24th INTERNATIONAL CONGRESS ON SOUND AND VIBRATION
23–27 July 2017, London

FXLMS-BASED ADAPTIVE VIBRATION CONTROL OF VERTICAL TAIL

Bin Li, Chengzhe Zou, Wenchao Niu, and Wei Wang

Northwestern Polytechnical University, School of Aeronautics, 127 Youyi West Road, Xi'an, China
email: leebin@nwpu.edu.cn

The vertical tail vibration problem usually leads to the fatigue failure of the tail structure, so that it is important to suppress the vibration of the vertical tail. During buffeting the fluid-structure interactions can bring the vertical tail with time-varying structural dynamic properties due to additional aerodynamic stiffness and damping effects. In order to overcome the challenges caused by time-varying dynamical features, an adaptive control system using distributed Macro Fiber Composite (MFC) actuators is developed to suppress the vibration of a scaled vertical tail model. An adaptive Filtered-x Least Mean Square (FxLMS) control algorithm, which is equipped with two important modifications, secondary path online model based on simultaneous equation method and reconstruction of reference signal, is proposed to the tail vibration alleviation problem. The vibration control experiment results show that although the above modifications can influence the convergence and stability of FxLMS, all the suppression results are maintained on satisfying levels.

Keywords: vibration control, buffeting, FxLMS, MFC

1. Introduction

For the modern high-performance aircrafts at high angles of attack, the flow emanating from the wing/fuselage usually becomes separated and turbulent. The unsteady and violent pressures that impinged on these surfaces resulting from the turbulent flow are referred as buffet, and the structural vibration response due to buffet is known as buffeting[1-3]. The buffet phenomenon threatens the safety of aircrafts, and the time and huge costs spend on maintenance damage the mission availability and increase the financial burdens.

In order to solve the buffeting problem, many solutions were put forward. The active vibration control for buffeting alleviation based on piezoelectric materials has attracted more and more attention in recent years[3,4]. In the previous researches, the control laws were usually designed based on the time-invariant hypothesis of the structure. However, the fluid-structure interactions can bring the vertical tail with time-varying structural dynamics. Previous wind tunnel results showed that vertical tail structural dynamical behaviors were closely related with airspeed and angle of attack. In order to maintain optimal control result under different conditions, the adaptive control algorithm should be developed. FxLMS control algorithm, as the standard method in active noise control (ANC), showed its superiority over other adaptive algorithms and it has been found to offer effective performance in structural vibration control[5]. In this work, the feedback FxLMS algorithm with secondary path online identification is proposed to suppress the vibration of a vertical tail model.

2. Classical FxLMS algorithm

Figure 1 illustrates the classical FxLMS algorithm, which was originally put forward by Widrow[6]. It has been widely used in active noise control (ANC) in practical engineering, and it also shows brilliant prospects in the active vibration control (AVC).

In the AVC problem, $x(n)$ is the reference signal which should reflect the characteristics of external disturbance. The primary path P(z) represents the transfer role of the structure and acquisition plants between the exciting source and the output response $d(n)$, where $d(n)$ is structural vibration response without control. The secondary path S(z) represents the transfer role of the actuator, control plants and structure between the control signal $y(n)$ and control response $y'(n)$, where $y'(n)$ is structural vibration response generated by the actuator. $e(n)$ is the superposition result of $d(n)$ and $y'(n)$, which can be called residual vibration response. W(z) is the adaptive controller whose coefficients are updated based on the LMS algorithm. Here $\hat{S}(z)$ is the estimated secondary path, $x'(n)$ is filtered reference signal.

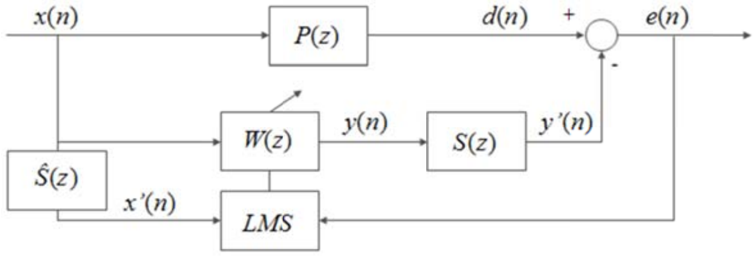


Figure 1. Classical FxLMS block diagram

It is worth noting that P(z) and S(z) exist as physical entities and perform in actuality, however, W(z) and $\hat{S}(z)$ are purely mathematical models. The detailed derivation and analysis of the FxLMS algorithm are demonstrated in Ref. [7], and the final operational equation of FxLMS algorithm is

$$W(n+1,z) = W(n,z) + 2\mu e(n)x'(n) \quad (1)$$

where μ is the step size of FxLMS algorithm.

