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PIEZOELECTRIC-BASED VERTICAL TAIL BUFFET VIBRATION SUPPRESSION USING ADAPTIVE MODIFIED POSITIVE POSITION FEEDBACK

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Aerodynamic buffet is a forced vibration because of the unsteady airflow exerting forces on a vertical tail, which can lead to premature fatigue damage to aircraft vertical tail structures, especially for aircrafts with twin vertical tails at high attack angles. In the paper, the Macro Fiber Composite was used as actuators, and the strain of a vertical tail root was adopted as the input signal of the feedback system. Modified positive position feedback uses two parallel compensators ,which are respectively the first-order and second-order compensators .The first-order term amplifies the damping, and the second-order term focuses on resonant modes of vibration. The phase lag between the input signals and output signals influences the control law in this non-collocated sensor/actuator plants. The phase compensation was identified experimentally. Additionally, frequency estimated method was applied to identify the natural frequencies of the vertical tail in order to update the parameters of the controller. The experiment results verify the effectiveness of MPPF. And the controller performs brilliantly in alleviating the vibration of vertical tail whose natural frequencies is variable to a narrow band external disturbance.

Keywords: buffeting suppression, modified positive position feedback, adaptive, MFC

1. Introduction

Modern double vertical tail aircraft must keep high angles of attack for a long time under the high maneuver flight. However, the highly disorder and unstable separation vortex is caused in both sides as the airflow across the leading edge of a wing, which is terrible for aircraft in the process of flight. Additionally, the flight envelop of the aircraft is greatly limited when the unstable separation vortex pass the vertical tail. If the natural frequencies of some vertical tail modes are contained in the band of separation vortex, vertical tail buffeting is excited by separation vortex. Seriously, it can lead to the fatigue damage to aircraft vertical tail structure, which results that the maintenance and repair costs of the aircraft are increased. Due to the characteristics of light weight, high flexibility, fitting for surface structure, low-cost and low-energy, piezoelectric materials for the structure vibration suppression becomes one of the most popular and effective methods. As a matter of fact, The piezoelectric materials with the characteristics of the direct piezoelectric effect and inverse piezoelectric effect can be used as the transducers and actuators respectively and have been applied in different fields[1,2]. Exploring the better controller for the structure vibration suppression is still an important topic in this area.

Positive position feedback(PPF) controller is one of the most common active controllers in the field of vibration suppression, whose principle is that a second-order compensator is added in the feedback loop of system. The phase of external excitation is opposite to the phase of disturbance generated by actuators, which causes the decrease of the system response. In the mid of 1980s, the concept of PPF controllers was firstly put forward by Goh and Caughey[3], where the stability conditions and the range of parameters were introduced. In the 21st century, PPF controller was studied by lots of researchers. The parameters adjustment methods(e.g. gain and damping coefficient of the controller) and the performance of PPF controllers were discussed in [4]. The single performance of the second-order compensator can't meet the requirement of suppressing both the transient response and the periodic response greatly. Modified positive position feedback(MPPF) controller which consists of a first-order compensator and a second-order compensator working in parallel, a new modified form of PPF controller, was presented in [5],where the damping and the performance of the controller was illustrated. Subsequently, Omidi and Mahmoodi made a series of researches about MPPF controller. Modified positive velocity feedback(MPVF) controller , modified positive acceleration feedback(MPAF) controller and the parameters adjustment method of these controller were discussed[6,7].

According to the characteristics of high gain and damping, MPPF controller has an effect on the transient response and periodic response of the system, which can be utilized to suppress vertical tail buffet vibration. However, the natural frequencies of the vertical tail are time-varying since they are affected by aerodynamic stiffness and damping of the aircraft in the process of the flight. Therefore, frequency estimation method is combined with MPPF controller in the paper. Likewise, the adaptive performance of adaptive modified positive position feedback(AMPPF) controller is improved. For the sake of verifying the effectiveness of the controller, a vertical tail model is used as a test platform for experimental evaluation. Finally, the experimental results are demonstrated and discussed, then final conclusion is made.

