Aeroelastic Limit Cycle Oscillations in High Performance Aircraft

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ABSTRACT

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An overview is presented of limit cycle oscillations (LCO) that occur due to the nonlinear aeroelastic response of high performance aircraft. Both theoretical/computational and experimental work including wind tunnel and flight test data are discussed.

Primary emphasis is on (1) computational/experimental correlation and (2) recent developments in constructing rapid solution methods for computational models that retain state of the art high fidelity accuracy.

Results for a High Altitude Long Endurance (HALE) configuration, a fighter aircraft and a morphing (folding) wing illustrate the state of the art and also demonstrate the sensitivity of flutter and LCO prediction that may occur due to modest changes in key system parameters.

1.0 ACKNOWLEDGEMENTS

The author would like to acknowledge the members of the Duke team who have contributed to his education on this topic over the years including Peter Attar, Elizabeth Bloomhardt, Howard Conyers, Chad Custer, Kenneth Hall, Justin Jaworski, Robert Kielb, Tomokazu Miyakozawa, Meredith Spiker, Deman Tang and Jeffrey Thomas. He would also like to acknowledge his longtime mentor from whom he first learned about aeroelasticity and continues to learn so much, John Dugundji of MIT, and his current collaborators from other organizations including Charles Denegri Jr. of the SEEK EAGLE Office, Philip Beran and Victor Giurgiutiu of the AFRL and Moti Karpel and Daniella Raveh of the Technion. And indeed to the attendees of this symposium and our many colleagues in the aeroelastic community appreciation is given.

1.1 INTRODUCTION

In this paper the fundamental physical phenomena associated with limit cycle oscillations (LCO) of aeroelastic systems are discussed. There have been a number of excellent reviews of the relevant literature [1-13] and the reader is referred to those for a more comprehensive account of the subject. Among the subjects that have been considered by aeroelasticians and aerospace engineers are (1) flutter and LCO of fighter aircraft with various wing store combinations, (2) wing rock and abrupt wing stall (AWS) of fighter aircraft at high angles of attack, (3) flutter and LCO of High Altitude Long Endurance (HALE) configurations and (4) panel flutter of supersonic and hypersonic aircraft. Wing rock and abrupt wing stall are still the subject of intense study [9], but involve primarily the rigid body modes of the aircraft and hence are not further considered here. Panel flutter has been studied for many years including the important effects of the dominant structural nonlinearities [1]. The fundamental physical phenomena are well understood [1], but new applications to hypersonic vehicles may require further advances in our ability to account for the effects of viscous fluid boundary layers thermal stresses [13]. Panel flutter is not considered further here. Finally, freeplay is a commonly encountered structural nonlinearity that may lead to LCO [1-13]. But it has been discussed extensively in the literature and is not further considered here.

On the other hand emerging issues in nonlinear aeroelasticity include flutter and LCO of morphing aircraft and MAVs. Thus a brief introduction to these topics is included here. For a recent book on MAVs that has a discussion of aeroelastic issues inter alia see [14]

1.2 A BRIEF HISTORY OF NONLINEARITY AEROELASTICITY

Nonlinear aeroelastic phenomena per se are not new, what is new is our greater awareness of their presence in an ever increasing number of configurations and flight regimes and our improved ability to model theoretically/computationally such phenomena and to conduct relevant wind tunnel and flight tests.

1.2.1 Stall Flutter and LCO

For example, stall flutter in turbomachinery blades and rotorcraft blades has been of concern for decades. Stall flutter is generally attributed to separated flows and has been studied for many years by relatively simple empirical models. However recent studies have used more elaborate and hopefully more accurate models based upon computational fluid dynamic (CFD) models that solve to some approximation the Navier-Stokes equations for the aerodynamic flow. See [3-8]. Separated flow is thought to be an important nonlinear fluid mechanism for LCO in the F-16 aircraft as well especially as the separated flow interacts with oscillating shock waves.

1.2.2 Rotorcraft Blade Flutter and LCO

Because these blades are of high aspect ratio and often very flexible, large deformations of the structure may occur prior to and subsequent to the onset of a dynamic aeroelastic instability. A nonlinear structural model is essential to the prediction of the onset of these instabilities and the subsequent nonlinear oscillations. Indeed the motion may be so large that flow separation may be induced by the structural motion. The fundamental physical phenomenon have been known from the work on hingeless rotors dating back to the 1970s.

HALE aircraft are thought to be prone to similar nonlinear aeroelastic response.

1.2.3 Panel Flutter

Early major differences between theory and experiment were resolved when it was realized that structural nonlinearities are essential to understanding the physical phenomena. The first reported incidence of panel flutter was on the V-2 rocket of WWII. However panel flutter continues to be a concern for all supersonic and hypersonic aircraft especially as the panel stiffness may be degraded by thermal stresses.

1.2.4 Hydrodynamic Stability and Turbulence

One of the great unsolved problems of all of science and engineering is to model the dynamics of turbulent flows from first principles. Despite many years of work this remains in many respects an unresolved challenge. From a modern perspective, a laminar flow becomes dynamically unstable at some critical Reynolds number and then goes into a very complex limit cycle oscillation that may even be chaotic with a broadband frequency content. It appears that near the critical Reynolds number for the onset of the dynamic instability, the frequency content may be dominated by a fundamental frequency and a few additional harmonics. Indeed this simpler motion is sometimes not considered turbulence per se, but instead the term turbulence is often reserved for describing the broad band response that occurs once the critical Reynolds number has been exceeded by a great margin (orders of magnitude). Hence from a dynamics perspective, turbulence is a very complex and well developed LCO due to a Hopf bifurcation (flutter). Recognizing this is a first step, but only a first step, in attempting to model this very complex dynamic response.

Turbulence is also a term often usually reserved for the relatively small scale (on the order of the boundary layer thickness) random-like fluid motions that occur due to laminar flow instabilities. However it appears (although this is tentative conclusion) that larger scale dynamic instabilities of separated viscous flows may occur for wings at high angles of attack that lead to abrupt wing stall. It is an open question as to what theoretical/computational model for the fluid will adequately describe turbulence and abrupt wing stall.

1.3 RECENT PROGRESS

1.3.1 Computational Models

Over the last several decades computational models of ever greater fidelity have been developed to describe dynamics of the aerodynamic flow and the structure. It is now common for aeroelastic research groups to have available to them a CFD code for solving the Euler or Navier-Stokes fluid model on the one hand and a nonlinear elastic model of the structure on the other hand. Of course a Navier-Stokes solution today is usually approximate with the Reynolds Averaged Navier-Stokes (RANS) equations requiring an empirical turbulence model of uncertain accuracy for unsteady flows. More refined Navier-Stokes models based upon the ideas of Large Eddy Simulation and Detached Eddy Simulation offer promise, but are largely unused in the context of aeroelastic analysis today even by research groups. However one may expect such models to be considered more often in future aeroelastic work.

