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| 14. ABSTRACT<br>Future air vehicles will be highly flexible and will include deformable sub-systems resulting in new physical interactions between a vehicle's structure, the surrounding flowfield, and the dynamics of the vehicle that are fundamentally nonlinear. Although existing aeroelastic methodologies might be considered reliable for traditional applications, they fail (as evidenced by current experiences) to properly capture the complex physics expected for these vehicles. Challenges include non-traditional and time-varying geometries, separated flows, nonlinear dynamic vehicle states, and high-fidelity modeling requirements for highly integrated vehicles. In short, there are no means for understanding the basic interactions that occur in systems dominated by nonlinearities in all three disciplines -structure, flow, and dynamics, nor are the computational interfaces adequate to handle the nonlinear interdisciplinary interactions. |  |                                           |  |                                                              |  |
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**PHYSICS-BASED AEROELASTIC ANALYSIS  
FOR FUTURE AIR VEHICLE CONCEPTS  
USING A FULLY NONLINEAR METHODOLOGY**

Final Performance Report  
March 1, 2004 – June 30, 2007

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Herein, the investigators summarize activity on the topic “Physics-based aeroelastic analysis for future air vehicle concepts using a fully nonlinear methodology”. At the end of this summary report the principle investigators list the primary deliverables in the form of the peer-reviewed publications; professional interactions and transitions at conference and workshop venues; consultative functions to AFRL; and, accomplishments from the graduate research assistants supported on the project.

**Abstract**

Future air vehicles will be highly flexible and will include deformable sub-systems resulting in new physical interactions between a vehicle’s structure, the surrounding flowfield, and the dynamics of the vehicle that are fundamentally nonlinear. Although existing aeroelastic methodologies might be considered reliable for traditional applications, they fail (as evidenced by current experiences) to properly capture the complex physics expected for these vehicles. Challenges include non-traditional and time-varying geometries, separated flows, nonlinear dynamic vehicle states, and high-fidelity modeling requirements for highly integrated vehicles. In short, there are no means for understanding the basic interactions that occur in systems dominated by nonlinearities in all three disciplines - structure, flow, and dynamics, nor are the computational interfaces adequate to handle the nonlinear interdisciplinary interactions.

Performance requirements of future air vehicles, such as endurance, autonomous behavior, mobility, payload requirements, and vehicle size, drive designs that well exceed our present capabilities to accurately analyze the behavior of candidate systems. Even existing air vehicles

and pilot performance are limited by nonlinear behavior that are not understood and which are the subject of current research investigations. The development of new Uninhabited Air Vehicles (UAVs) and Micro-UAVs (MAVs) will require improved understanding of large-amplitude nonlinear interactions, flow physics, and nonlinear and multi-functional structures.

The investigators pursue a multiphase effort to address three classes of flight vehicles: (I) vehicles of small structural deformations (*i.e.*, conventional configurations), (II) vehicles of moderate-to-high deformations (*e.g.*, high-altitude UAV class vehicles), and (III) vehicles of very high dynamics (MAV-class vehicles). Each vehicle presents challenges associated with dynamics, scale, flow field conditions, and computational issues related to fluid-structure boundary interactions. The research activities include development of the nonlinear structural equations of motion for benchmark configurations that permits in-plane, out-of-plane, and torsional couplings. The structural equations of motion for the vehicle will be included to assure static and dynamic trim to capture rigid body motions, maneuvers, and body-freedom flutter mechanisms. Consideration of the unsteady aerodynamic approaches must address the range of possible flow fields, ranging from low Reynolds number, highly separated flows to transonic flows with shock/boundary layer interaction. New vehicle benchmark models will be developed such as a very high aspect ratio with high flexibility (indicative of optimized payload capacity designs) and representative frequency characteristics and a wing with a highly deformable geometry. Research will include development of a solution methodology that assures synchronous interaction between the nonlinear structure and fluid including a consistent geometric interface between the highly-deforming structure and flow field. This research will also include nonlinear analysis to fully explore the bifurcation characteristics (especially subcritical branches), potential parametric resonances, and parameter space related to design.