3. Adaptive FxLMS control algorithm

There are two problems in the vertical tail vibration control. The first problem is how to adapt the time-varying properties of vertical tail because the fluid-structure interactions can introduce additional aerodynamic stiffness and damping to the tail, so that structural dynamic characteristics show time-varying behavior. The second problem is how to construct a reference signal for FxLMS control algorithm when exciting force is difficult to be measured.

In our work, an adaptive feedback FxLMS control algorithm with online identification of secondary path is proposed. Figure 2 shows the flow chart of the proposed control algorithm.

In Fig. 1, the estimated secondary path Ŝ(z) can not be changed, and therefore it cannot be treated with the time-invariant hypothesis. In order to keep performance of FxLMS on high level, the Ŝ(z) should be estimated online to track the variations of vertical tail. In this work, a new online secondary path modeling technique based on the simultaneous equation method (SEM)[8] is investigated, which is indicated in Fig. 2. An adaptive filter $\hat{S}(z)$ is introduced and its coefficients are updated by LMS algorithm so that the output of $H(m, z)$ - $H(k, z)$ is equal to the output of the product of $W(k, z)$ - $W(m, z)$ and $\hat{S}(z)$, then $\hat{S}(z)$ is expected to converge on $S(z)$. Therefore the secondary path can be modeled online as shown in Fig. 2.

From Eq. (1), it can be known that the accuracy of the reference signal is vital for the successful implementation of FxLMS. In the ANC problem, the reference signal can be obtained by reference microphone located far from the error sensor. However, in the buffet problem, a feedforward sensor usually is not available since it is difficult to install a feedforward sensor to measure the turbulent flow, so that we suggest $d(n)$ to replace $x(n)$ as the reference signal in our work. But $d(n)$ is strongly coupled with $y'(n)$, thus the reference signal cannot be acquired directly. In order to solve the problem, the feedback FxLMS algorithm should be achieved to reconstruct the reference signal, which is derived from error signal and identified secondary path.

$$\hat{d}(n) = e(n) + y(n)\hat{S}(z) \tag{2}$$

where $\hat{d}(n)$ is referred as the reconstructed reference signal.

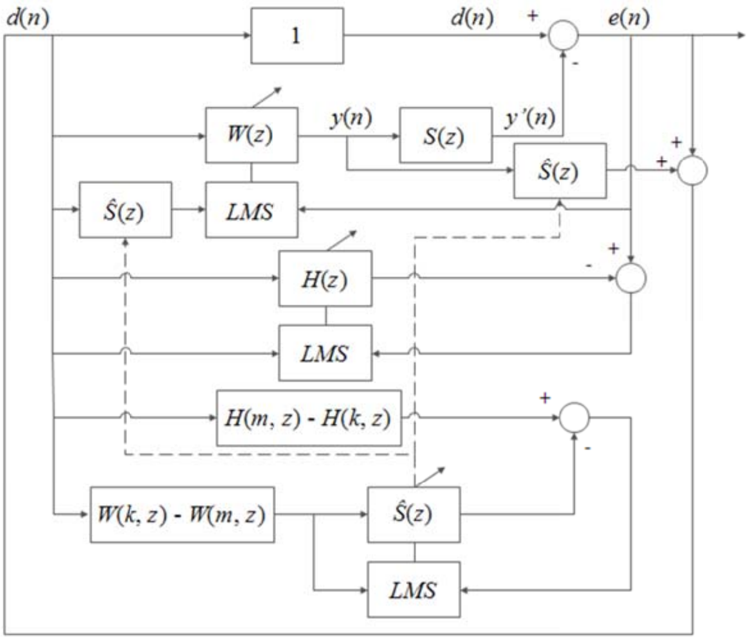


Figure 2. Feedback FxLMS algorithm with SEM

It can be noted that the reconstructed reference signal is dependent on the identified secondary path considerably, so that the secondary path should be identified accurately to guarantee the quality of the reconstructed reference signal.

4. Experiment study

A 1/2 scaled vertical tail shown in Fig. 3 is manufactured as our research object. The modal test experiment is conducted to validate our Finite Element Method (FEM) model. From Table 1, it can be seen that both of the natural frequencies and modal shapes of the modal test agree quite well with the FEM results. And we get clear understandings about the dynamic characteristics of the tail, which is helpful for the following work including distributions of MFC actuators and adaptive control experiment.

Table 1. Comparison of natural frequencies between test and FEM

Unit/Hz	1st mode	2nd mode	3rd mode	4th mode
FEM	13.60	46.21	75.60	103.85
Test	13.58	46.59	74.98	104.36
Error	0.15%	0.8%	0.8%	0.5%

The vibration control experiment uses M8557-P1 MFC actuators which are produced by Smart Material Corporation and based on the d_{33} effect of piezoelectric materials. The size of a M8557-P1 MFC patch is 85mm×57mm, and its operating voltage range is from -500V to 1500V.