For all such CFD models the question of their utility even for research studies is critical because of the enormous computational resources required for traditional time marching solutions of the CFD models.

Thus a great deal of work has been done recently on constructing a variety of approaches to increase computational speed and reduce computational cost. These are often lumped together under the name Reduced Order Models (ROM). There are several distinct ideas and methods that may be used separately or together to reduce computational cost, and these are discussed next.

1.3.2 Modal Models for the Fluid and Structure

The highest fidelity computational models of the fluid and structure are usually based upon finite difference or finite volume or finite element methods for discretizing the spatial description of the flow field and structure. For many years, finite element models of the structure have been used to extract eigenmodes or natural modes of the structure. These modes form a reduced order model of good accuracy that has then been used to describe the structure in an aeroelastic analysis. However only relatively recently has it been realized that one may also find fluid modes that can serve a similar role and thus reduce the size of the computational fluid model (i.e. reduce the number of degrees of freedom) and thereby reduce the computational cost and increase the computational speed for obtaining aeroelastic solutions. It is true that the fluid modes are literally and figuratively more complex. The fluid eigenvalues are complex corresponding to the frequency and damping of each fluid mode and the computational challenge to determine fluid modes is considerably greater than that for their structural counterparts. Indeed an alternative to fluid eigenmodes has been found to be more advantageous, i.e. proper orthogonal decomposition modes. The reader is referred to the literature for the details, but suffice it to say that less than 100 POD modes are usually sufficient to describe the fluid with the same accuracy as the original CFD model that usually has 100,000 to a 1,000,000 or more degrees of freedom. Moreover POD modes are easier to compute than eigenmodes; POD modes may also be used to find eigenmodes if that is desired for some purposes.

However there is still a major challenge to the research community which is just now yielding to recent progress. Reduced order models based upon POD modes (POD/ROM) are easiest to construct for small amplitude fluid motions (linear dynamic perturbations about a nonlinear steady flow) and far more difficult to construct for large amplitude fluid motions (which may be induced by large amplitude structural motions). However a recent paper by Thomas, Dowell and Hall [15] has demonstrated one promising approach for constructing nonlinear POD/ROM aerodynamic flow models.

1.3.3 Temporal Models

Another form of Reduced Order Model seeks to reduce the number of variables required to describe the temporal response. [The POD or eigenmode approach of course is an approach to reduce the number of degrees of freedom required to describe the spatial response.] Two approaches have been considered. In one the idea of a transfer function in the frequency domain is invoked (Pade approximant for example) or alternatively the related method of a Volterra series in the time domain. Data from the original CFD model are used to determine the convolution kernels in the Volterra series or the parameters in the transfer function. By using only a few kernels or a relatively low-dimensional (in frequency) transfer function a very substantial reduction in computational cost may be realized. However it is also true in this case that these models are much more fully developed for small amplitude motions and extending them to nonlinear dynamic models of the fluid is a major challenge not yet fully met.

Another approach to reducing the computational cost that addresses the temporal representation is to use a novel form of Harmonic Balance (HB) rather than time marching to obtain a solution. In the usual HB approach it is assumed that the motion is periodic in time, although in principle non-periodic motions may be treated if they are motions composed of two or more incommensurate frequencies. For the rest of this discussion and for simplicity we consider only periodic motions. If the motion is periodic then the motion whether small or large may be represented as a Fourier series in time. For typical aeroelastic LCO only a few terms (harmonics) in the Fourier series need be used. Moreover there is a one to one correspondence between the coefficients in the Fourier Series and the solution at discrete times over a (single) period of oscillation. The number of discrete times is $2*N + 1$ where N is the number of harmonics. So for say two harmonics there are five discrete times. Thus rather than doing a time simulation with thousands of time steps to reach the periodic oscillation one needs to only solve for the solution at a few discrete times. This typically reduces the computational cost by a factor of 10 to 100.

Note the HB method described above allows large amplitude (nonlinear) fluid or structural motions.

1.3.4 Wind Tunnel and Flight Experiments:

Wind tunnel and flight tests have also advanced significantly over the last several decades and continue to do so in both methodology and available experimental data sets. Rather than discussing the experiments separately, we shall consider representative examples and data when discussing correlations between computations and experiments in the next section of this paper.

In the oral presentation we shall present several videos showing computer simulations and test results for LCO of a HALE configuration, the F-16 and a morphing (folding) wing. Table I describes the content of these videos. These are available from the author upon request. Still pictures from each video are shown in Fig. 1-6.

1.4 CORRELATION OF COMPUTATIONS AND EXPERIMENTS

1.4.1 Generic LCO Response

We first consider the possible types of generic LCO response before considering specific examples.

In Fig. 7 two schematics of limit cycle oscillation response are shown. There are basically two types of response that are possible. In the left hand figure a "good response" or supercritical response is shown. That is, there is a critical flow velocity or flutter velocity below which the system is stable and any disturbance to the system generates a transient in time, but the long time solution is no oscillation. Above the flutter speed a limit cycle oscillation occurs due to a nonlinearity in the fluid and/or structure and the amplitude of the LCO increases as flow velocity increases. If the flow velocity decreases, then the amplitude response retraces the same path as when the flow velocity increases.

By contrast in the right hand figure, when the flow velocity reaches the flutter velocity there is a sudden jump in LCO amplitude and then for further increases in flow velocity the LCO amplitude continues to increase in a smooth way. But now as the flow velocity is decreased, although the LCO response retraces its path until the flutter velocity is reached, for further reductions in the flow velocity, the LCO response does not return to zero, but rather has some finite amplitude until a lower flow velocity is reached at which point the LCO response then suddenly jumps back to zero. Thus LCO may exist below the flutter velocity. Indeed if the system is given a large enough disturbance, the LCO may exist even when the flow velocity is increasing. This is called a sub-critical response and it clearly is a bad and potentially dangerous response scenario. This second scenario is sometimes called hysteresis.

1.4.2 A HALE Configuration

This configuration, the wind tunnel test and the computational model are all discussed in considerable detail in [16-18]. Flutter, LCO and gust response were all measured and calculated. Both the structural and fluid computational models are nonlinear. The structural model is one that was originally developed for large elastic deformations of rotorcraft blades and the aerodynamic model was originally developed by Tran and Petot of ONERA for rotorcraft blades as well. The latter is basically a strip theory Theodorsen model with nonlinear terms added to account for flow separation and stall aerodynamics. The form of these nonlinear terms is postulated and the coefficients are determined using a system identification method based upon wind tunnel data for the NACA 0012 airfoil section.