## Objectives

1. Develop an understanding of the physical, multi-disciplinary interactions fundamental to the operation of future air vehicles. Key single-discipline phenomena to be considered include:
  - Structural nonlinearities (*e.g.*, stiffening)
  - Aerodynamic nonlinearities (*e.g.*, separated and/or transonic flow)
  - Dynamic nonlinearities (*e.g.*, body degrees of freedom)
  - Geometric nonlinearities (*e.g.*, preservation of surface area)

Key interaction phenomena that will be considered include:

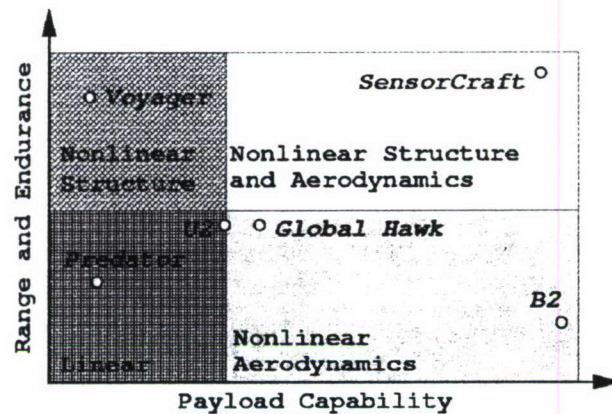
- Stability loss due to nonlinear dynamic responses such as limit-cycle oscillation
- Subcritical Hopf bifurcations and solution non-uniqueness (multiple LCO states)
- Dynamic equilibrium states (vehicle trim conditions)
- Interactions between highly separated flows and highly flexible structures
- Vehicle responses and instabilities owing to shock-boundary layer interaction

2. Develop new, high-fidelity computational methodologies necessary for the study of these future air vehicle concepts and their unique physics. These will include:
  - Physics-based models of the nonlinear aeroelastic system (*e.g.*, aerodynamics, structural dynamics, and algorithms) with commensurate levels of fidelity
  - Effective nonlinear functional analysis (bifurcation characteristics) of the system
  - Scaling issues related to low Reynolds number flows
  - Full-configuration, time-accurate and synchronized simulations of nonlinear responses that will utilize a multidisciplinary computational environment
  - Interpolation methods for highly deforming structures
3. Explore vehicle concepts with the potential for meeting key performance requirements. These will include:
  - Develop configuration benchmark applications to facilitate comprehensive examination of issues 1 and 2.
  - Affect the design and analysis capabilities of future aircraft configurations by identifying similarity parameters (*e.g.*, frequency ratios, threshold displacement ratios such as tip deflection to span) that identify nonlinear regimes.

### **Challenges for Future Air Vehicle Design and Analysis**

The analysis and design tools currently in use are not suited for analysis of new classes of future aircraft such as SensorCraft UAVs (see Fig. 1). The fundamental science issues associated with managing nonlinear aeroelastic effects have not been adequately explored in configurations of this scale (200+ feet wingspans with aspect ratios (span/chord)  $> 30$ ). Novel computational strategies are required to reveal the physics of the fluid-structure interactions. Active wing technologies, such as those explored in the Active Aeroelastic Wing (AAW) program, utilize pronounced twisting and bending to achieve desired aerodynamic loads. For high-aspect ratio wings, major benefits of such active wing technology are shape optimization for lightweight design to improve payload capacity and gust load alleviation. Mission profiles (*e.g.*, 60,000 ft. cruise at Mach 0.65) will produce transonic conditions over large sections of an extremely flexible wing.

Shock-induced flow separation will also be a major concern for this class of air vehicles, and optimal performance may require laminar flow constraints. Structural nonlinearities that are inherent in the flexible, high-aspect-ratio wing are exacerbated in envisioned joined-wing configurations. Nonlinear responses driven by these phenomena are anticipated to be of large amplitude with multiple potential solution states. Existing single-discipline analysis tools cannot capture the complex physical interactions that may constrain the performance of future systems. As a result, it will be necessary to couple the best analysis tools into a computational framework capable of robust and flexible multi-disciplinary analysis. These tools must be reliably and accurately coupled to enable the design analysis of future flight vehicles that will necessarily be described by highly nonlinear solution spaces.



**Figure 1. Design and performance analysis requirements of new UAV concepts exceed current capabilities.** (figure credited to Major David Lucia, AFRL SensorCraft Program)

### Nonlinear Behavior

In recent years, studies of nonlinear fluid-structure interactions have been motivated by evidence that there are adverse aeroelastic responses attributed to system nonlinearities. For example, limit-cycle oscillations (LCOs) occur in nonlinear aeroelastic systems and remain a persistent problem on fighter aircraft with store configurations. Nonlinear phenomena such as LCOs have been observed as reported by Bunton and Denegri<sup>1</sup>, and Denegri<sup>2</sup>. Such LCOs are unacceptable since aircraft performance, aircraft certification, mission capability, and human factor issues such as pilot fatigue are adversely affected. The existence of residual pitch oscillations (RPOs) has also been found during flight tests of the B-2<sup>3</sup>, and this interaction of flexible body and rigid body modes found in unusual vehicle configurations may be present in new geometries. Research has improved the understanding of LCO responses that limit vehicle and pilot performance, and such research efforts are relevant to understanding behavior of new air vehicle concepts, including MAVs and high altitude, long endurance UAVs.

