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Theoretical Predictions of F-16 Fighter Limit Cycle Oscillations for Flight Flutter Testing

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A computational investigation of the flutter onset and limit cycle oscillation behavior of various F-16 fighter weapons and stores configurations is presented. A nonlinear harmonic balance compressible Reynolds-averaged Navier–Stokes computational fluid dynamic flow solver is used to model the unsteady aerodynamics of the F-16 wing. Slender body/wing theory is used as an approximate method for accounting for the unsteady aerodynamic effects of wing-tip launchers and missiles. Details of the computational model are presented along with an examination of the sensitivity of computed aeroelastic behavior to characteristics and parameters of the structural and fluid dynamic model. Comparisons with flight-test data are also shown.

I. Introduction

THE SEEK EAGLE Office at Eglin Air Force Base performs an essential task in clearing new aircraft/stores configurations through flight tests for safe and effective operation. Many of these flight tests are for the F-16 aircraft which continues to be a workhorse for the U.S. Air Force with continually new stores (missiles, bombs, and fuel tanks) being considered for aircraft operations. Similar aeroelastic flight tests are expected for future fighter aircraft as they go into service in the coming years.

The number of needed flight tests is projected to be well beyond the financial and staff resources available. Hence there is a pressing need to identify the most critical aircraft/store configurations for the limited flight-test resources available and also insofar as possibly reduce the number of flight tests needed.

Virtual flight testing may be the answer. Using new improved computational capability that provides much more rapid solutions, computational simulation can help identify the most critical aircraft/store configuration and also has the potential of reducing the number of needed flight tests if confidence can be established in the capability of simulations to correlate with flight-test data.

A new methodology has been developed to produce these computer simulations based upon the notion that because the response is periodic in time, the solution need only be obtained over a single period of oscillation in time. By avoiding the traditional time marching solution which computes the long transient before a steady-state periodic oscillation is reached, computational times are reduced by a factor of 10–100. This enables a sufficiently rapid solution to make such simulations a practical reality for the flight-test engineer and support team. Future developments of this methodology hold the promise of further substantial reductions in computational cost and are being vigorously pursued. Also further refinements in the physical fidelity of the simulation models are being considered.

This paper is a summary of the research efforts reported by Thomas et al. in [1–4], where the harmonic balance (HB) technique for modeling nonlinear unsteady aerodynamics (see Hall et al. [5] and Thomas et al. [6–8]) is used to determine the limit cycle oscillation (LCO) behavior of the F-16 fighter aircraft.

Many other researchers are also actively modeling the aeroelastic behavior of the F-16 fighter; for example, Denegri and Dubben [9–11] are using doublet-lattice methods for flutter onset analysis and transonic small-disturbance methods for flutter onset and limit cycle oscillation prediction. Parker et al. [12,13] are using time-domain computational fluid dynamics (CFD) simulations to study the effects of viscosity in addition to modeling external stores for computed F-16 limit cycle oscillations. Lieu and Farhat [14] and Lieu et al. [15] are developing reduced order models for F-16 flutter analysis based upon proper orthogonal decomposition (POD). Prananta et al. [16] are using a time-domain coupled computational fluid dynamic and modal based structural method for modeling the limit cycle oscillation response of the F-16. Melville [17] has also recently investigated time-domain CFD simulations for modeling LCO response of the F-16.

Flutter onset and LCO response behavior of the F-16 fighter are in general dependent on the specific external stores being carried by the airplane as well as the Mach number and altitude at which the aircraft is being flown. In the following, we will demonstrate how a novel nonlinear frequency domain harmonic technique can be used to rapidly determine the flutter onset Mach number for a specified altitude and also the subsequent finite amplitude LCO dynamic response of the aircraft for higher Mach numbers beyond the flutter onset boundary.

The aerodynamic solver portion of the aeroelastic model consists of a high fidelity nonlinear unsteady frequency domain compressible Reynolds averaged Navier–Stokes (RANS) solver for the F-16 wing aerodynamic pressures. The structural portion consists of a linear modal based model using mode shapes and modal masses obtained from a NASTRAN finite element model of the entire airplane configuration including fuselage, horizontal tail, and external weapons and stores. The structural damping is taken to be zero in the present study, although recent investigations have studied the effect of this parameter as well.

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