In Fig. 8 the response (rms of the flapwise motion of the elastic axis at the wing tip) of the HALE wing is shown versus flow velocity from both computations and the wind tunnel test. This figure repays careful study.

First of all hysteresis occurs, that is the response obtained when increasing flow velocity is not the same as when the velocity is being decreased. This is an important consequence of system nonlinearities. In the computational model, by considering the structural and fluid nonlinearities individually as well as together, it was determined that the hysteresis is primarily a result of the aerodynamic nonlinearity due to flow separation.

When increasing the flow velocity and being careful that all disturbances to the system are small, the flutter velocity and also the flow velocity at which LCO is first observed is about 36 m/sec. Further increase in flow velocity increase the LCO response. Then when the flow velocity is reduced the LCO persists to about 32 m/sec in the experiment and to about 34 m/sec in the calculation. The response levels from computation and test are generally in good agreement as are the frequencies of the oscillation, see Fig. 9.

It is remarkable that a relatively simple and semi-empirical aerodynamic computational model gives such good agreement with measurement. The open question is, can a CFD based aerodynamic model do as well or even better?

1.4.3 F-16

Charles Denegri and his colleagues in the SEEK EAGLE Office of the US Air Force Research Laboratory (AFRL) have done pioneering work on conducting flight tests to determine the LCO response of the various F-16 configurations. Because of advances in computational solution techniques, notably the development of the Harmonic Balance solution method, comparisons are now possible between CFD based RANS aeroelastic models and flight test results. Note that the structure is modeled as linear. There is work underway by the SEEK EAGLE team to measure the degree of nonlinearity in the F-16 structure, but the results are not yet conclusive. It appears that the F-16 wing structure per se is basically linear over the response range of interest. However there may be important nonlinearities in the connections between the wing and stores. This is still an open question.

Thus the present discussion focuses on the aerodynamic nonlinearities that arise from flow separation and the interaction of the separated flow with oscillating shock waves. However there are other possible nonlinearities including structural nonlinearities and a listing of some of these is provided in Fig. 10.

Some eight F-16 wing/store configurations have now been studied computationally and a portion of those results are discussed here. We will focus on three configurations that illustrate some of the complexities and progress made in better understanding F-16 LCO.

In Fig. 11 a typical set of flight test data for Configuration 1 is shown for various altitudes. The results are similar for the several altitudes with a low level response at lower Mach numbers where the time history is essentially a response to atmospheric turbulence and has a random character. At the higher Mach numbers the response grows rapidly over a relatively narrow range of Mach number and the time history is a very nearly simple harmonic motion that is dominated by a single frequency with some detectable but small higher harmonics.

The motion is typically dominated by two structural modes, the lowest two anti-symmetric modes of the structure with rigid body roll and the higher anti-symmetric modes playing some modest role in the response. Not surprisingly therefore the flutter/LCO frequency is near the structural frequencies of the two dominant modes which themselves are close together. See Fig. 12 for a picture of the spatial deformation of these two structural modes and their frequencies. Note the two structural frequencies are only about .5 Hz apart.

The computed flutter/LCO onset boundary for this configuration is shown in Fig. 13. For this configuration no hysteresis is predicted nor was any detected in the flight test. Also the computed flutter mode and frequency are very near that found in flight.

The store arrangements for Configurations 1, 2 and 3 are shown in Fig. 14 and the structural natural frequencies of the four lowest modes are shown in Fig. 15. Note that the lowest two natural frequencies are closest together for Configuration 2 and furthest apart for Configuration 3. As will be seen later, this placement of the structural natural frequencies is thought to explain some of the variation seen in flight test and aircraft operation results.

First however consider the LCO response for Configuration 1 as measured in flight tests and as computed using a RANS CFD aerodynamic model and a linear structural model. See Fig. 16. Three different computational results are shown to demonstrate the sensitivity of the results to changes in the aeroelastic model. Consider first the result for the nominal configuration. The Mach number at which the flight test results shows a shift from small random response to large harmonic response is in the range of M = .8-.85; the computed value for the onset of LCO (and also flutter) is M = .9. Moreover the LCO frequency and structural model content is well predicted by the computation. On the other hand the LCO amplitudes measured in flight test lie somewhat above those computed.

The computational model was then improved by including the aerodynamic forces on the tip launcher (there is no tip missile for Configuration 1). This improves modestly the prediction compared to flight test. Finally to examine the sensitivity of the computed results to small changes in structural frequencies a 1% change in one of the structural frequencies was made. This further improved the agreement between computation and flight tests. However it should be emphasized that the amount and direction of the change made in the structural frequencies was reasonable, but arbitrary. Had the direction of the change in the structural frequency been reversed, the agreement between computed and measured results would have been less good than for the nominal configuration. Thus this result only shows the sensitivity of the results to small changes in structural frequencies and that, if desired, one can "tune" the model to achieve better agreement between computation and flight test.

Now consider flight test results for Configurations 2 and 3. See Fig. 17. In the first row of this figure results are shown for Configuration 2 for several different altitudes and in the second row are shown results for Configuration 3. In each case the flight tests were repeated three times for each altitude. Note the much greater scatter in the data from one flight test to the next for Configuration 2 compared to Configuration 3. This is thought to be a consequence of the difference in structural natural frequencies. Computations show that the flutter/LCO response of Configuration 2 is more sensitive to small differences in structural frequencies than Configuration 3 as expected from our earlier discussion of Fig. 15.

Finally in Fig. 18, we consider these same three configurations and the effect of computationally modelling or not modelling the aerodynamic forces on the tip missile and/or launcher. Configuration 2 has both an launcher and missile while Configurations 1 and 3 have only a launcher. Results for the flutter/LCO onset boundary are shown with and without the tip aerodynamics included. For Configurations 1 and 3 there is little difference in the two results. However for Configuration 2 there is a very large difference which subsequent computations have shown is primarily attributable to the aerodynamic forces on the missile fins. Indeed it is only with the aerodynamics of the tip missiles included that flutter/LCO is predicted for Configuration 2 and then there is reasonable agreement between theory and experiment. Compare Figure 17 and 18.

Calculations continue for these and other configurations with the usual outcomes being the following: (1) flutter/LCO modes and frequencies are well predicted; (2) in most cases the Mach number for flutter/LCO is reasonably well predicted; (3) but the LCO amplitudes are substantially more challenging to predict with results ranging from good to poor.

1.4.4 Folding Wing

Very recently a generic folding wing model was tested in the Duke University wind tunnel test and there is a forthcoming paper on this subject that has been accepted for publication in the Journal of Aircraft. The purpose of this work was to see if (1) standard methods of flutter analysis could predict the onset of flutter and (2) if LCO would occur in the wind tunnel test model. The answers to the above questions are yes and yes. In Fig. 19 and 20 the computed and measured flutter velocity and flutter frequency are shown for a range of fold angles. The agreement between computations and tests is good. Also it was found that LCO did indeed occur and current work is underway to include the relevant nonlinearities in the computational model to predict LCO. How well this can be done remains to be seen.