We (see Kim and Strganac<sup>4</sup>) studied LCOs of a cantilever wing with three possible nonlinearities, including aerodynamic, structural, and store-induced nonlinearities. When these three nonlinearities were combined, LCOs were observed at speeds below the flutter velocity. This study was limited to specific conditions, such as velocity and store properties. The presence of subcritical LCOs was dominated by the structural nonlinearity, yet the aerodynamic and store nonlinearities change the characteristic of the nonlinear responses. Most recently, Beran, Strganac and Kim<sup>5</sup> presented studies on an approach to couple nonlinear structural and aerodynamic methods to examine LCOs in the transonic flow regime.

Development of the fully coupled nonlinear equations of motion include: (1) formulation of nonlinear structural response via direct solution of the partial differential equations; (2) formulation of the nonlinear aerodynamic loads via high-fidelity computational fluid dynamic methods; and (3) coupling methodology that accounts for the structural, aerodynamic and kinematic interdependence found in the aeroelastic system.

The research activities include development of the nonlinear structural equations of motion for configurations that permit in-plane, out-of-plane, and torsional couplings. The equations of motion for the vehicle are included to assure static and dynamic equilibrium (trim) to capture rigid body motions, maneuvers, and body-freedom flutter mechanisms. For purposes of examining responses associated with high altitude sensorcraft and similar UAV designs, a benchmark is developed. In particular, the benchmark considers frequency ratios that permit examination of parametric resonances and multi-axial (in-plane, out-of-plane, transverse, torsional) responses. The benchmark represents high aspect ratio ( $AR > 30$ ) responses, including large deformations (tip displacement  $> 30\%$  span). Analysis includes aircraft trim states to capture vehicle dynamics including rigid body motion and vibration modes. Full parameter space must be considered leading to the need for improved computational interfaces, a continuous bifurcation model capability, and proper consideration of scaling parameters. Herein, a cantilever wing is considered and the research includes the wing in trimmed flight.

In order to describe nonlinear behavior of the cantilever wing, several nonlinear beam theories were considered. This effort identified limitations that must be overcome. For example, the benchmark configuration must be modeled to account for bending about multiple axes, as well as torsional couplings. The nonlinear equations of motion for a cantilever wing are derived from the equations of motion for flexural-flexural-torsional vibrations. The formulation follows an approach developed by Crespo da Silva<sup>6</sup> but includes mass imbalances, point masses and inclusion of nonlinear interface for the aerodynamics. The equations contain structural coupling terms and include both quadratic and cubic nonlinearities due to curvature and inertia. The equations are as follows:

$$\text{in-plane:} \quad m\ddot{u} - I_z \ddot{u}'' + D_z u'''' = G_u + A \quad (1)$$

$$\text{out-of-plane:} \quad m\ddot{w} - m e \ddot{\alpha} - I_x \ddot{w}'' + D_x w'''' = G_w + N \quad (2)$$

$$\text{torsion:} \quad I_y \ddot{\alpha} - m e \ddot{w} - D_y \alpha'' = G_\alpha + M_{EA} \quad (3)$$

where the system nonlinearities are described as follows,

$$\begin{aligned} G_u = & \beta_y (\alpha' w'') - \beta_z [u' (w' w'')] + (\beta_z - 1) \left[ (w'' \alpha + u'' \alpha^2) - w'' \int_0^s u'' w' ds \right] \\ & - \left\{ \frac{1}{2} u' \int_L^s \left[ \int_0^s (w'^2) ds \right]'' d\bar{s} - e^* u' \int_L^s \ddot{u}' ds \right\} \\ & + e^* \left[ \frac{1}{2} (\alpha^2 - w'^2)'' - (u' \ddot{u} + w' \ddot{w})' \right] + \frac{1}{2} e^* [(w'^2 + u'^2 + \alpha^2)]' \end{aligned} \quad (4)$$

$$\begin{aligned} G_w = & -\beta_y (\alpha' u'') - [w' (w' w'')] + (\beta_z - 1) [(u'' \alpha - w'' \alpha^2)] \\ & - \left\{ \frac{1}{2} w' \int_L^s \left[ \int_0^s (w'^2) ds \right]'' d\bar{s} - e^* w' \int_L^s \ddot{u}' ds \right\} + e^* \left[ \int_0^s w' u'' ds \right]'' \end{aligned} \quad (5)$$