2. Adaptive modified positive position feedback controller

Figure 1 demonstrates the block diagram of the closed-loop configuration with the MPPF controller. The controller is added to the feedback loop of system where $G_1(s)$ denotes the transfer function of external excitation and structural response, $G_2(s)$ represents the transfer function of actuator and the structure response, u is error signal and y stands for the response signal of the structure caused by actuator.

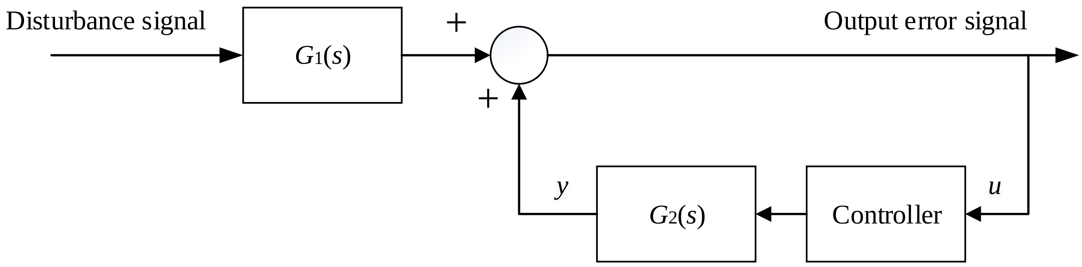


Figure 1 Block diagram of the closed-loop system

For a second-order single degree of freedom system, the modal displacement transits the MPPF controller, then the output of controller feeds back to the system response. The system includes in three equations, one describing the structure and the other two describing the compensators:

$$\ddot{\xi} + 2\zeta_c \omega_c \dot{\xi} + \omega_c^2 \xi = \omega_c^2 \left(\alpha y + \beta z \right) \tag{1}$$

$$\ddot{y} + 2\zeta_f \omega_f \dot{y} + \omega_f^2 y = \omega_f^2 \xi \tag{2}$$

$$\dot{z} + \omega_f z = \omega_f x \tag{3}$$

where ξ represents the modal coordinate of the structure, ζ_c and ω_c are the damping ratio and the natural frequency of the structure respectively, α and β are the gains of controller, y and z stand for the coordinates of the controller, ζ_f and ω_f are the damping and frequency of the controller. The transfer function of controller can be written as:

$$K(s) = \frac{\omega_f^2}{s^2 + 2\zeta_f \omega_f s + \omega_f^2} + \frac{\omega_f}{s + \omega_f} \tag{4}$$

MPPF controller has an essential effect on the transient response and periodic response of structure. For the transient response, MPPF controller needs higher damping to suppress interference faster, and for the periodic response, the vibration can be greatly reduced by MPPF controller with higher gain and low damping[5].

3. Experimental setup

Due to the natural frequencies of the vertical tail are time-varying, it is very significant to study the MPPF controller performance for vertical tail with time-varying natural frequencies buffeting suppression in the section. However, MPPF controller doesn't have an influence on the time-varying mode since it is only effective to a special mode whose natural frequency is fixed. In the paper, frequency estimation method is combined with the MPPF controller so as to adjust the parameters of the controller. The phase lag between the input signals and output signals influences the control law in this non-collocated sensor/actuator plants. Therefore, the phase compensation was applied in the loop of system, which is identified experimentally in order to adjust the phase of system. Figure 2 illustrates that a vertical tail model clamped on the root is used as test platform and twelve piece of Macro Fiber Composite (MFC) actuator are attached to both side of vertical tail symmetrically using epoxy. As it has been mentioned, the MFC is placed closed to the based in order to be capable of suppressing vibration of the first-order mode. In addition, mass blocks are fixed to the tip of vertical tail so as to change the natural frequency of vertical tail. There are three cases, listed in Table 1, to test the performance of AMPPF controller and indicate its self-adaption.