Considering the geometry size of the vertical tail, twelve M8557-P1 MFC actuators are prepared for the vibration control of the first bending mode. In order to make these actuators produce the best possible performances, the distribution scheme of these actuators, including the location and the angle, is optimized based on the following analysis. These actuators are distributed symmetrically on the inboard and outboard surface of the tail.

The whole control system is demonstrated by Fig. 3. The external exciting load is given by magnetic shaker (JZK-10, Sinocera) and power amplifier (YE5872A, Sinocera). The Quanc real-time semi-physical simulation system (Quanser) is used for the adaptive control experiment, and the QPID terminal board (Quanser) has 8 input and 8 output channels. The root strain is selected as the feedback signal. The strain signal is amplified by dynamic strain device (DH3840, Donghua) and its acquisition is achieved by Vibrunner (m+p international). The voltage saturation part is designed to limit the amplitude of the control voltage to protect the MFC actuators. The MFC actuators are actuated by the high voltage amplifier (HVA 1500/50-4, Smart Material Corporation).

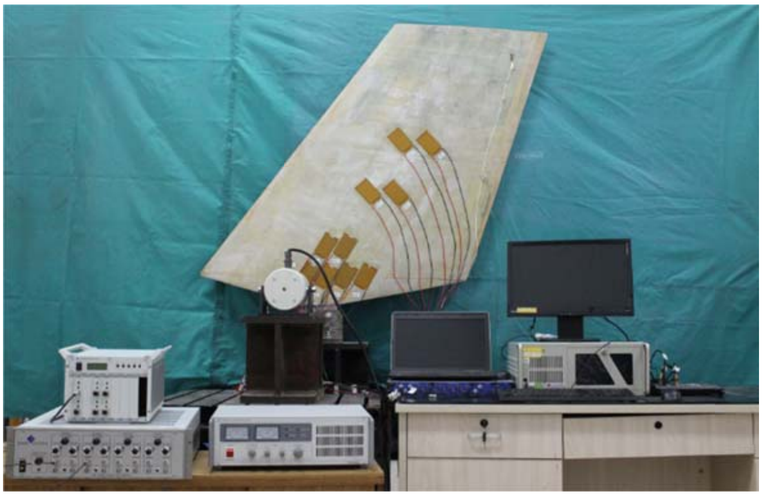


Figure 3. Experiment site and related facilities

In order to compare with classical FxLMS, the secondary path should be identified offline in advance. The input signal used for identification is sinusoidal sweep signal, whose frequency range is from 5Hz to 20Hz, and the sweep time is 30 seconds. A band pass filters are used to reserve first bending vibration response of the structure. The ARX model is used to describe the secondary path, and the identification is performed by the Matlab Toolbox. Figure 4 shows the comparison of frequency response between the identified and actual secondary path, and it is obvious that the identified frequency response agrees quite well with the measured one, and maximum relative error is less than 4%. Therefore it can be concluded that the identified model is accurate enough to describe the actual secondary path, and it can be used in the control experiment with offline identification of secondary path.