$$\begin{aligned}
G_\alpha = & -(\beta_z - 1) \left[ (w''^2 - u''^2) \alpha - w'' u'' \right] + I_y^* \left[ \left( \int_0^s w'' u' ds \right)'' - (\dot{w}' u')^* \right] + (I_z^* - I_x^*) \left[ \dot{w}'^2 \alpha - \dot{u}' \dot{w}' \right] \\
& + e^* \left\{ -\frac{1}{2} \ddot{w} (w'^2 + \alpha^2) + \frac{1}{2} w' \left( \int_0^s (w'')^2 ds \right)'' + \ddot{u} \alpha \right\}
\end{aligned} \tag{6}$$

where  $u, w$  and  $\alpha$  represent the in-plane bending deflection, out-of-plane bending deflection and torsional rotation, respectively.  $m$  represents the wing mass per unit span.  $e$  represents the chordwise distance between the centroidal and elastic axes.  $I_x, I_y$  and  $I_z$  represent mass moments of inertia per unit span about the  $x$  and  $y$  axes, respectively.  $D_x$  represents out-of-plane bending stiffness,  $D_z$  represents in-plane bending stiffness and  $D_y$  represents the torsional stiffness.  $N, A$  and  $M_{EA}$  represent the aerodynamic normal, drag, and moment loads (referenced to the elastic axis in vehicle fixed coordinates) per unit span, respectively. Primes and over dots are used to denote  $\partial/\partial y$  and  $\partial/\partial t$ , respectively.

A few important observations are made about these equations. First, in-plane motion (often referred to as the ‘lead-lag mode’ in the rotorcraft community) is included in the above equations. This assumption is required for extremely high aspect-ratio vehicles. Second, the right-hand side of the equations contains the nonlinear terms (including the aerodynamic terms). We note that dynamics of interest for the nonlinear system become evident for certain classes of the stiffness ratio  $\beta_z = D_z/D_x$  and aspect ratio,  $AR = \text{span}/\text{chord}$ . These nonlinearities may be classified into 4 sets: (a) geometric stiffening effects due to large structural deformations, (b) inertially coupled nonlinear responses due to mass distributions; (c) kinematical-induced nonlinearities due to the position of stores; and, (4) aerodynamic nonlinearities as captured in  $N, A$  and  $M$ . Third, the parameter space is vast, requiring the need for bifurcation analysis.

This research includes nonlinear analysis to explore the bifurcation characteristics (especially subcritical branches), potential parametric resonances, and parameter space related to design. The benchmark considers frequency ratios that permit examination of parametric resonances and multi-axial (in-plane, out-of-plane, transverse, torsional) responses. The benchmark allows responses associated with a high aspect ratio ( $AR > 30$ ) configuration with large deformations (tip displacement  $> 30\%$  span). Full parameter space is considered leading to the need for improved computational interfaces, a continuous bifurcation model capability, and proper consideration of scaling parameters. It is found that response is multi-dimensional and, most importantly, in-plane motion is included which plays a role in the instability mechanism. Related couplings lead to internal resonances. Further, equilibrium (trim) about nonlinear states are considered as results show states unique to the trimmed vehicle.

It is recognized that the interaction of aerodynamics and structural dynamics leads to the need for a time accurate, synchronized solution scheme. Research includes development of a solution methodology that assures synchronous interaction between the nonlinear structure and fluid including a consistent geometric interface between the highly-deforming structure and flow field. The aerodynamic loads depend upon motion but, simultaneously, the motion depends upon the aerodynamic loads. Furthermore, the boundaries between the fluid and structure must be considered, and the boundary constraint problem is aggravated by large motions of the structure and fluid. The approach is to transform the nonlinear structural equations of motion into a

discrete form by employing the natural vibration modes of the coupled structural system in a Galerkin projection procedure that dynamically accounts for system nonlinearities. Therein, nonlinear aerodynamic loads are computed with a transonic small disturbance theory well as a simple aerodynamic stall model. The algorithmic procedure was verified based on data available from the approach of Kim and Strganac. The procedure was developed to accept aerodynamic loads from any model.

### Unsteady Aerodynamic Models

One objective of this research is to explore computational aerodynamic methods that properly capture the participating nonlinear features of the flow field and provide computational efficiency. Consideration of the unsteady aerodynamic approaches address the range of possible flow fields, ranging from low Reynolds number, highly separated flows to transonic flows with shock/boundary layer interaction. One method used by others is the Computational Aeroelastic Program – Transonic Small Disturbance (CAPTSD) resource of NASA Langley Research Center. CAPTSD solves the three-dimensional, transonic, small-disturbance, potential-flow equations for partial and complete aircraft configurations.

