Virtual Aeroelastic Flight Testing for the F-16 Fighter with Stores

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In the following, we present computational aeroelastic flutter onset and limit cycle oscillation response trends for various stores and weapons configurations of the F-16 fighter. 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. However, slender body/wing theory is used as an approximate method in accounting for the unsteady aerodynamic effects of wingtip launchers and missiles.

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 Air Force with continually new stores (missiles, bombs and fuel tanks) being considered for aircraft operations. Similar, aeroelastic flight tests are expected for the F-22 and F-35 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 possible 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.

The new methodology to produce these computer simulations is based upon the notion that since the response is periodic in time the solution need only be obtained over that single period of 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 to 100. This enables a sufficiently rapid solution to make such simulations a practical reality for the flight test engineer and support team. Further 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 also being considered.

A main focus of this 2007 U.S. Air Force T&E Days conference paper is demonstrating how one may add simplified aerodynamic models of the external weapons and stores which aid greatly in improving the overall accuracy of the computational aeroelastic solution in correlating with flight test results.

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Config.	1	2	3	4	5	6	7	8	9
1	LAU-129	LAU-129/AIM-9P	AGM	0% Full FT	-	0% Full FT	AGM	LAU-129/AIM-9P	LAU-129
2	LAU-129/AIM-9L	LAU-129/AIM-9L	AGM	50% Full FT	-	50% Full FT	AGM	LAU-129/AIM-9L	LAU-129/AIM-9L
3	LAU-129	LAU-129/AIM-120	GPB	25% Full FT	-	25% Full FT	GPB	LAU-129/AIM-120	LAU-129
4	LAU-129/AIM-120	LAU-129	GPB	100% Full FT	-	100% Full FT	AGM	LAU-129/AIM-120	LAU-129
5	LAU-129/AIM-120	LAU-129/AIM-9P	GB	100% Full FT	FT	100% Full FT	GB	LAU-129/AIM-9P	LAU-129/AIM-120
6	LAU-129	LAU-129/AIM-9P	AGM	50% Full FT	FT	50% Full FT	AGM	LAU-129/AIM-9P	LAU-129/AIM-9P
7	LAU-129	LAU-129/AIM-9L	CB	-	FT	-	CB	LAU-129/AIM-9L	LAU-129
8	LAU-129/AIM-9P	LAU-129/AIM-9P	AGM	100% Full FT	FT	100% Full FT	AGM	LAU-129/AIM-9P	LAU-129

Table 1. F-16 Weapons and Stores Configurations.

This work is a follow-on to the research efforts reported in Thomas, Dowell, and Hall[1–3] where the harmonic balance (HB) technique for modeling nonlinear unsteady aerodynamics (see Hall et al.[4] and Thomas, Dowell, and Hall[5–7]) 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. e.g. Denegri and Dubben[8–10] 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.[11,12] are using time-domain CFD simulations to study the effects of viscosity in addition to the modeling external stores for computed F-16 limit cycle oscillations. Lieu et al.[13,14] are developing reduced order models for F-16 flutter analysis. Pranata et al.[15] are using a time-domain coupled computational fluid dynamic and modal based structural method for modeling limit cycle oscillation response of the F-16. Melville[16] has also recently investigated using time-domain CFD simulations for modeling LCO response of the F-16.

A. Accounting for Wingtip Stores Using Slender Body/Wing Theory

In an effort to reduce the computational cost of CFD modeling of complex geometric wingtip stores, we have recently started to investigate the use of slender body/wing theory (see e.g. Bisplinghoff, Ashley, and Halfman[17]) as an approximate method to account for the unsteady aerodynamic effects of wingtip launchers and missiles on the overall unsteady aerodynamics of the F-16 fighter. All that is required for slender body/wing theory is the geometry of the wingtip launchers and missiles, their specific spanwise locations on the F-16 wing, and the chordwise unsteady motion of the wing at the spanwise locations of the wingtip launchers and missiles, the later of which is available from the HB/CFD aeroelastic simulations of the clean F-16 wing. Slender body/wing theory provides, via a simple algebraic formula, a method to modify the overall F-16 configuration unsteady generalized aerodynamic forces to approximately account for the presence of wingtip launchers and missiles. Slender body/wing theory can also be used to approximately model the unsteady aerodynamic effects of inboard wing stores. At the present time, we have limited slender body/wing theory to just the wingtip launchers and missiles.