1.5 CONCLUSIONS

LCO can be predicted based upon appropriate nonlinear models. However the computations are more complex than for classical flutter analysis since they require nonlinear aeroelastic models.

Recent advances in new and more rapid solutions techniques for CFD based aeroelastic models with state of the art accuracy and physical fidelity give promise for the future of such calculations.

In general prediction of LCO will be more difficult than the prediction of flutter per se and it will always be more difficult to predict the nonlinear LCO response of a structure at various locations compared to the prediction of a global property of the system such as the flutter boundary or the boundary for the onset of LCO.

For aeroelastic models where the nonlinearity in the model has been considered in the design process (e.g. the HALE wing discussed here) the correlation between theory and experiment is generally better than for systems which were designed based upon linear computational models (e.g. the F-16). In the latter case one is in the position of having to consider a broad range of possible sources of nonlinearity in the aeroelastic system, but not knowing a priori which one may be most important.

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TABLE I

THE FOLLOWING SIX VIDEOS ARE FOR THE HALE WING, THE F-16 AIRCRAFT, AND A FOLDING WING, RESPECTIVELY.

- VIDEO #1 IS A VIDEO FROM A COMPUTATIONAL SIMULATION OF A NONLINEAR AEROELASTIC MODEL OF THE *HALE WING* THAT IS BASED UPON
  (1) A LARGE AMPLITUDE NONLINEAR STRUCTURAL MODEL
  AND
  (2) A NONLINEAR AERODYNAMIC (ONERA) MODEL THAT INCLUDES THE EFFECTS OF FLOW SEPARATION

- VIDEO # 2 IS A VIDEO OF THE WIND TUNNEL TEST OF AN AEROELASTIC MODEL OF THE *HALE WING*

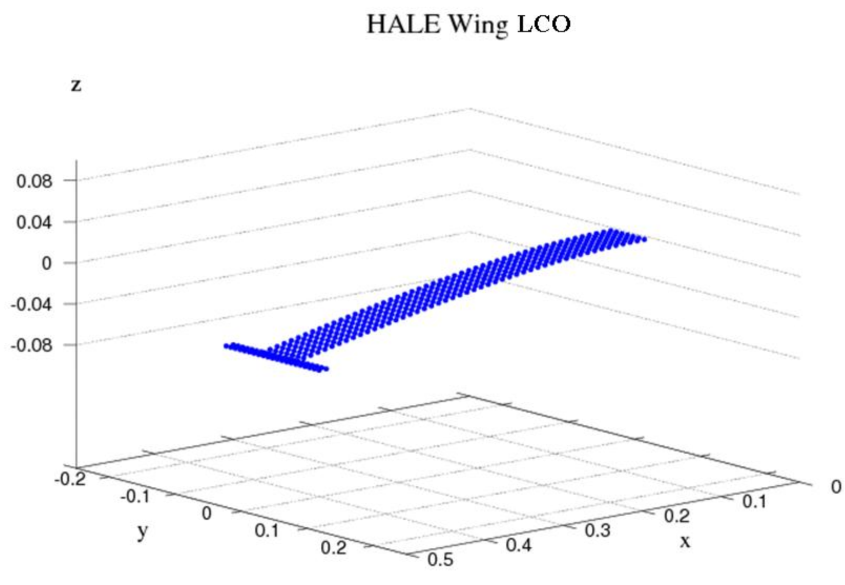
  NOTE THE COMPUTATIONAL SIMULATION AND THE WIND TUNNELTEST BOTH SHOW THE SAME LCO PHENOMENA.

- VIDEO #3 IS A VIDEO FROM A COMPUTATIONAL SIMULATION OF A NONLINEAR AEROELASTIC MODEL OF AN F-16 CONFIGURATION THAT IS BASED UPON
  (1) A NONLINEAR NAVIER-STOKES AERODYNAMIC MODEL AND
  (2) A LINEAR STRUCTURAL MODEL.
  THE INSET SHOWS THE LCO AMPLITUDE AT THE WING TIP PLOTTED VERSUS MACH NUMBER. THE VIDEO PER SE SHOWS THE STRUCTURAL MOTION OF THE ENTIRE WING AT THREE DIFFERENT MACH NUMBERS LABELED AS POINTS 1, 2 AND 3. NOTE THAT THE STRUCTURAL NODE LINES ARE MOVING DURING THE LCO AS INDICATED BY THE LIGHT AND DARK SHADING.

- VIDEO #4 IS A VIDEO FROM THE SAME COMPUTATIONAL SIMULATION, BUT NOW SHOWING AN END-ON VIEW OF THE WING TIP AND ALSO SHOWING THE FLOW FIELD IN TERMS OF MACH NUMBER CONTOURS. THE SHOCK IN THE FLOW AND THE TRAILING EDGE SEPARATION ARE VISIBLE IN THE VIDEO. NOTE THE STRUCTURAL MOTION IN THIS VIDEO IS THE ACTUAL SIZE WHILE IN VIDEO #3 THE STRUCTURAL MOTION HAS BEEN MAGNIFIED FOR EASIER VIEWING.

- VIDEO #5 TOP VIEW OF FOLDING WING FLUTTER AND LCO WIND TUNNEL TEST.

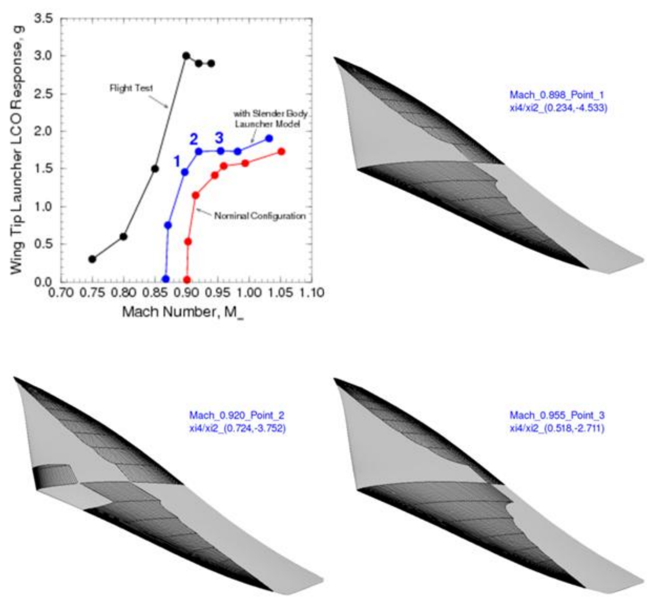
- VIDEO #6 END VIEW …… .