Although models such as CAPTSD have the benefit of a fast turnaround time, they do not capture all the flow physics, especially for compressible, viscous flows. For this reason, the unsteady aerodynamic model used herein is based on the mass, momentum and energy conservation equations, that is, the Navier-Stokes equation. The viscous effects are modeled using the  $k - \omega$  turbulence model.

The Navier-Stokes equations are expressed in vectorial form

$$\frac{\partial}{\partial t} \int_V \bar{Q} \cdot dV + \oint_S (\bar{F}_{inv} - \bar{F}_{vis}) \cdot dS = \int_V \bar{G} \cdot dV \quad (7)$$

where  $\bar{Q}$  is the state vector of conservative variables,  $\bar{F}_{inv}$  is the vector of inviscid fluxes,  $\bar{F}_{vis}$  is the vector of viscous fluxes, and  $\bar{G}$  is the vector of source terms. The state vector of conservative variables is  $\bar{Q} = (\rho, \rho u, \rho v, \rho w, \rho E)^T$ , where  $\rho$  is the density of the fluid,  $u$ ,  $v$  and  $w$  are the  $x$ -,  $y$ - and  $z$ -components of the velocity, and  $E$  is the total energy of the fluid particle. The time dependent integral form of the  $k - \omega$  turbulence model equations are expressed in a vectorial form similar to the Navier-Stokes equations. The state vector of turbulent conservative variables is  $\bar{Q}_t = (\rho k, \rho \omega)^T$ , where  $k$  was the turbulence kinetic energy and  $\omega$  is the specific dissipation rate.

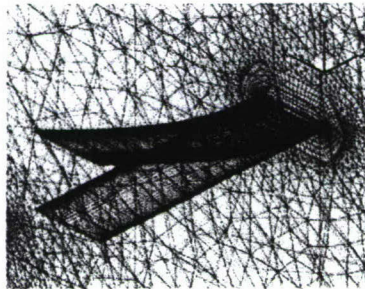
The governing equations are solved using a finite volume method. The computational domain is discretized using an unstructured mixed mesh. The computational mesh deforms according to the wing displacement. Time marching is used to calculate the unsteady solution. The computational domain is discretized using a hybrid grid, which consisted of prismatic and hexahedral elements. The computational domain is divided into layers that are topologically identical, and that spans from the wing root to past the wing tip. The topologically identical nodes of adjacent layers are interconnected to generate the volume elements that are either prisms or hexahedra. Each layer has a structured O-grid around the wing, and an unstructured grid at the exterior of the O-grid. The O-grid improves the control over the mesh size near the

airfoil and allows clustering cells in the direction normal to the wing to properly capture the boundary layer flow. The unstructured grid is flexible in filling the rest of the domain and allows an efficient algorithm for the grid deformation.

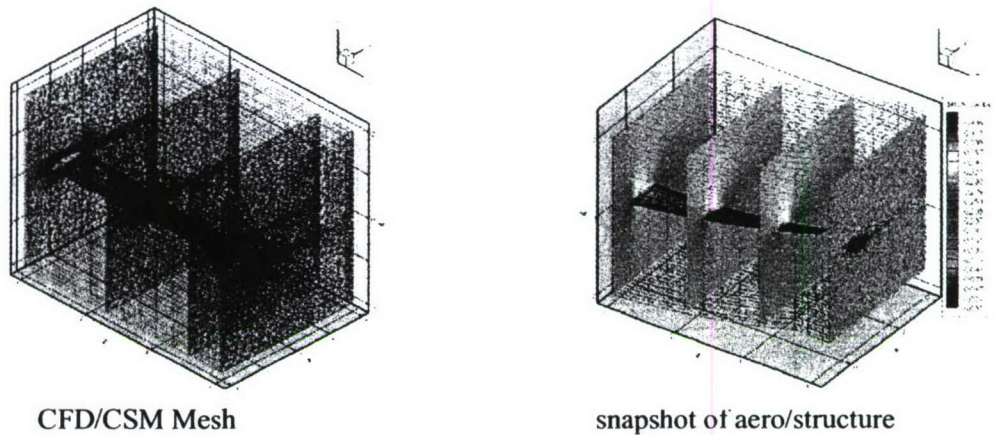
The wing deforms under variable aerodynamic loads. As the deflection of the wing varies in time, the computational grid changes accordingly by deforming the grid without modifying grid connectivity. The moving grid follows the time-dependent wing configuration as it deforms under the time-varying loads. A requirement for the grid-deforming algorithm is to generate a moving grid that is both perpendicular to the wing surface and to the outer boundary of the computational domain.