B. F-16 Weapons and Stores Configurations

We are currently in the process of investigating eight different F-16 weapons and stores configurations. Table 1 shows the particular weapons and stores for each F-16 configuration at each of the nine F-16 wing attachment locations. In Table 1, AGM stands for Air Ground Missile, GPB stands for General Purpose Bomb, GB stands for Guided Bomb, AGM stands for Air Ground Missile, GB stands for Guided Bomb, and FT stands for Fuel Tank.

II. Flutter Onset

We have computed flutter onset altitude versus Mach number for all eight F-16 configurations. For the symmetric F-16 configurations (#1, #2, #3, #5, and #7), we use the first two anti-symmetric structural mode shapes in the aeroelastic model, and for the asymmetric F-16 configurations (#4, #6, and #8), we use the first four structural mode shapes. A structural modal convergence study was done using more modes and this led to the choice of modes for the flutter onset and LCO simulations presented. In all cases, the computed aeroelastic flutter onset and LCO frequencies match well with flight test. Figure 1 shows the computed F-16 flutter onset altitude versus Mach number trends for each of the eight F-16 configurations.

Note, our computations indicate that configuration #7 does not flutter, and this is in agreement with flight test results.

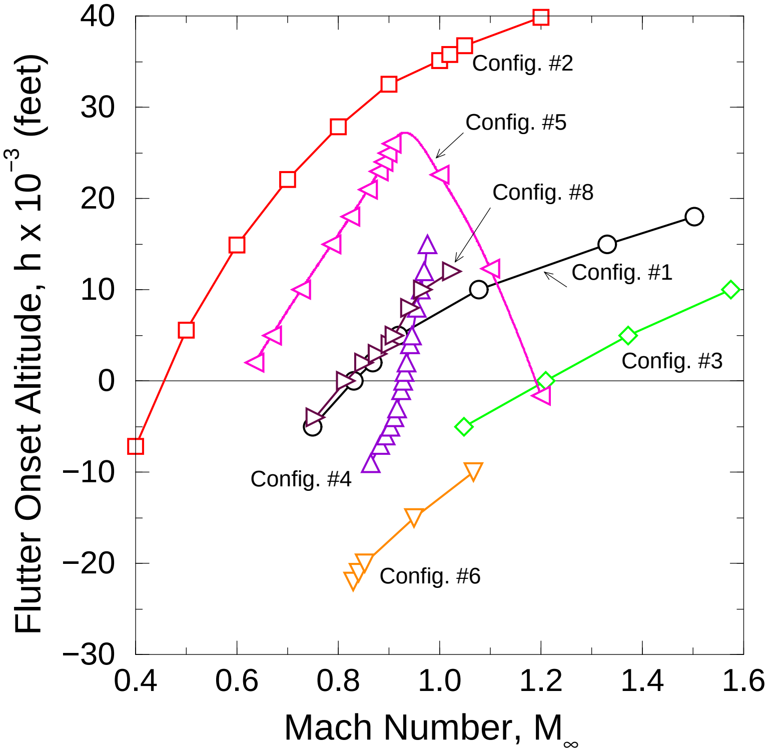

Figure 1. Computed F-16 Fighter Flutter Onset Altitude versus Mach number.

