Journal of Sound and Vibration 430 (2018) 101–114

Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

Vibration active control of structure with parameter perturbation using fractional order positive position feedback controller

Wenchao Niu, Bin Li*, Tao Xin, Wei Wang

School of Aeronautics, Northwestern Polytechnical University, Xi'an, Shaanxi 710072, China

A R T I C L E I N F O

Article history:
Received 11 December 2017
Received in revised form 13 May 2018
Accepted 25 May 2018

Handling Editor: D. J. Wagg

Keywords:
Fractional-order control
Positive position feedback
Smart structure
Parameter perturbation uncertainty
Active vibration control

A B S T R A C T

A Fractional-Order Positive Position Feedback (FOPPF) controller is developed by transforming the integer-order exponent of the Positive Position Feedback (PPF) controller into a fractional format to increase the number of designable parameters. The sensitivity of these fractional-order exponents is investigated to assess their influence on the behavior of the FOPPF controller in frequency domain. An optimal design method of FOPPF controller is presented by taking account of the uncertainty of object structure, and constructing an objective function. This objective function is the weighted sum of the suppression ratio of the peak value of power spectral density and the suppression ratio of the root-mean-square value of the random response in the target frequency band. The performance of this controller is analyzed by numerical simulation and experiment using a vertical tail attaching macro fiber composite piezoelectric actuator. Results indicate that a wider band of effective phase compensation is obtained using the FOPPF controller than using the PPF one, and a higher robustness is achieved as well. The FOPPF controller is more effective on suppressing the both periodic and random vibration responses comparing with the PPF and modified PPF controller.

1. Introduction

Due to light-weight, high-flexibility, and suitability for curved surface, active vibration control (AVC) using macro fiber composite (MFC) piezoelectric actuator is widely recognized as one of the most effective ways to suppress the unwanted vibration. This technique has already been applied to control the aircraft body, the flexible cantilever plates and the flexible-link manipulator [1–3]. There are many active control methods that have been proposed in previous research, such as LQR [4], LQG [5], PID [6], positive position feedback (PPF) [7], modified PPF [8], robust [9] and adaptive control [10], etc. [11].

PPF controller is a classical AVC device [7], used to introduce a highly damped second-order compensator, which can be tuned to work at the natural frequency of structure [12]. The PPF controller only affects the selected structural mode [13]. And it is able to keep good roll-off property, allowing high order mode stabilization [14]. Also, the collocated sensor/actuator is applied in the PPF control system without the complex full-state feedback or multipoint feedback. These advantages of PPF controller make it widely used in structural vibration active control, such as the active buffeting control of the aircraft vertical

* Corresponding author.
E-mail address: leebin@nwpu.edu.cn (B. Li).

https://doi.org/10.1016/j.jsv.2018.05.038

tail and ventral fin [1,15]. However, the classical PPF controller usually only shows good suppression effect for steady structure. When the controlled structure is a time-varying system, or its parameters show some degree of uncertainty, the classical PPF controller tends to spill over [14]. The vertical tail of aircraft is a good example. Under high angle of attack, the turbulent flow emanating from the wing/fuselage flows downstream to impinge upon the vertical tails. This unsteady flow typically contains considerable energy and its spectrum covers the dominant vibration modes of the vertical tails. Therefore the fluid-induced structural vibration response, referred to as buffeting, is of high magnitude and essential to the safety of aircrafts. The active vibration control is highly potential means to suppress the buffeting of aircraft structures [15], especially for the twin-vertical tail fighter [16]. Throughout the described fluid-structure interaction process, the vertical tail is coupled with the aerodynamics and thus its structural dynamics are changed, so that the classical PPF controller cannot adapt to the change of the dynamic characteristic of vertical tail. Some adaptive PPF controllers have been developed to improve the adaptability to the changes of system characteristics [17,18]. Nima Mahmoodi developed an adaptive modified PPF (MPPF) controller to improve the ability of system anti-parameter uncertainties [19]. However, all of them need to introduce an adaptive online parameter estimator to update the natural frequencies of system and the error of this estimator cannot meet the requirement in this work [17,20]. Therefore, the robustness of the closed-loop system still exists as a challenge in controller design.

