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Active Control of Smart Fin Model for Aircraft Buffeting Load Alleviation Applications

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Following the program to test a hybrid actuation system for high-agility aircraft buffeting load alleviation on the full-scale F/A-18 vertical fin structure, an investigation has been performed to understand the aerodynamic effects of high-speed vortical flows on the dynamic characteristics of vertical fin structures. Extensive wind-tunnel tests have been conducted on a scaled model fin integrated with piezoelectric actuators and accelerometers to measure the aft-tip vibration responses under various freestream and vortical airflow conditions. Test results demonstrated that the airflow induced considerable damping to the fin structure, which generally increased with airflow speed as well as the vertical fin angle of attack relative to the airflow direction. Moreover, it was observed that at the angle of attack of 10 deg, the high-speed airflow introduced large deflection to the smart fin structure and caused significant frequency shift to the vibration modes due to nonlinear geometrical coupling of bending and torsional modes. These aerodynamic effects may adversely affect the performance and robustness of the closed-loop control laws developed based on vertical fin dynamic model identified without considering the varying aerodynamic effects. To explore this problem, the structured singular values synthesis technique was adopted to develop robust control law using smart fin model identified without aerodynamic excitations, and the aerodynamic effects on the fin structure were assumed as smart fin parametric and dynamic uncertainties. The effectiveness and robust performance of the control law was demonstrated through extensive closed-loop wind-tunnel tests using various airflow conditions. This provided a verified control law design strategy for future flight tests of the full-scale aircraft buffeting load alleviation system.

Nomenclature

D = vortex generator cross-sectional dimension, m
f = peak vortical airflow frequency, Hz
f_M = vortical airflow frequency in the wind tunnel, Hz
K = fin model ratio
k = Strouhal number
V = airflow speed, m/s
V_M = airflow speed in the wind tunnel, m/s
u_1 = input to group 1, V
u_2 = input to group 2, V
y_1 = aft-tip acceleration, g
y_2 = front-mid acceleration, g

Introduction

IN THE development of high-agility fighter aircraft, new designs such as leading-edge extensions (LEX), blended wing and fuselage configurations, and canards are introduced to generate strong leading-edge vortices during high angle-of-attack (AOA) maneuvers. The additional lift generated by the vortices can increase the maximum AOA during maneuvers and extend the flight envelope to the stall and poststall regime [1]. However, the vortices break at very high angles of attack and interact with the aircraft empennage, which may cause severe vibration problems to the fin structure known as buffeting [2]. Under the circumstances, the vortices emanating from the leading edge of the LEX, fuselage, or canards burst upstream of the empennage and cause extremely high-energy turbulent flows downstream to impinge on the fin structures of the aircraft. The intense and unsteady buffeting aerodynamic loads are characterized by a broadband spectrum with narrowband peak distributions. As a result, the lower vibration modes of the vertical tail are excited and introduce significant high-level dynamic stresses to the fin and empennage structures. Prolonged exposure to the buffeting loads usually leads to premature fatigue damage to the vertical fin skin and stub structures, reducing mission availability of the aircraft and increasing maintenance cost of the fleet.

The vertical fin buffeting problem affects aircraft with both twin vertical fin and single vertical fin configurations [3]. However, it is a difficult task to design fighter aircraft fin structures to withstand the intense buffeting loads. Many approaches have been investigated to alleviate the buffeting damage on the vertical fins. The flow control approach modified the vortical flowfields to reduce the intensity of the buffeting loads on the vertical fin. Rigid fences or vents have been installed to the F/A-18 LEX to create a second unsteady vortex that interacts with the vortices created by the leading-edge extension to disperse the vortices before they impinge on the vertical fin [4]. However, this modification provided limited reduction of buffet loads and was effective only at a specific range of flight conditions along with the weight and aerodynamic penalties. Moreover, the

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