To demonstrate the potential dramatic effects of using slender body/wing theory, Fig. 2 shows the computed flutter onset altitude for F-16 weapons and stores configurations #1 and #2 with and without the use of slender body/wing theory. Both configuration exhibit flutter above sea level in flight test. The primary difference between configurations #1 and #2 is that configuration #2 has AIM-9L missiles located on the wingtip launchers. We have discovered that by adding the slender wing/body model of both the LAU-129 launchers and AIM-9L missiles to the overall HB/CFD aeroelastic solutions procedure for configuration #2, the predicted flutter onset characteristics change dramatically as can be seen in Fig. 2. In using slender wing/body theory, it can be seen that configuration #2 is predicted to flutter above sea level around a Mach number of 0.5 at sea level which is near to the test results flight test results as will be shown later in Fig. 4. By contrast, modeling the tip launcher unsteady aerodynamics for configuration #1 has little effect of the computational flutter onset results.

III. Limit Cycle Oscillation Response

So far, we have investigated the LCO characteristics of F-16 configurations #1, #2, #4, and #5 when using slender body/wing aerodynamic theory to account for wingtip launchers and missiles. For each configuration, we consider an altitude of 2000 feet and a mean wing angle-of-attack of $\bar{\alpha}_0 = 1.5$ degrees.

A. Configuration #1 Limit Cycle Oscillation Response

Figure 3 shows the computed and flight test LCO response characteristics of F-16 configuration #1. Shown are computed LCO response trends both with and without slender body/wing aerodynamic modeling of the wingtip launchers. As can be seen, slender body/wing aerodynamic modeling aids in bringing the computing LCO response closer to the flight test results.

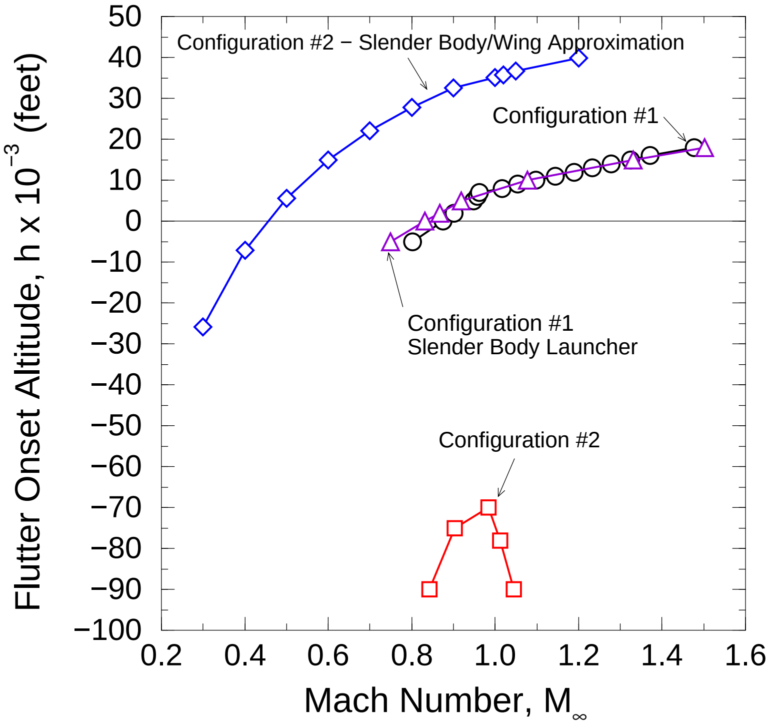

Figure 2. Computed F-16 Fighter Flutter Onset Altitude.

