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Design of active flutter suppression and wind-tunnel tests of a wing model involving a control delay

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ABSTRACT

In this study, a delayed controller was designed for active flutter suppression of a three-dimensional wing model. The design of controller can be divided into two steps. At the first step, a short time delay was artificially introduced into the control loop and the dynamic equations of the aeroelastic system with delayed control were converted into a set of delay-free state-space equations by using a state transformation. At the second step, the control law was synthesized by using the theory of optimal control for the delay-free state-space equations. To demonstrate the performance of the delayed controller, the margin of time delay was studied. The numerical results showed that the delayed controller had good robustness with respect to the time delay. Moreover, the delayed controller was digitally implemented and tested for the three-dimensional wing model in NH-2 subsonic wind-tunnel. The experimental results illustrated that the critical flow speed of flutter instability of the wing model could be effectively increased from 36.5 m/s to 39 m/s.

1. Introduction

Active Flutter Suppression (AFS) has a great potential to suppress the flutter instability of a flight vehicle. As reviewed by Mukhopadhyay (2003), the technique of AFS for aircraft structures has drawn much attention over the past decades.

From the viewpoint of control design, a number of studies have focused on how to synthesize advanced controllers to stabilize a wing section of two degrees of freedom (Wang et al., 2011; Lee and Singh, 2010). Huang et al. (2012a) proposed an indirect adaptive controller to stabilize the flutter instability of a three-dimensional wing model. The numerical results of those studies showed that the nonlinear controllers could suppress the aeroelastic vibrations effectively. However, only a few of studies have addressed the experimental verification of AFS in wind-tunnel tests. Andrighettoni and Mantegazza (1998) proposed an indirect adaptive controller to suppress the aeroelastic instability of a wing model. Their experimental results demonstrated that the open-loop flutter speed could be significantly increased. For the same wind-tunnel model, Bernelli-Zazzera et al. (2000) presented another adaptive controller by using the recurrent neural networks and digitally implemented the controller in a subsonic wind-tunnel test. Their experimental results showed that the open-loop flutter boundary could be increased by 34%. Although adaptive controllers have been recognized as a promising technology for the application of aeroelastic control, their reliability and safety are subject to further improvements (Livne, 2003). Compared

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Nomenclature

A	system matrix
B	input matrix of the control
$\mathbf{B}_{\xi\xi}$	diagonal matrix of modal damping
b	semi-chord of the wing
C	output matrix of the system
$e(k)$	difference between the desired and actual positions of the control surface, deg
G	matrix of the gust input
$\mathbf{K}_{\xi\xi}$	diagonal matrix of modal stiffness
k	discrete time step
l	output dimension of the system
$\mathbf{M}_{\xi\xi}$	diagonal matrix of modal mass
$\mathbf{M}_{\xi\delta}$	inertial coupling matrix between elastic modes and control surface mode
n	dimension of the state vector
q_d	dynamic pressure
T_s	sample interval
u_{TEO}	real deflection of the trailing-edge outboard control surface, deg
$u_{c(TEO)}$	control command of the trailing-edge outboard control surface, deg
V_{OLF}	open-loop flutter speed, m/s
V_∞	flow speed, m/s
w	Gaussian random input to turbulence in spectral form
$\bar{\mathbf{x}}$	transformed state vector of the delayed system
τ	time delay

with the adaptive nonlinear controllers, linear controllers are reliable and safe for the implementation on airplanes. Mukhopadhyay conducted a series of studies on the design of linear controllers for AFS. For example, Mukhopadhyay et al. (1982) synthesized a linear, reduced-order, and optimal control law via the optimization technology and showed that the robustness of the reduced-order controller could be improved by using the robustness recovery technique. The related experimental studies for AFS were conducted based on the Active Flexible Wing (AFW) and Benchmark Active Control Technology (BACT) Projects (Mukhopadhyay, 1995; Mukhopadhyay, 2000), respectively. The theory of robust control can also be applied to synthesizing control laws for AFS. For example, Waszak (2001) used the robust multivariable control theory to synthesize a control law of AFS for the BACT wing model.

Among the above mentioned studies on AFS, however, the effects of time delays on the stability of a closed-loop aeroelastic system have not been well addressed. In the real control loop of such a system, the digital/analog convertors, amplifiers, and noise filters do introduce time delays. The effects of those time delays become significant when the system is near a neutrally stable status. Some recent studies have focused on the effects of time delays in a control loop on the stability of controlled aeroelastic systems. For instance, Marzocca et al. (2005) investigated the effects of time delay on linear/nonlinear feedback control of a two-dimensional lifting surface and revealed some complex phenomena. Yuan et al. (2004) studied the effect of delayed feedback control on the flutter instability boundary of a two-dimensional supersonic lifting surface. For the Multiple-Actuated-Wing (MAW) model, Huang et al. (2012b) revealed the effects of time delay in control loop on the linear feedback control. Their numerical results showed that the stability of the closed-loop aeroelastic system with a conventional LQG controller could be improved as an increase of the input time delay. However, the stability of closed-loop system would decrease when the system had an input time delay of $\tau = 0.015$s. To improve the margin of time delay of the control law for AFS, they proposed a novel delayed optimal controller in the study. Their numerical results showed that the well-designed delayed controller for AFS could improve the closed-loop stability of the aeroelastic system. To the best knowledge of authors, however, no study has been made for the delayed controller for AFS of any three dimensional wing model in a wind-tunnel test.

The main objective of this study is to experimentally investigate the delayed control of AFS for a three-dimensional aeroelastic system. The methodology used for synthesizing the delayed controller is based on the optimal control theory in conjunction with the state transformation of a delayed state-space model (Haraguchi and Hu, 2008; Huang et al., 2012b). The delayed controller was digitally implemented for AFS of a three dimensional wing model in a subsonic wind-tunnel test.

2. Description of the aeroservoelastic system

Fig. 1 shows the geometrical and structural properties of the Multiple Actuated Wing (MAW) model. As shown in Fig. 1(a), the Leading-Edge Outboard (LEO) and Trailing-Edge Outboard (TEO) control surfaces were selected as the possible control inputs for AFS. The Leading-Edge Accelerometer (LEA) and Trailing-Edge Accelerometer (TEA) were used to sense the dynamic response of the MAW model. Fig. 1(b) presents the three-dimensional configuration of the finite-element model of the wing frame with root fixed. Fig. 2 shows the seven dominant natural modes used for aeroservoelastic modeling. The natural frequencies and mode shapes were computed via finite element analysis and modified according to the experimental data from a ground vibration test. During the numerical modal analysis and ground vibration test, the LEO and TEO control surfaces were locked to the wing structure via the servo motors. In the study, moreover, only the TEO control surface and TEA were used as the control input and sensor, respectively.