Table 1 Experiment case

Case	Additional weight	1st bend mode
1	0	13.5Hz
2	0.98kg	12Hz
3	1.96kg	10.75Hz

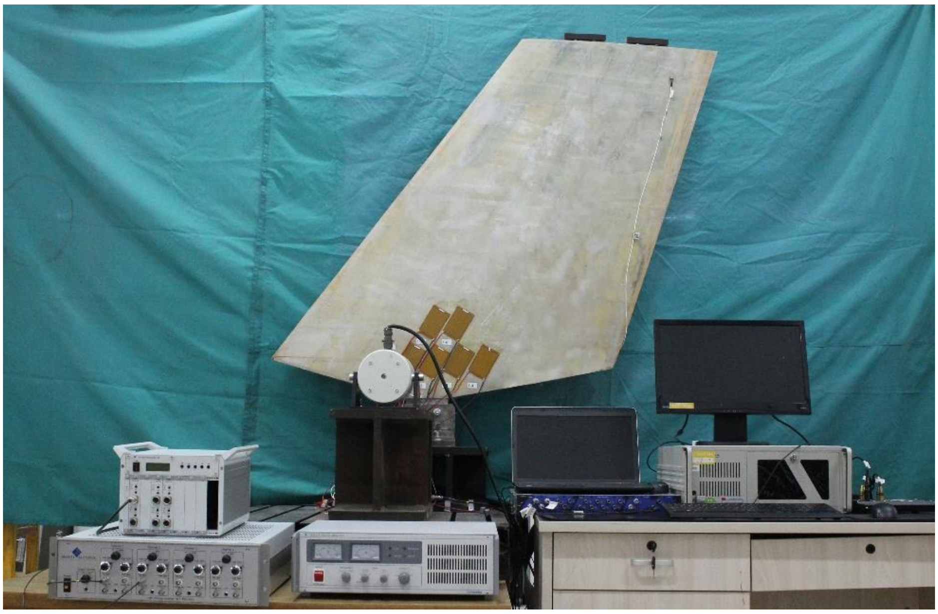


Figure 2 Vertical tail model pasting MFC

Figure 3 depicts the block diagram of vertical tail buffeting suppression experiment system. The experiment system is mainly consisted of vertical tail model pasting MFC, strain sensor, power amplifier, Quanser® board that uses Quanc® and MATLAB Simulink®, and signal acquisition system using m+p smart office®.