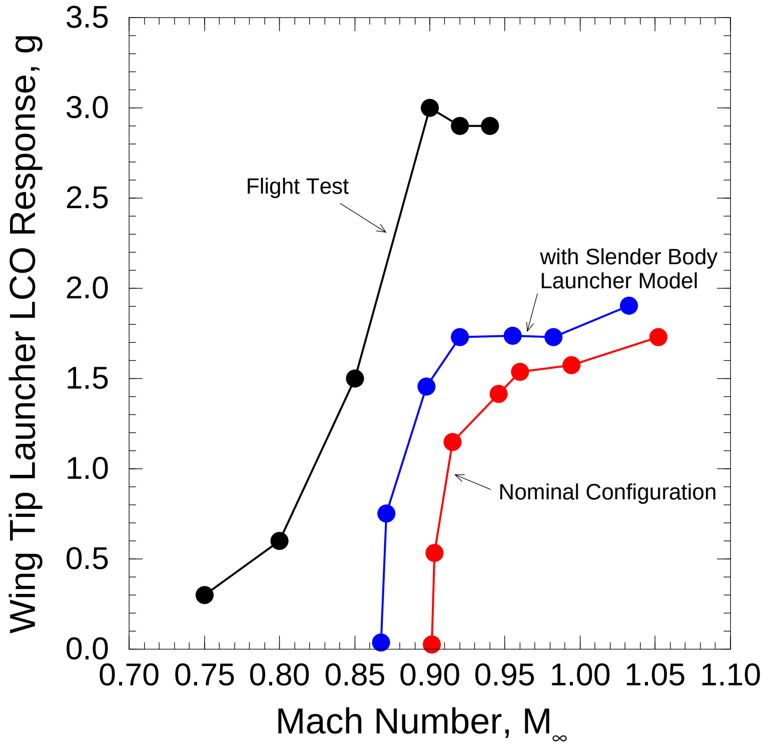

Figure 3. F-16 Configuration #1 Computed and Flight Test Forward Wingtip Launcher Accelerometer LCO Response Level Versus Mach Number for an Altitude of 2000 feet and a Mean Angle-of-Attack of $\bar{\alpha}_0 = 1.5$ degrees.

B. Configuration #2 Limit Cycle Oscillation Response

Figure 4 shows the computed and flight test LCO response characteristics of F-16 configuration #2. As can be seen, slender body/wing aerodynamic theory aids greatly in better matching the flight test flutter onset Mach number. Recall, as per Fig. 2, F-16 configuration #2 without slender body/wing aerodynamic theory is not predicted to flutter above sea level for any Mach number. Also, from the three flight test results, flutter onset appears to be possible anywhere between $M_\infty = 0.5$ and $M_\infty = 0.7$. Note that configuration #2 appears to have more uncertainty from flight test to flight test than configuration #1. As far as LCO response, the computational model is not currently predicting strong nonlinear behavior as is observed in the flight tests. We believe this may be due to the fact the computational flutter onset Mach number is below $M_\infty = 0.5$. We suspect there is not a strong enough nonlinear unsteady aerodynamic mechanism at the computed flutter-onset Mach number. If the computed flutter-onset Mach number was slightly higher, we believe stronger nonlinear LCO response would be observed. This in fact will be demonstrated for F-16 configuration #5. Note that small changes in the structural modal frequencies, for example, might lead to changes in the predicted flutter onset Mach number of configuration #2.