The grid deformation algorithm is applied in two steps: first a translation, and then a rotation about the three axes. The O-grid layers are translated as a block, without being deformed, since it is assumed that the wing cross-section does not deform. This limitation may be removed as more detailed structural models are implemented. The unstructured grid is deformed in the  $y$ - and  $z$ -directions using a spring analogy technique. The nodes of each layer are also translated in the  $x$ -direction according to the wing deformation.

First, the grid is rotated about the  $x$ -axis, along the elastic axis. The nodes of the O-grid rotate with the wing as a rigid body. The unstructured grid is deformed using a spring analogy technique. Then, the grid is rotated about the  $y$ -axis, along the elastic axis. The nodes between the leading edge and trailing edge are rotated as a solid line. The nodes between the leading edge (or trailing edge) and the outer computational domain are deformed in the  $x$ -axis direction such that the layer was tangential at both ends. This is achieved using with a cubic mapping function. Finally, the last rotation is about the  $z$ -axis. This rotation uses the same algorithm as the  $y$ -axis rotation. The numerical values of these rotation angles,  $\theta_x$ ,  $\theta_y$ , and  $\theta_z$  are calculated based on the data provided by the structural solver. Figures 2 and 3 depicts the CFD approach.



**Figure 2. The wing / mesh system undergoing large deformations.**

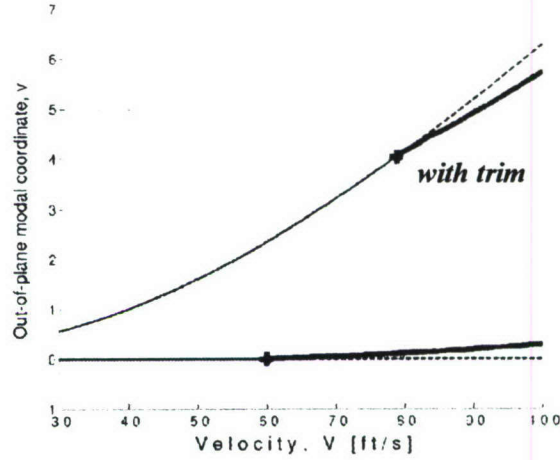


**Figure 3. The CFD/Structure Coupling Approach.**

### **Bifurcation Analyses**

The nonlinear analyses in this research consider the vast parameter space, with emphasis on subcritical branches. Various bifurcation characteristics, unique to the aeroelastic system, have been identified. These include both subcritical and supercritical bifurcations, the nature of which must be examined in detail. The former case is of significant interest because flight test experiences indicate the presence of subcritical Hopf-type bifurcations, in which limit cycle oscillations below the classical flutter boundary. In addition, subcritical bifurcations depend upon the system disturbance, and have a hysteresis between onset and recovery speeds. This sub-flutter behavior cannot be studied with linear methods that are common to today's approaches. Subcritical bifurcations are anticipated for highly deformable, high aspect ratio wings characteristic of high altitude UAV concepts, with important effects on optimal vehicle performance.

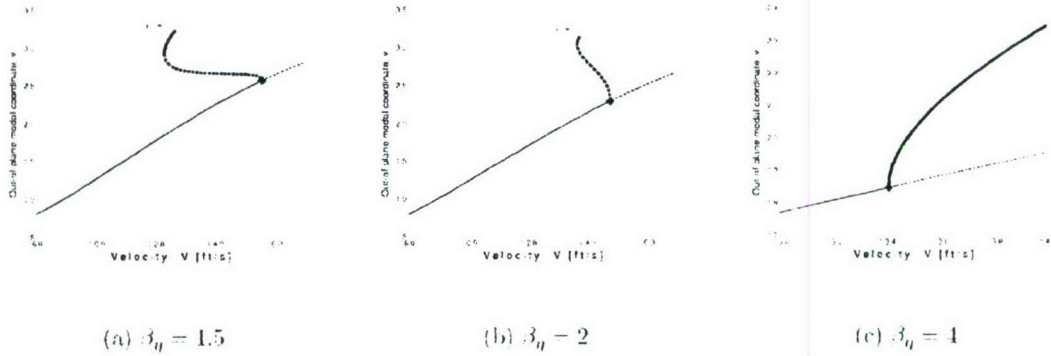
Figure 4 is an example of a bifurcation diagram created as part of the continuation tool. The tool permits nonlinear analysis of the set of governing equations. The approach detects the bifurcation points, determines equilibria and stability states, determines amplitude of periodic solutions (e.g., stable LCOs), and rapidly identifies character of design. We have shown that it duplicates time-domain simulation, but such exhaustive simulation to "bracket" the stability boundaries is avoided.