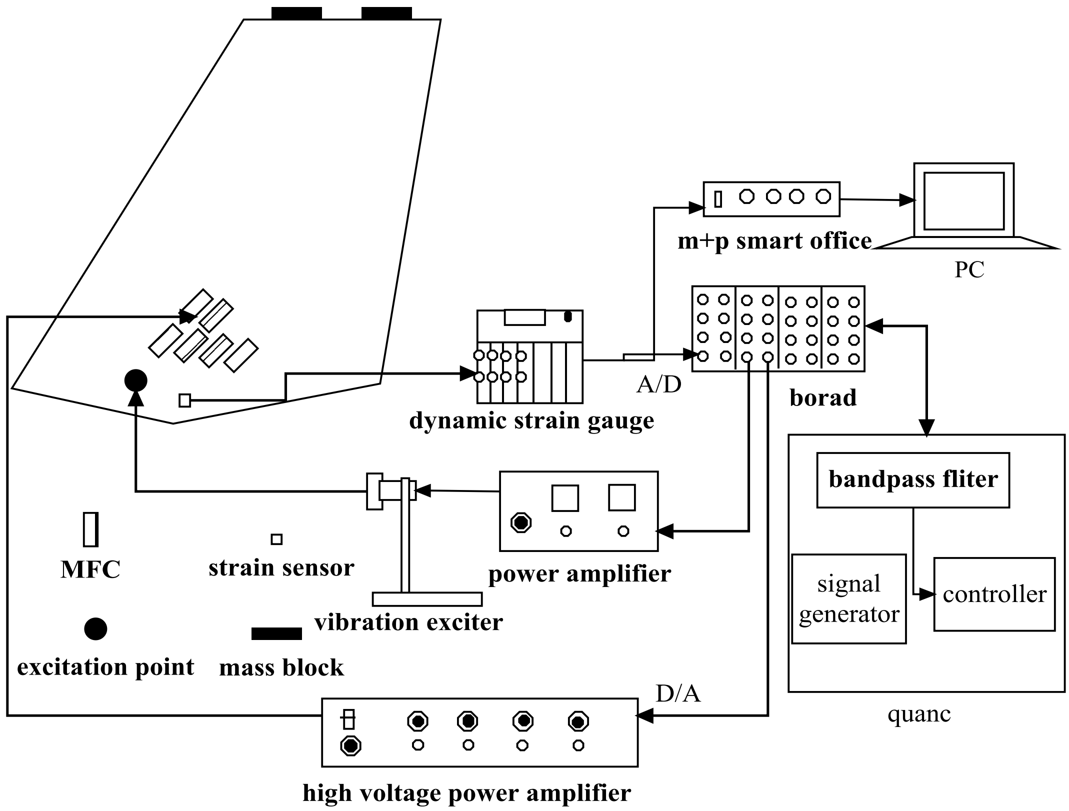


Figure 3 Block diagram of vertical tail buffeting suppression experiment system

Vertical tail buffeting active control experiment system includes:

Part 1. Vertical tail model and the layout of the actuators and sensors are indicated.

Part 2. Strain signal acquisition system is used to record the response of structure. A band-pass filter whose band is [5Hz, 20Hz] is utilized in the acquisition system as so to filter out noise signals.

Part 3. Vertical tail buffeting load system is applied to simulate the buffeting load. A signal generator modules, whose signal inputs to the power amplifier from the output of board, is added in the Simulink. Subsequently, the signal amplified by power amplifier inputs to the exciter and the vertical tail vibration response is excited.

Part 4. Vertical tail buffeting control system is utilized to suppress the vibration of vertical tail. The strain signal inputs to Quanc® board from dynamic strain indicator, then inputs to the high voltage power amplifier after the operation of AMPPF controller. Finally, MFC is driven by high voltage power amplifier.

4. Experimental results and discussions

The vertical tail buffeting ground control experiment is carried out in this section. The performance of AMPPF controller, including in the control law of impulse response, fixed frequency excitation response and random response, is compared with APPF controller for the sake of validating the effectiveness of AMPPF controller. The experiment cases listed in Table 1 include that the natural frequencies of the first-order mode are 13.5Hz, 12Hz and 10.75Hz respectively. In addition, the RMS value of external excitation is about 30N in this experiment.

4.1 Impulse response

After the impulse excitation is exerted on the tip of vertical tail, the damping ratios of structure listed in Table 2 are calculated by the strain signal of the root. As it is depicted, the damping ratios of structure are basically unchanged when the natural frequency of vertical tail is changed. After the controller is applied in the feedback loop, the damping ratio is increased by a few times. The damping ratios of AMPPF control system were greater than that of APPF control system in three cases.

Table 2 Damping ratio of vertical tail

Case	13.5Hz	12Hz	10.75Hz
Uncontrolled	0.0077	0.0071	0.0074
APPF	0.0378	0.0635	0.0637
AMPPF	0.0464	0.0856	0.0652

4.2 Fixed frequency response

Table 3 illustrates the control laws for fixed frequency response of two control systems in the three cases. The fixed frequency responses of vertical tail are decreased obviously, and all of the responses in its natural frequency are reduced by above 81%. The control laws of the AMPPF controller are also greater than APPF controller in three cases.

