac{1}{2}m_{\text{W}}\dot{z}^2 + \frac{1}{2}m_{\text{e}}\dot{h}^2 + \frac{1}{2}I_{\text{C}}\dot{\theta}^2 \\ U = \frac{1}{2}K_h h^2 + \frac{1}{2}K_\theta \theta^2 \\ \zeta = \frac{1}{2}C_h\dot{h}^2 + \frac{1}{2}C_\theta\dot{\theta}^2 \end{cases} \tag{2}$$

where I_{C}, m_{W}, m_{e}, K_h, K_θ, C_h and C_θ are the moment of inertia about center of mass, wing mass, wing extra-mass, stiffness coefficient in plunge, torsion stiffness coefficient, damping coefficient in plunge and torsion damping coefficient, respectively.

For supersonic and hypersonic flow, the piston theory is widely used to calculate the aerodynamics acting on a lifting surface.[14] Applying the piston theory, the aerodynamic force and moment acting on the wing can be obtained as

$$\begin{cases} L = \frac{2\rho V\bar{\gamma}c}{M_\infty}\left[0.5c(1-x_0)\dot{\theta} + \dot{h} + V\theta + \frac{1}{12}V\bar{\gamma}^2(\kappa+1)M_\infty^2\theta^3\right] \\ M_{\text{T}} = \frac{\rho V\bar{\gamma}c^2}{M_\infty}\left[\frac{1}{6}c(4-6x_0+3x_0^2)\dot{\theta} + (1-x_0)\dot{h} + V(1-x_0)\theta + \frac{1}{12}\bar{\gamma}^2(\kappa+1)M_\infty^2(1-x_0)V\theta^3\right] \end{cases} \tag{3}$$