**Figure 4. Example bifurcation diagram, showing effect of trim constraint.**

The figure shows equilibria (light solid line), unstable LCOs (dashed lines) and Stable LCOs (as indicated, dark solid lines) which represent amplitudes of motion at velocities. An important observation is that the trim model shows a change in amplitude (both equilibria and LCOs). In addition, the tool allows one to explore the parameter space without missing details.

Sensitivity to the stiffness ratio between in-plane and out-of-plane is illustrated below.

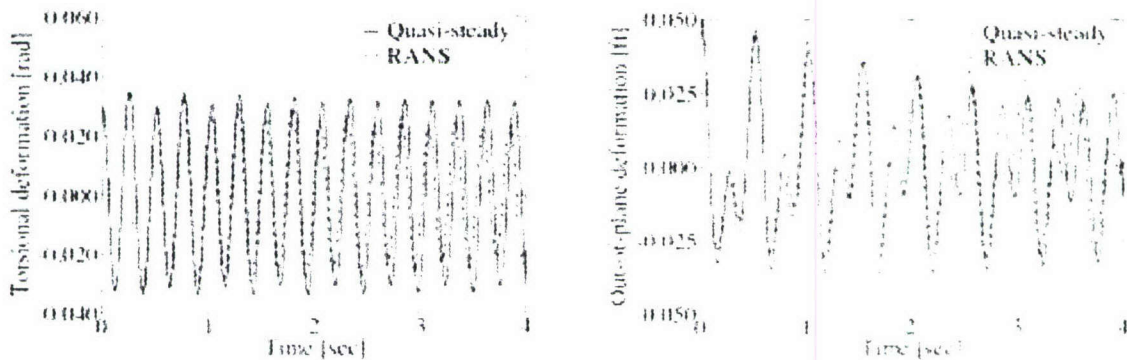


**Figure 5. Sensitivity to vehicle stiffness ratio is shown, showing transition from subcritical to supercritical behavior. Vehicle conditions:  $\alpha_0 = 5.6$ ,  $AR = 33$ .**

The vehicle transitions to subcritical branches at lower in-plane to out-of-plane stiffness ratios. The nature of bifurcation depends on the angle of attack imposed by the trim condition as well as system design properties such as the aspect ratio. It is noted that the magnitude of in-plane LCO increases with lower stiffness ratios.

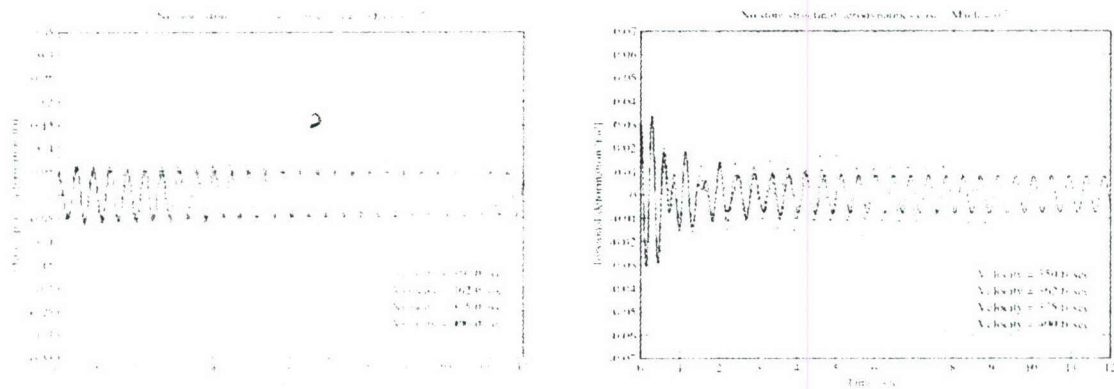
## Representative Results of the Aeroelastic Model

Aeroelastic results are presented for two aerodynamic models: a quasi-steady aerodynamic model, and a Reynolds-averaged Navier-Stokes (RANS) model. The results provide the stability boundary for the Heavy Goland Wing as calculated by computing the time response of the system for different velocities, keeping the Mach number constant. Figure 6 shows the torsional and out-of-plane deformations for the Heavy Goland Wing at a Mach number of 0.09. The results provide the time history of the first generalized modal deformations. The results show a good correlation between the RANS and quasi-steady models, for both the out-of-plane and torsional deformations.