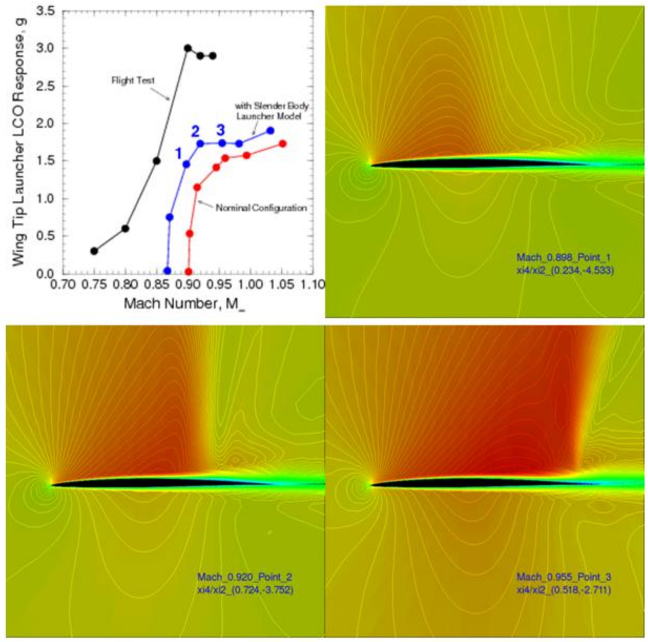
- FIGURE 1: Hale Simulations: Front View