Table 3 Control law for fixed frequency response in the first-order mode

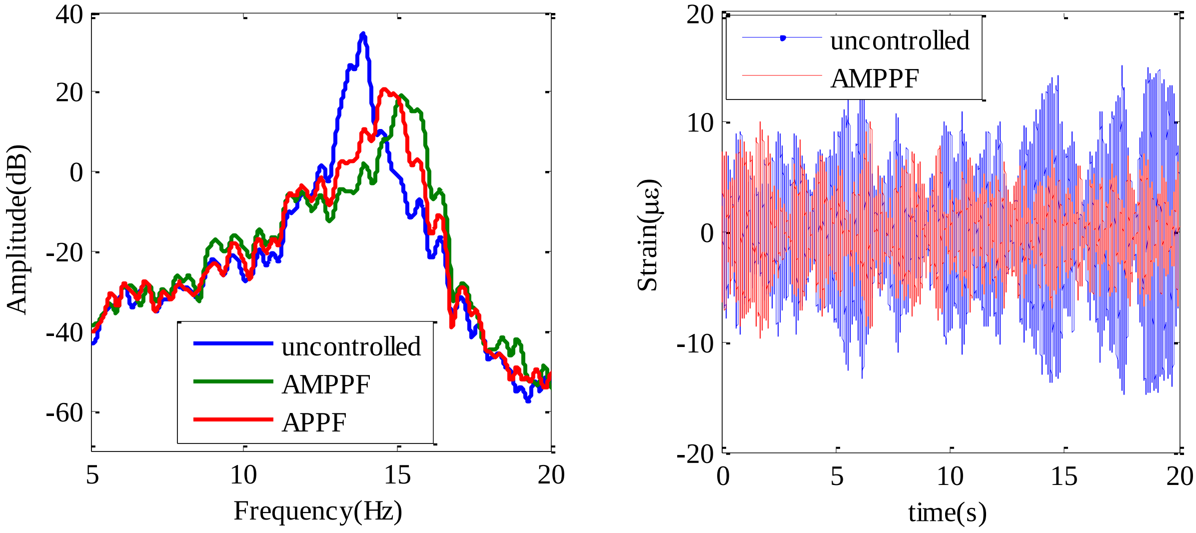
Case	13.5Hz	12Hz	10.75Hz
APPF	82.0%	82.5%	81.9%
AMPPF	86.3%	87.5%	88.3%

4.3 Random response

A special random excitation, whose band is [5Hz, 20Hz], is used to simulate the buffeting load. Table 4 shows the control laws for the RMS value and PSD peak of random response in the first-order mode. As it is depicted, the control laws of AMPPF controller are obviously higher than APPF controller. Figure 4 describes the PSD spectrum and time domain response of vertical tail in the first-order mode. In the band which is near the natural frequency, PSD spectrum peaks of AMPPF control system are lower than APPF controller, however, the PSD spectrum amplitudes of APPF controller are lower in some bands which are far away from the natural frequency.

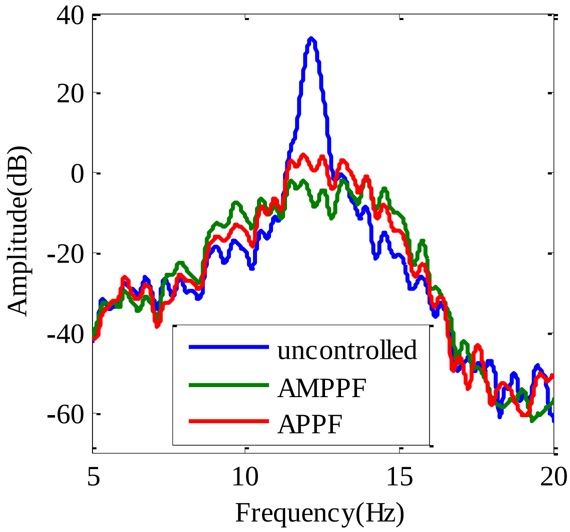
Table 4 Control law for the RMS value and PSD peak of random response in the first-order mode

case	13.5Hz		12Hz		10.75Hz	
	RMS	PSD	RMS	PDS	RMS	PDS
APPF	38.3%	79.6%	57.7%	96.5%	53.8%	95.3%
AMPPF	43.3%	83.2%	62.8%	98.3%	55.8%	95.0%