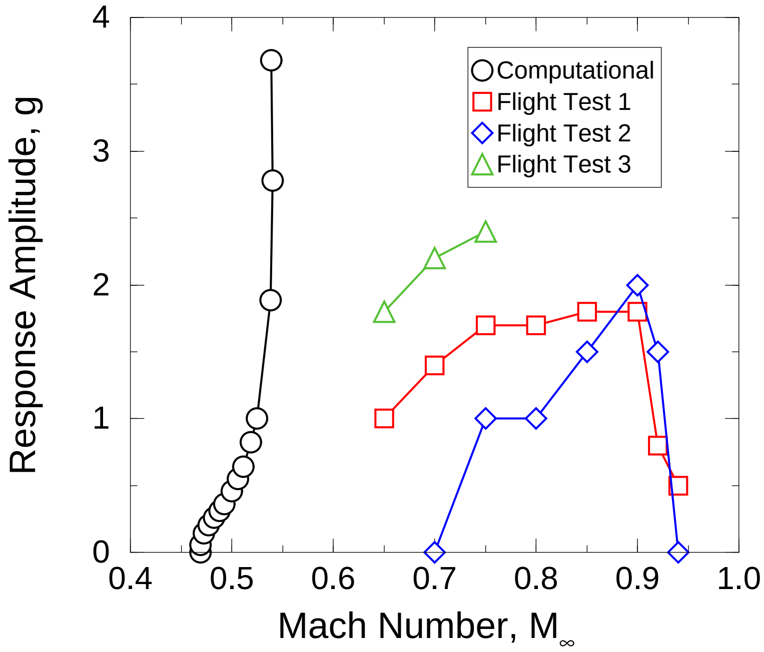

Figure 4. F-16 Configuration #2 Computed and Flight Test Forward Wingtip Launcher Accelerometer LCO Response Level Versus Mach Number for an Altitude of 2000 feet and a Mean Angle-of-Attack of $\bar{\alpha}_0 = 1.5$ degrees.

C. Configuration #4 Limit Cycle Oscillation Response

Figure 5 shows computed and flight test LCO response characteristics of F-16 configuration #4. The computational results so far are exhibiting an unstable LCO response. We have not seen this before in any of our previous calculations for various F-16 configurations. Further runs are being performed to determine if the computed LCO response curve bends back over to the right for larger LCO response amplitudes, or if the curve continues to the left and perhaps ultimately downward again.

D. Configuration #5 Limit Cycle Oscillation Response

Figure 6 shows computed and flight test LCO response characteristics of F-16 configuration #5. In this instance, the computational results match flight test reasonably well. Further runs are being conducted to determine if the LCO response curve ultimately peaks, then starts coming down again for higher Mach numbers as is observed from the flight test results. It is interesting to note, and as compared to configuration

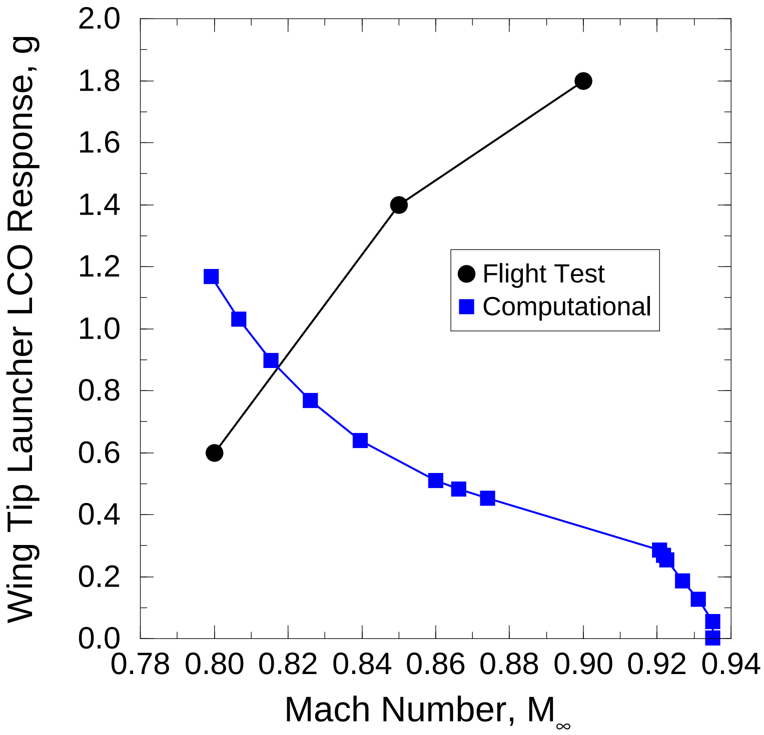

Figure 5. F-16 Configuration #4 Computed and Flight Test Forward Wingtip Launcher Accelerometer LCO Response Level Versus Mach Number for an Altitude of 2000 feet and a Mean Angle-of-Attack of $\bar{\alpha}_0 = 1.5$ degrees.