HALE WING LCO

- FIGURE 2: Hale Experiments: Front View

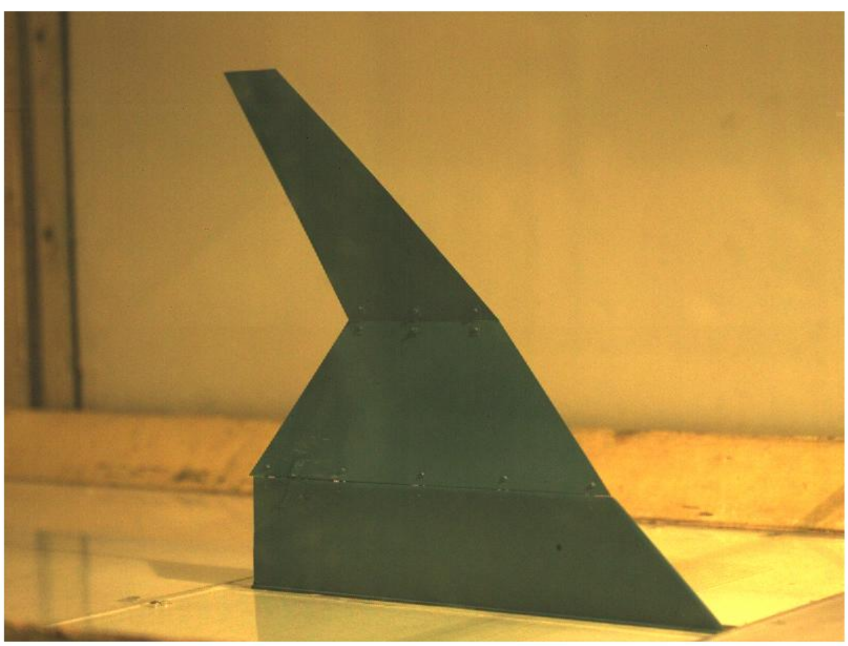


- FIGURE 3: F-16 LCO



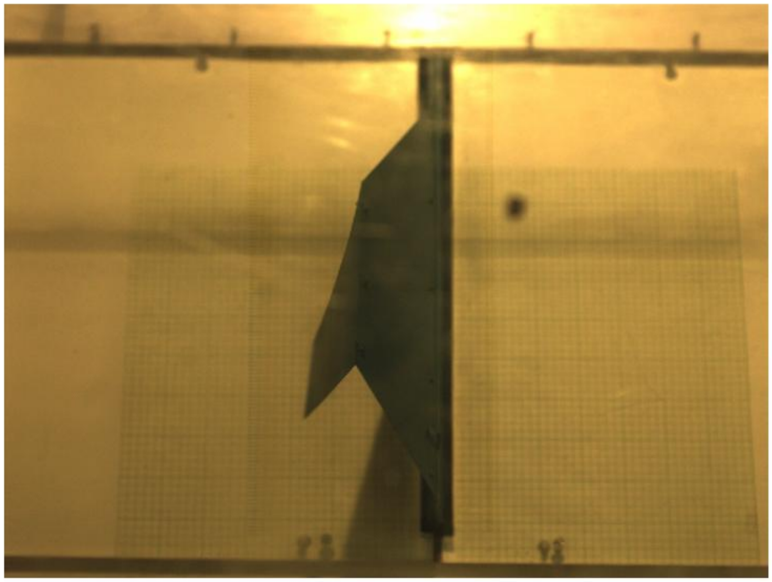
- FIGURE 4: F-16 LCO

FOLDING WING LCO

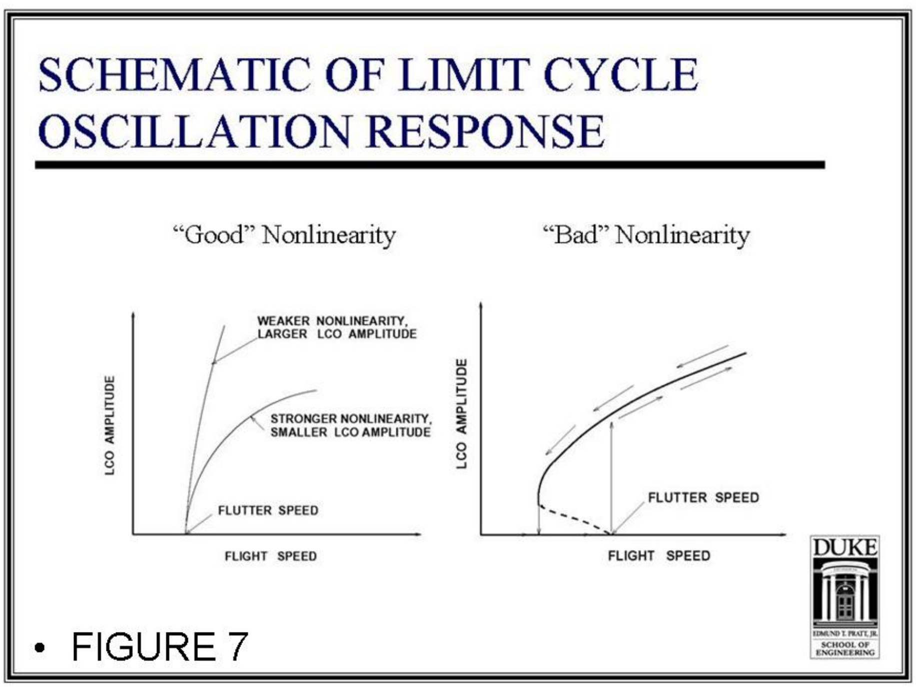


- FIGURE 5

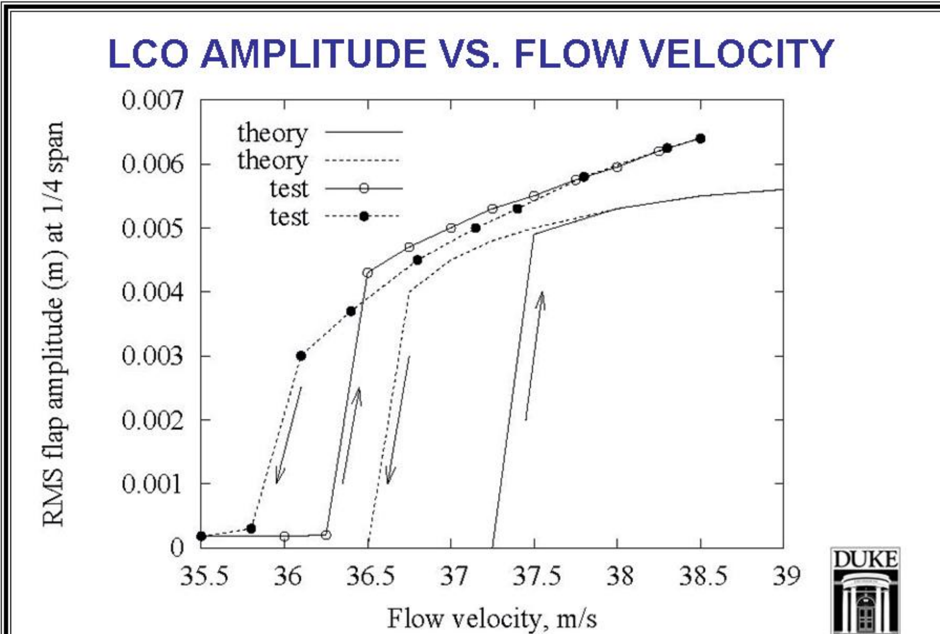
FOLDING WING LCO



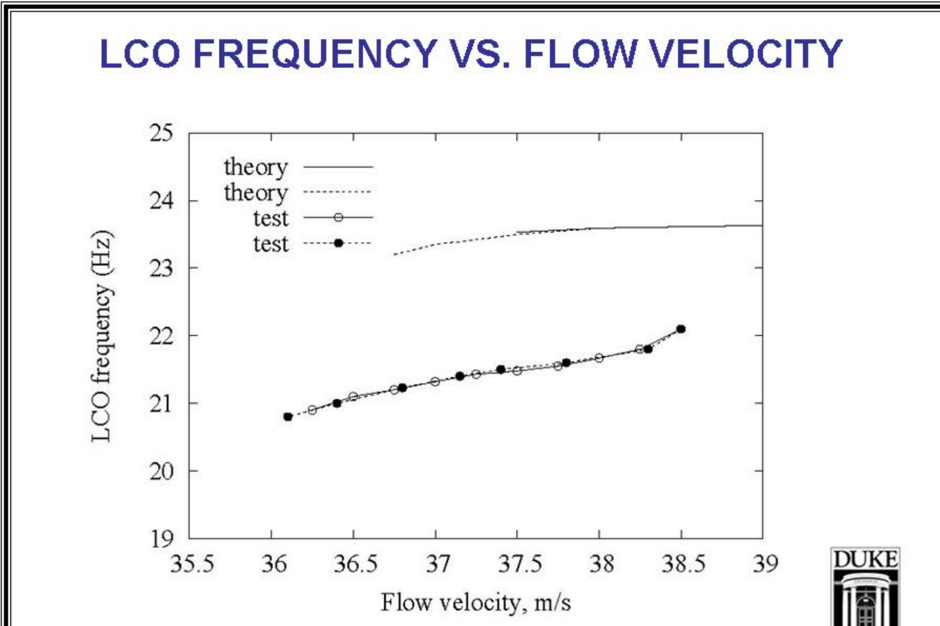
- FIGURE 6



- FIGURE 7



- FIGURE 8 **HALE WING LCO**



- FIGURE 9 **HALE WING LCO**

THE SEVERAL PHYSICAL SOURCES OF NONLINEARITIES

STRUCTURE

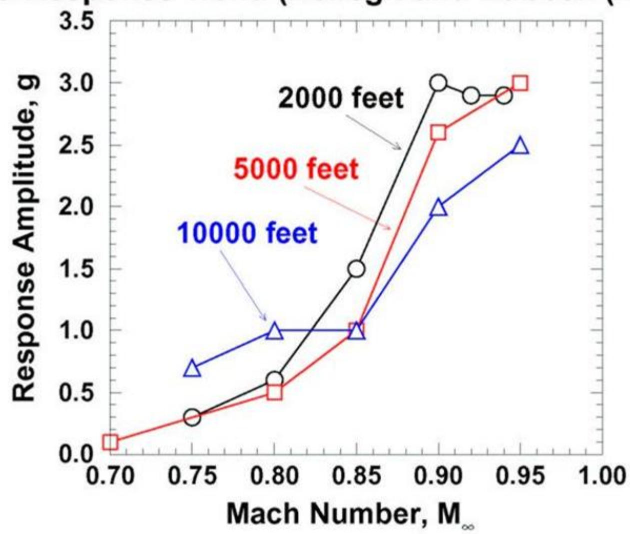
- CONTROL SURFACE FREE-PLAY (SUBCRITICAL & VERY STRONG)
- WING-STORE FREE-PLAY (?)
- PLATE-LIKE STIFFNESS (SUPERCRITICAL & STRONG)
- VERY HIGH ASPECT RATIO WING (SUBCRITICAL & MODERATELY STRONG)

FLUID (OUR FOCUS TODAY)