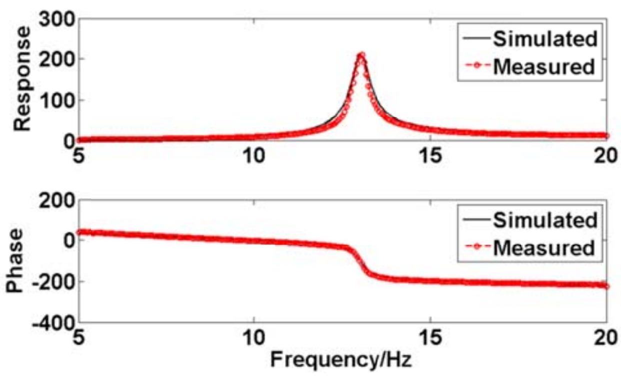


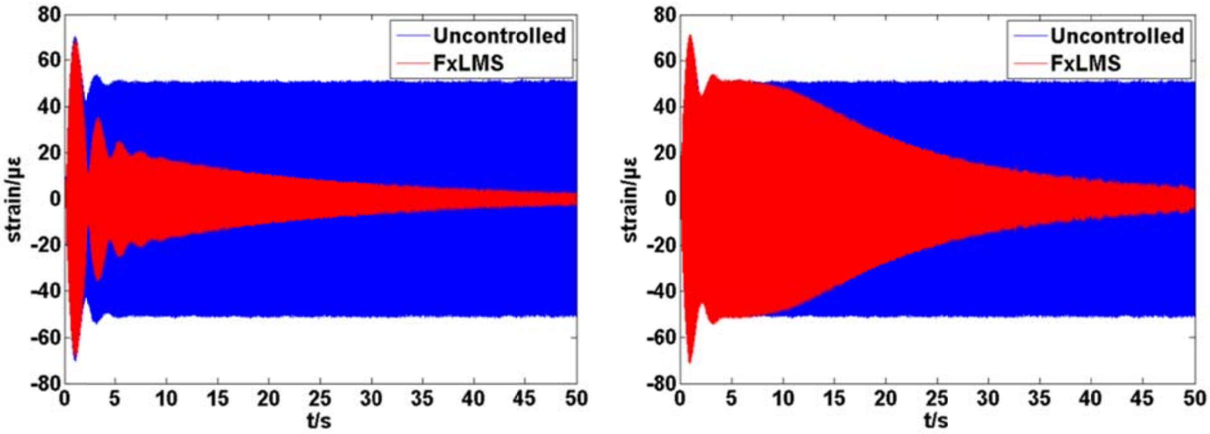
Figure 4. Comparison of frequency response between measured and identified model

5. Vibration Control Results

The external disturbing force is a sinusoidal function, and its frequency is 13.5Hz, which is around the first bending frequency of the tail. Figure 5 shows the suppression results of two control algorithms.

In classical FxLMS method, the final vibration response is reduced by more than 90% and the convergence speed is also faster than the adaptive algorithm because both of the reference signal and the secondary path are known. However, the control voltage is generated according to the feed forward exciting signal, instead of the vibration response, so that oscillations appear in the first 10 seconds of the experiment. It should be noted that the FxLMS controller shows adaptability during the whole experiment, and eventually the strain response should be reduced to zero under ideal conditions.

For adaptive FxLMS control algorithm, initially the secondary path is not provided, so that the FxLMS controller needs time to identify the secondary path online. Compared with last algorithm, it really requires more time to identify the secondary path because feedback system needs smaller step size to guarantee stability and convergence. This algorithm performs poorly in the first 10 seconds; however its control performance is improved notably as soon as the identified secondary path becomes accurate. Although the online identification process degrades its convergence speed, the eventual vibration response will suppressed by 70%, and system still keep same vibration suppression level with classical algorithm. Furthermore, the feedback adaptive system can play an active damping role which can suppress the transient signal effectively, so that the oscillations, that exists in the classical FxLMS control experiments, disappear.



(a) Classical Control algorithm (b) Proposed adaptive control algorithm

Figure 5. Experimental results for single frequency vibration suppression

6. Conclusions

In order to suppress the buffeting of vertical tail, this paper introduces an adaptive vibration control system based on MFC actuators to investigate the performance of FxLMS based algorithms. The proposed adaptive FxLMS control algorithm introduces an online identification secondary path to trace the variations of structural nature frequency response function. Due to the unavailability of exciting force in the vertical tail vibration control, a reference signal reconstructing method is proposed in this work. In the single frequency exciting experiment, the strain response can be suppressed by at least 70%. Experiment results show that the proposed adaptive feedback FxLMS, equipped with online identification of secondary path and reconstructed reference signal, can be implemented in the vertical tail vibration control problem.

Acknowledgements

This work was supported by National Natural Science Foundation of China (Grant No. 11172238, 11502208) Aeronautics Science Foundation of China (Grant No. 20152953030).

.

REFERENCES

1 Burnham J K, Pitt D M, White E V, et al. An advanced buffet load alleviation system[C]//Collection of Technical Papers-AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference. 2001, 5: 3579-3588.

2 Sheta E F, Moses R W, Huttsell L J. Active smart material control system for buffet alleviation[J]. Journal of Sound and Vibration, 2006, 292(3): 854-868.

3 Robert W. Vertical tail buffeting alleviation using piezoelectric actuators-Some results of the actively controlled response of buffet-affected tails (ACROBAT) program[J]. 1997.

4 El-Badawy A A. Structural identification and buffet alleviation of twin-tailed fighter aircraft[D]. Virginia Polytechnic Institute and State University, 2000.

5 Gan Z, Hillis A J, Darling J. Adaptive control of an active seat for occupant vibration reduction[J]. Journal of Sound and Vibration, 2015, 349: 39-55.

6 Widrow B, Glover Jr J R, McCool J M, et al. Adaptive noise cancelling: Principles and applications[J]. Proceedings of the IEEE, 1975, 63(12): 1692-1716.

7 Morgan D R. History, applications, and subsequent development of the FXLMS Algorithm [DSP History][J]. Signal Processing Magazine, IEEE, 2013, 30(3): 172-176.

8 Fujii K, Muneyasu M, Ohga J. Active noise control system using the simultaneous equation method without the estimation of error path filter coefficients[J]. Electronics and Communications in Japan (Part III: Fundamental Electronic Science), 2002, 85(12): 101-108.