#2, the computational results indicate rather strong nonlinear LCO response for a subsonic flutter onset flow condition, albeit at a slightly higher flutter onset Mach number than for configuration #2.

IV. Conclusions

The aeroelastic flutter onset and LCO response of various weapons and stores configurations of the F-16 fighter are modeled using a nonlinear frequency domain harmonic balance CFD approach. Slender body/wing theory is used to model wingtip launchers and missiles which results in a tremendous computational cost saving as compared to direct CFD modeling of the wingtip launchers and missiles. For those configurations where tip missile aerodynamics are important, slender body/wing theory improves the prediction of the flutter onset Mach number, but it may not improve the prediction of LCO response in all cases per se. That is, slender body theory is a linear theory which may be helpful in predicting the onset of flutter, but to predict the tip missile effect on finite amplitude LCO, flow separation on the missile fins may well need to be taken into account. A next step in improving the aerodynamic model would be to conduct a CFD analysis of the fin aerodynamic forces alone to add to those of the wing, but to neglect any aerodynamic interference between the fins and wing. This would essentially double the cost of the calculation, while including the aerodynamic interference would increase the cost of the calculation manyfold.

V. Acknowledgments

This work is being supported by AFOSR grant, ”Theoretical Predictions of Limit Cycle Oscillations for Flight Flutter Testing”. The program manager is Dr. John Schmisseur the key technical point of contact in the SEEK EAGLE office at Eglin Air Force Base is Dr. Charles Denegri Jr.

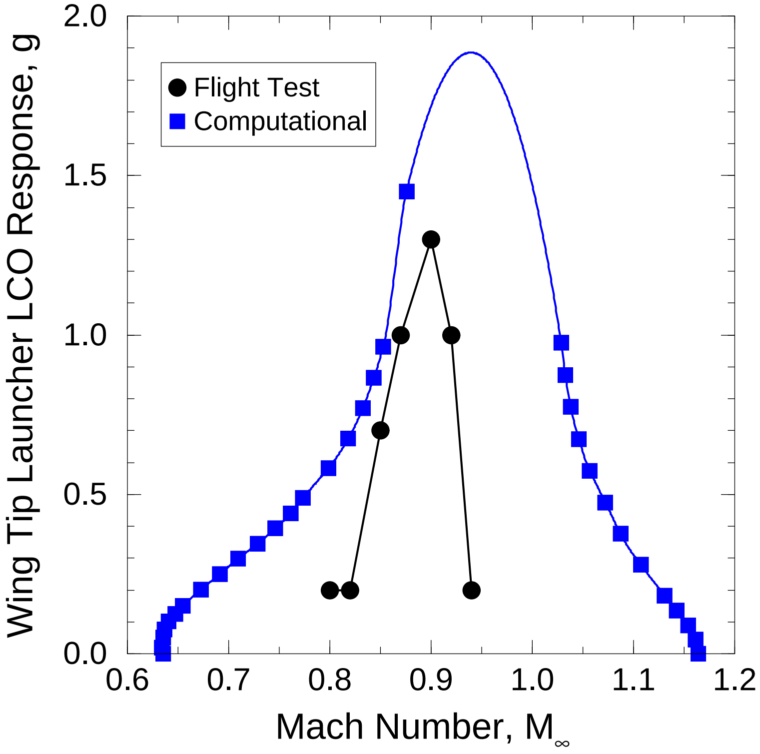

Figure 6. F-16 Configuration #5 Computed and Flight Test Forward Wingtip Launcher Accelerometer LCO Response Level Versus Mach Number for an Altitude of 2000 feet and a Mean Angle-of-Attack of $\bar{\alpha}_0 = 1.5$ **degrees.**

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