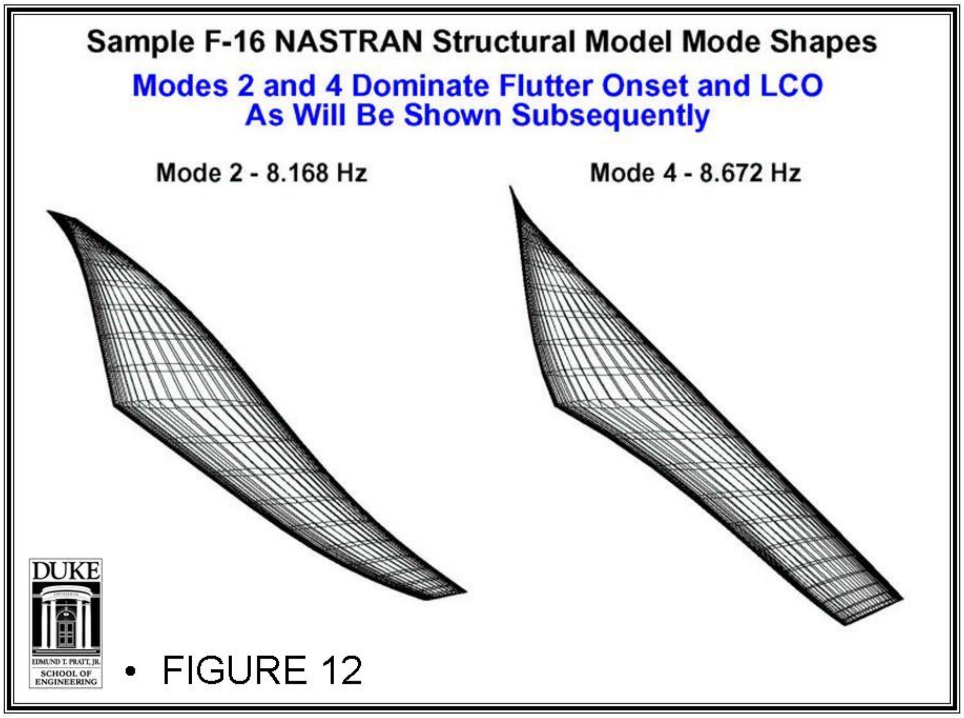
- SHOCKWAVES (SUB OR SUPERCRITICAL & WEAK USUALLY, BUT MAY BE STRONG)
- SEPARATED FLOW (SUB OR SUPERCRITICAL & STRONGER)

- FIGURE 10

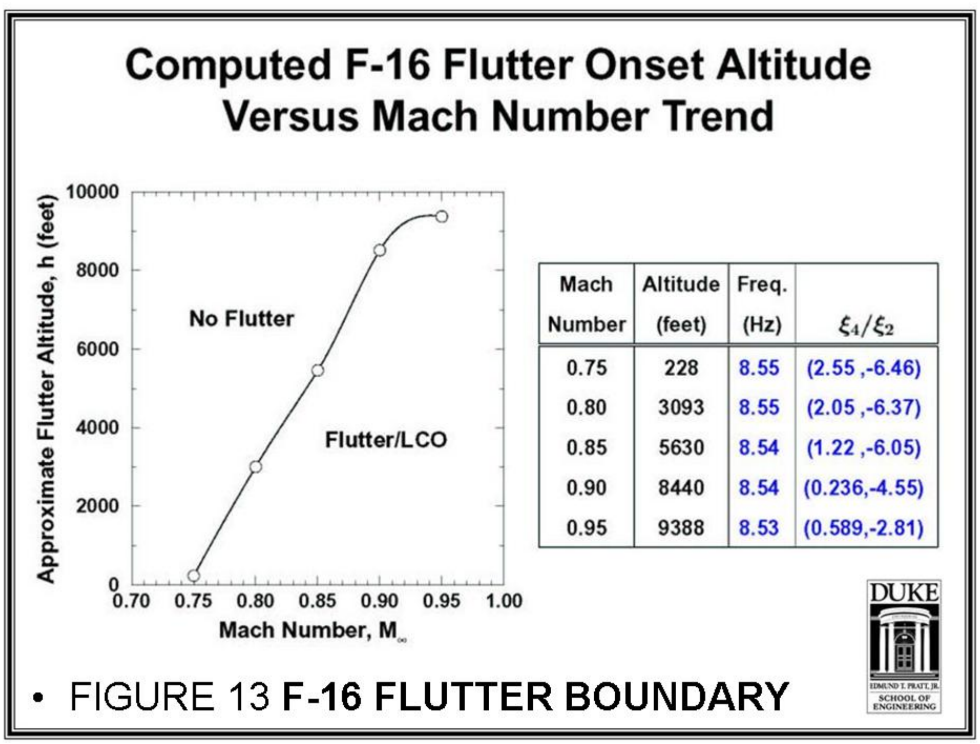
F-16 Forward Wingtip Launcher Accelerometer LCO Response Trend (Denegri and Dubben (2003))



- FIGURE 11 **F-16 LCO**



• FIGURE 12



Mach Number	Altitude (feet)	Freq. (Hz)	ξ_4/ξ_2
0.75	228	8.55	(2.55 ,-6.46)
0.80	3093	8.55	(2.05 ,-6.37)
0.85	5630	8.54	(1.22 ,-6.05)
0.90	8440	8.54	(0.236,-4.55)
0.95	9388	8.53	(0.589,-2.81)

• FIGURE 13 **F-16 FLUTTER BOUNDARY**

FIGURE 14: F-16 (Block 40) Experimental LCO Aircraft Weapons and Stores Configurations

Stn.	Configuration 1	Configuration 2	Configuration 3
1	LAU-129 launcher	AIM-9L missile/LAU-129 launcher	LAU-129 launcher
2	AIM-9P missile/LAU-129 launcher	AIM-9L missile/LAU-129 launcher	AIM-120 missile/LAU-129 launcher
3	Air-to-ground missile	Air-to-ground missile	General purpose bomb
4	Empty 370-gal fuel tank	Half-full 370-gal fuel tank	Quarter-full 370-gal fuel tank
5	Empty station	Empty station	Empty station
6	Empty 370-gal fuel tank	Half-full 370-gal fuel tank	Quarter-full 370-gal fuel tank
7	Air-to-ground missile	Air-to-ground missile	General purpose bomb
8	AIM-9P missile/LAU-129 launcher	AIM-9L missile/LAU-129 launcher	AIM-120 missile/LAU-129 launcher
9	LAU-129 launcher	AIM-9L missile/LAU-129 launcher	LAU-129 launcher

FIGURE 15: F-16C Configuration Natural Frequencies

Mode	Configuration 1	Configuration 2	Configuration 3
First Bending (f_{1ab})	8.17 Hz	5.47 Hz	6.50 Hz
First Twisting (f_{1at})	8.67 Hz	5.74 Hz	7.32 Hz
Second Bending (f_{2ab})	10.9 Hz	7.87 Hz	8.37 Hz
Second Twisting (f_{2at})	12.3 Hz	8.01 Hz	8.97 Hz
$f_{1at} - f_{1ab}$	0.504 Hz	0.265 Hz	0.820 Hz

Antisymmetric Modes Via NASTRAN

FIGURE 16: LCO Response vs Mach Number: Sensitivity to Uncertainty in Aerodynamic Modeling of Tip Missile and Structural Natural Frequencies

