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Active flutter suppression of a multiple-actuated-wing wind tunnel model

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Abstract In this study, a multi-input/multi-output (MIMO) time-delay feedback controller is designed to actively suppress the flutter instability of a multiple-actuated-wing (MAW) wind tunnel model in the low subsonic flow regime. The unsteady aerodynamic forces of the MAW model are computed based on the doublet-lattice method (DLM). As the first attempt, the conventional linear quadratic-Gaussian (LQG) controller is designed to actively suppress the flutter of the MAW model. However, because of the time delay in the control loop, the wind tunnel tests illustrate that the LQG-controlled MAW model has no guaranteed stability margins. To compensate the time delay, hence, a time-delay filter, approximated via the first-order Pade approximation, is added to the LQG controller. Based on the time-delay feedback controller, a new digital control system is constructed by using a fixed-point and embedded digital signal processor (DSP) of high performance. Then, a number of wind tunnel tests are implemented based on the digital control system. The experimental results show that the present time-delay feedback controller can expand the flutter boundary of the MAW model and suppress the flutter instability of the open-loop aeroelastic system effectively.

1. Introduction

Active flutter suppression is a relatively mature, but still rewarding research area in aeroservoelasticity. The past three decades have witnessed extensive studies on active flutter suppression and various control schemes have provided promising results. For example, Gangsaas et al.[1] presented a low-order, robust and multi-loop controller to actively suppress the flutter instability of a flexible airplane by using a modified linear quadratic Gaussian synthesis. Mukhopadhyay et al.[2] developed a reduced-order, robust and optimal control law by using optimization techniques and showed that it was difficult to choose the free design variables. Furthermore, Rockwell International Corporation, NASA Langley Research Center and the Air Force Wright Laboratories initiated a program called Active Flexible Wing (AFW) in 1985.[3] This program resulted in several control laws for active flutter suppression for the AFW wind tunnel model.[4] For example, from the

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viewpoint of the flutter mechanism, Waszak and Srinathkumar[5] synthesized a simple low-order, single-input/single-output (SISO) controller via traditional methods. Mukhopadhyay[6] designed a 5th-order SISO control law by using the reduced-order linear quadratic Gaussian method. Both controllers were tested in the Transonic Dynamics Tunnel (TDT) located at NASA Langley Research Center and the wind tunnel tests showed that the two controllers could significantly increase the flutter dynamic pressure of the AFW model. Zhang and Ye[7] constructed a transonic aeroservoelastic model in state-space by coupling the structural state equations with the aerodynamic state equations of the wing section with a trailing-edge control surface. They obtained the aerodynamic state equations by using the linear reduced-order model (ROM) approach and designed a sub-optimal control law based on output feedback. Zeng et al.[8] studied how the pivot stiffnesses of all-moveable horizontal tail (HT) and canard affected the aeroservoelastic stability of a canard-configured hypersonic vehicle (HSV). Yang et al.[9] suppressed the flutter of an MIMO airplane configuration, i.e., an imitational F/A-18A model, by means of active controllers, which were firstly designed by using the linear quadratic-Gaussian (LQG) method and then truncated by a balanced truncation method. Quite recently, Huang et al.[10] proposed a new approach to design a time-delay LQG controller to actively suppress the flutter instability of the MAW model involving an input time delay. Compared with the conventional LQG controller, the time-delay LQG controller can stabilize the aeroelastic system with an input time delay effectively. The success of their new approach in numerical simulations motivates one to testify the approach for active flutter suppression of a practical aeroelastic system with high dimensions.

In previous studies, numerous SISO controllers have been designed to actively suppress the flutter of aeroelastic systems and verified in wind tunnel tests. Meanwhile, some MIMO controllers have also been designed for active flutter suppression, but only a few of them have been testified in wind tunnel tests. The studies show that both SISO and MIMO control laws can expand the flutter boundary of open-loop systems. Compared with SISO controllers, MIMO controllers have several advantages as follows. Firstly, much smaller deflections of control surfaces are required and the wing can be subject to much larger twist than a conventionally designed wing when an MIMO controller is used. Secondly, a control reversal may occur when the twist due to the control-surface deflection negates the control-induced maneuvering loads,[11] if only a trailing-edge control surface is used. However, the control reversal problem can be improved by using a leading-edge control surface at the same time.

In active flutter suppression, it is essential to properly select and use actuators. A recent study shows that ultrasonic motors serve as a promising kind of actuator for flutter suppression of a small aeroelastic system since they present many attractive features, such as simple structure, high torque, low weight, and no electromagnetic contamination. For example, Yu and Hu[12] used an ultrasonic motor to drive the control surface of a two-dimensional airfoil model. They established the mathematical model of the ultrasonic motor via a second-order transfer function for the aeroservoelastic modeling of the two-degree-of-freedom wing section. For the aeroservoelastic modeling of a three-dimensional wing model, however, their mathematical model of the ultrasonic motor cannot be used directly because three state variables are needed for modeling the aeroservoelastic equation of a wing model.

This paper attempts to address these issues. Firstly, an MIMO time-delay feedback controller was synthesized and implemented in wind tunnel tests to actively suppress the flutter instability of the MAW model. Secondly, two ultrasonic motors were used to drive the leading and trailing-edge control surfaces, respectively. The mathematical model of the ultrasonic motors was represented by a new state-space description and then the aeroservoelastic model for the three-dimensional MAW model was established.

2. Mathematical modeling

2.1. Wind tunnel model of MAW

The MAW wind tunnel model illustrated in Fig. 1 has two control surfaces, that is, the leading-edge outboard (LEO) and trailing-edge outboard (TEO) control surfaces. Each control surface can be activated by a rotary ultrasonic motor, mounted on the wing root, for active suppression of possible flutter. In addition, two accelerometers are fixed at the leading-edge tip (LET) and trailing-edge tip (TET) of the wing, respectively, so as to measure the responses of the MAW model as the controller inputs. Thus, the MAW model has two control inputs and two control outputs. More details about the finite element modeling of the MAW model can be found in the early work.[13]

The comparison between the wind tunnel test of the initial MAW model and the numerical simulation of the corresponding finite element model showed strong discrepancies. In order to reduce the discrepancies, all gaps among the plastic foams in the MAW model have been filled with sponge, and the backlashes between the control surface and the wing have been plastered with tinfoil and rubber membrane.

2.2. Dynamic modeling of actuators

In wind tunnel tests, both control surfaces of the MAW model can be actuated by ultrasonic motors. As shown in Fig. 2,[14] an ultrasonic motor is driven by a mechanism that a gross motion is generated through the amplification and repetition of micro-deformations of piezoelectric materials. The piezoelectric materials induce an orbital motion on the surface of a stator at the contact points with a rotor. The frictional interface between the rotor and the stator rectifies the micro-motion to produce a macro-motion of the rotor. An ultrasonic motor can produce a high torque at a low rotational speed when the

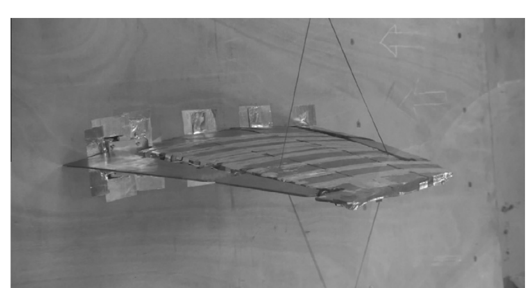

Fig. 1 MAW wind tunnel model.