With the development of the numerical method for solving the fractional order calculus, different types of fractional order controllers have been developed, such as fractional order PID controller [21,22], fractional order robust controller [23] and factional order adaptive controller [24]. Such controllers possess more designable parameters [21] and higher robustness [25]. The fractional order control provides a new solution to the PPF controller, able to change the frequency domain characteristics of the traditional controller in the whole target frequency band [26]. Therefore, a fractional-order positive position feedback (FOPPF) controller is developed in this paper by transforming the integer exponents of the classical PPF controller into a fractional format. This method introduces three additional designable parameters to the classical PPF controller, which improves the degrees of freedom for controller design [25]. The influence of the fractional order exponents on the FOPPF controller is also analyzed in this research. An optimization method is developed to design the FOPPF controller with high robustness. Experiments are conducted to check its feasibility for practical implementation.

2. Classical positive position feedback

The block diagram of closed-loop system using classical positive position feedback is plotted in Fig. 1(a), where $G_f(s)$ is the transfer function between the excitation F_p and the open-loop structural vibration response d. In the feedback loop of the system, a compensator $K(s)$ is introduced, which can also be called the transfer function of PPF controller. $G_k(s)$ is the transfer function between the control voltage u and response y. Here, y is the output response generated by the active actuators $G_k(s)$ to counterbalance d. And the closed-loop vibration response e is the superposition results of y and d, which is fed back to the controller. For a collocated sensor/actuator configuration, $G_k(s)$ and $K(s)$, each one provides -90° of phase shift at the selected natural frequency. Since the phase of controller is added in series, the responses of the structure and PPF controller in total contribute -180° of phase shift at the natural frequency [14], which provides an opposite response y to counterbalance the response d.

For a multi-degree of freedom system, the motion equation of a controlled target mode, i.e. the generalized second-order differential equation, is described in Eq. (1), and the corresponding classical PPF controller is shown in Eq. (2).

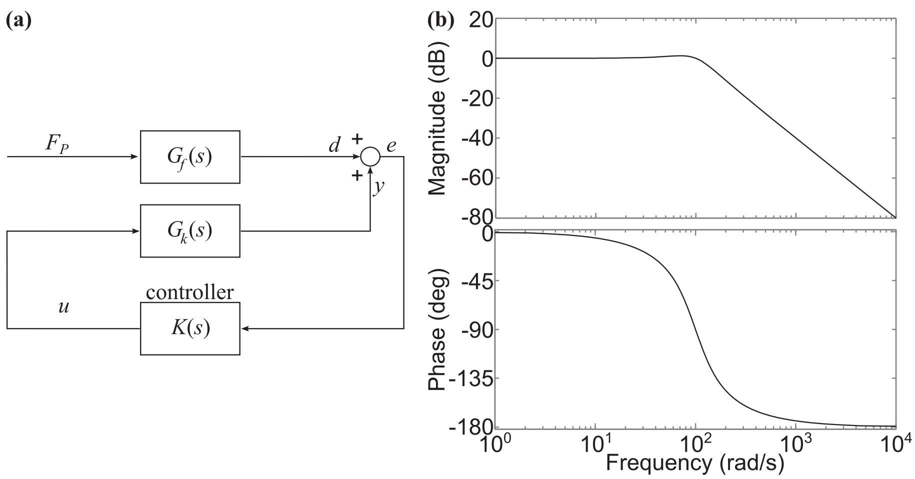

Fig. 1. Diagram of PPF control system. (a) Block diagram of closed-loop system. (b) Bode diagram of PPF controller, where $\zeta_f = 0.5$, and $\omega_f = 100$ rad/s.