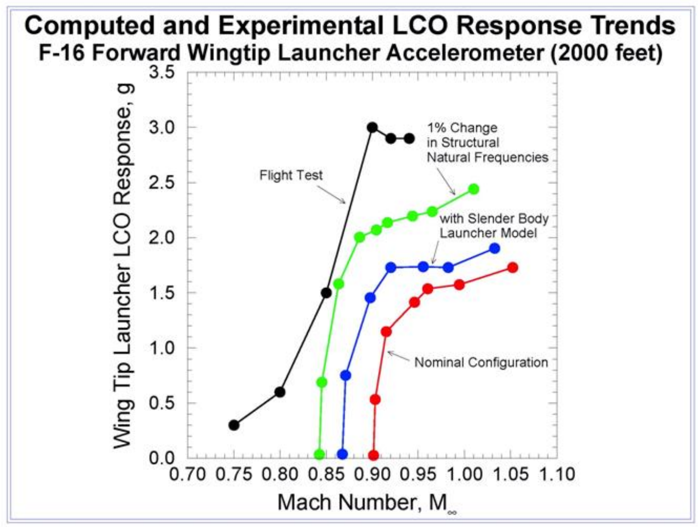


FIGURE 17: F-16 Flight Test Wingtip LCO Response

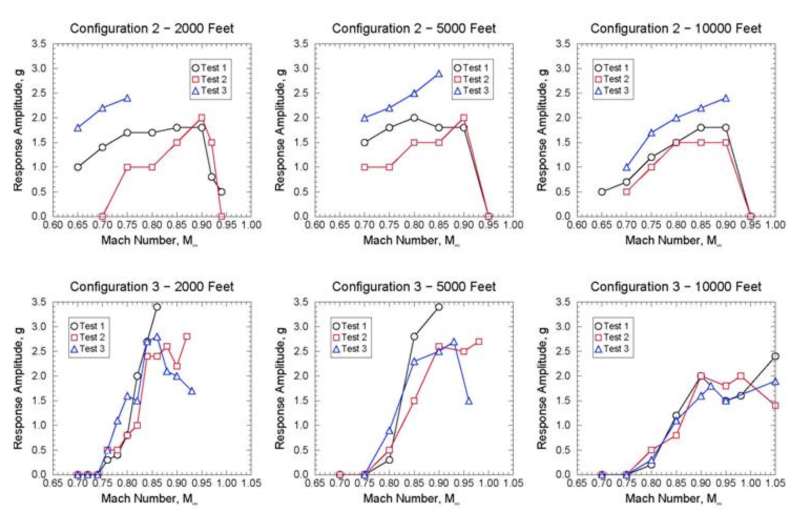
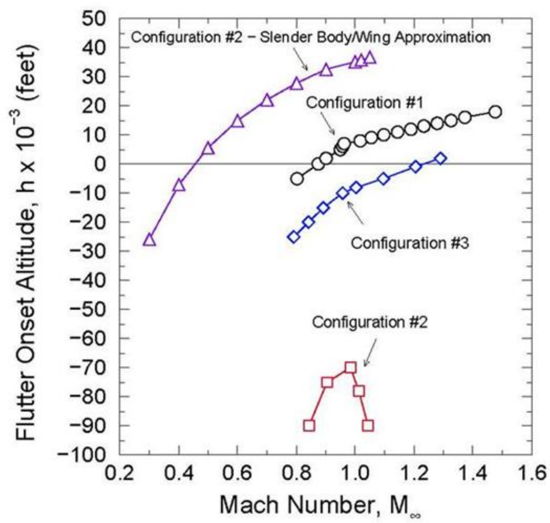
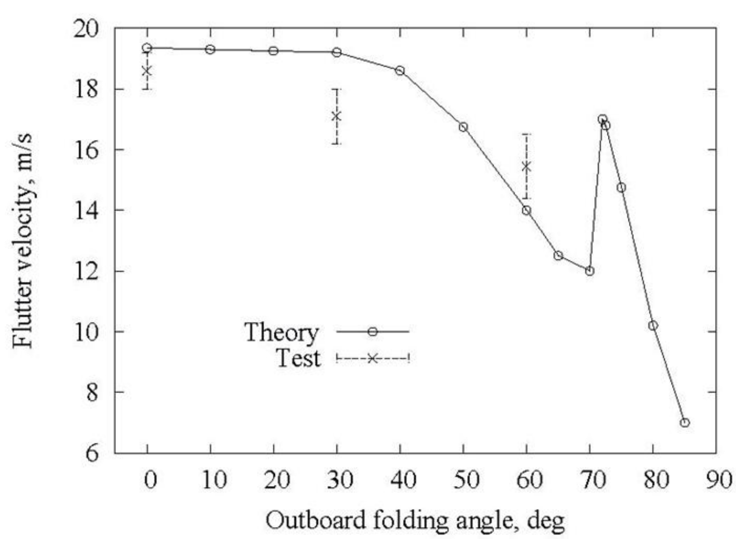


FIGURE 18: Flutter Onset Altitude vs Mach Number

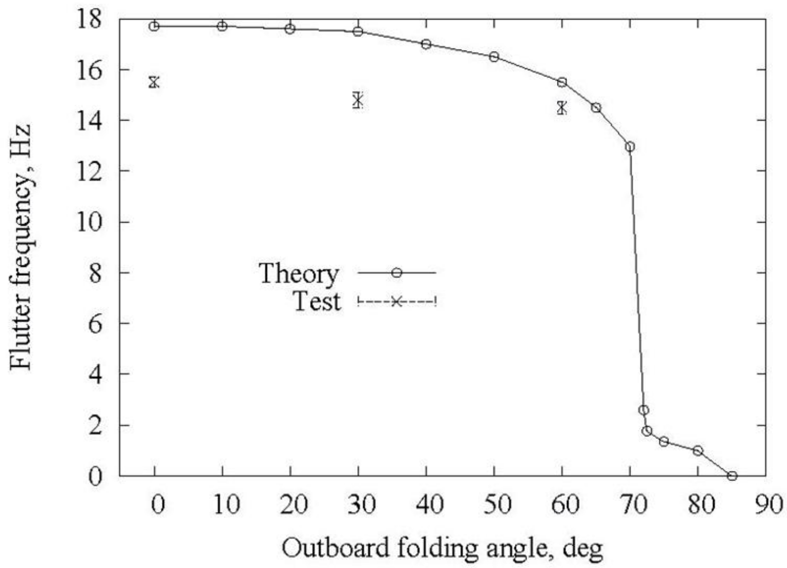


FLUTTER VELOCITY VS. FOLDING ANGLE



- FIGURE 19 **FOLDING WING FLUTTER BOUNDARY**

FLUTTER FREQUENCY VS. FOLDING ANGLE



- FIGURE 20 **FLUTTER FREQUENCY**