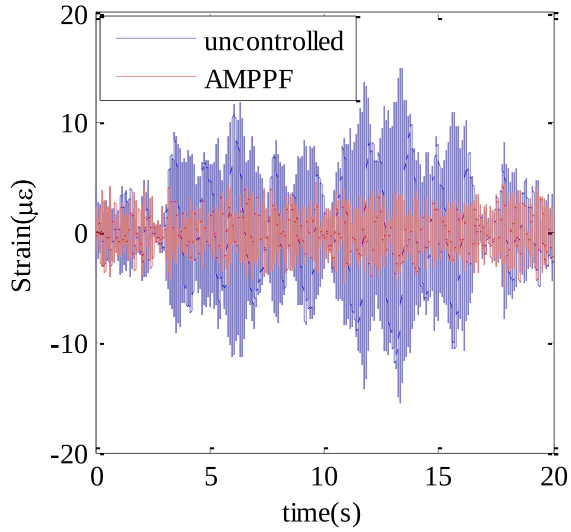


(a) PSD spectrum in the natural frequency of 13.5Hz

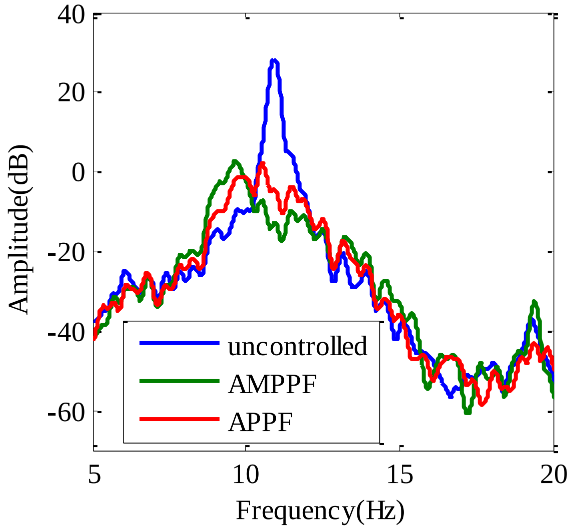
(b) time domain response in the natural frequency of 13.5Hz



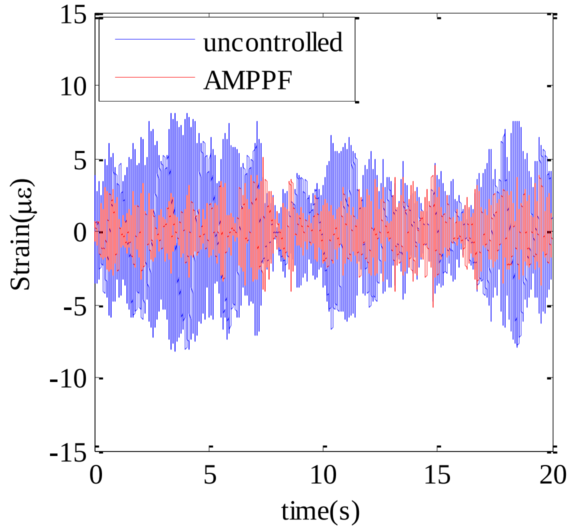
(c) PSD spectrum in the natural frequency of 12Hz



(d) time domain response in the natural frequency of 12Hz



(e) PSD spectrum in the natural frequency of 10.75Hz



(f) time domain response in the natural frequency of 10.75Hz

Figure 4 PSD spectrum and time domain response of vertical tail in the first-order mode

The experimental results show that all of the performance of AMMPF controllers is greatly better than APPF controller, and the damping ratio of the control system is increased obviously. Especially, the control laws for fixed frequency response and random response are higher. When the natural frequencies of vertical tail is time-varying, the AMPPF controller combined with frequency estimation method can meet the requirement of vertical tail buffeting suppression.

5. Summary

Adaptive MPPF controller which is applied for suppressing vertical tail buffeting is introduced in this paper, and the frequency of controller is adjusted automatically. The performance of AMPPF controller is compared with APPF controller in the impulse response, fixed frequency excitation response and random response. The vertical tail whose natural frequencies is time-varying, as controlled object, is utilized to verify the performance of AMPPF. Finally, the experimental results indicate that the effectiveness of AMPPF controller is obviously for suppressing the vibration of the vertical tail.

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