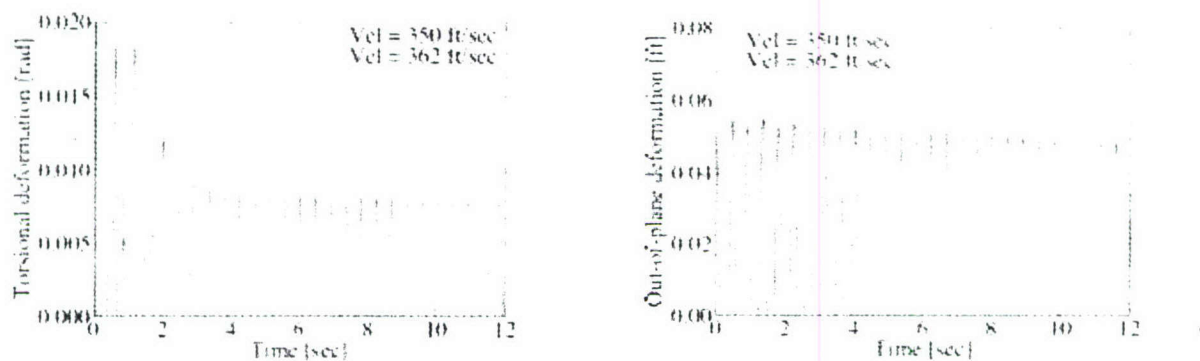
**Figure 6. First generalized modal deformations for the Heavy Goland wing at Mach = 0.09**

Figure 7 shows the modal amplitudes for torsional and out-of-plane deformations for Mach = 0.7 and different velocities. As the velocity increased, the system became unstable and the disturbances were amplified. For a Mach number of 0.7 and the RANS model, it was found that the system was stable at a velocity of 350 ft/sec, whereas a velocity of 362 ft/sec made the system unstable.



**Figure 7. First generalized modal deformations for the Heavy Goland wing at Mach = 0.7**

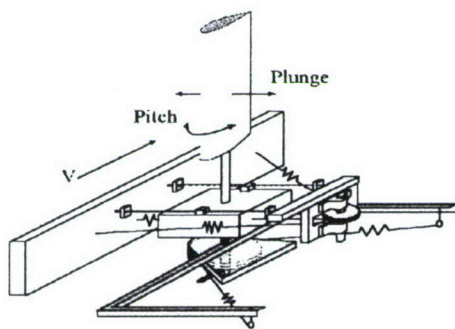
The case with a velocity of 350 ft/sec was the only stable case, as shown by the decrease of the deformations. This decrease is made more evident by rescaling the time-response plot, shown in Fig. 8.



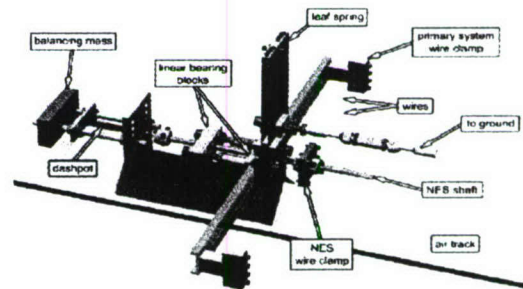
**Figure 8. Details of modal amplitudes at Mach = 0.7**

## Nonlinear Energy Sink

We conclude with brief results of the suppression of Limit Cycle Oscillations via the Nonlinear Energy Sink (NES). Details are provided in the reports cited herein. Experiments were conducted at A&M. The nonlinear energy sink and related theories were developed at U. Illinois.

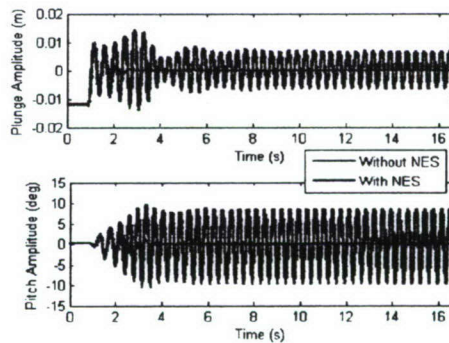


Experiments – Texas A&M University  
Thomas Strganac et al.

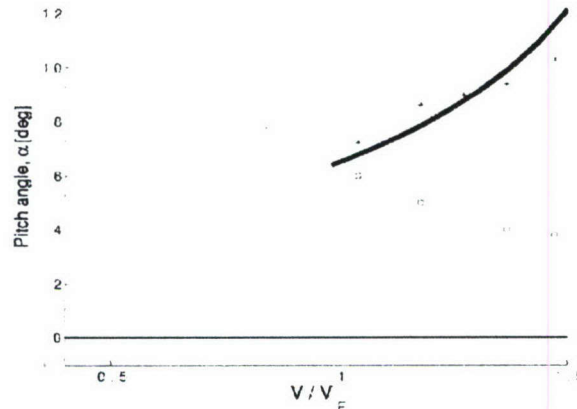


NES Theory – University of Illinois  
Larry Bergman et al.

**Figure 9. Joint experiments between the Texas A&M and Illinois teams explored the NES.**



**Figure 10. Results show that NES successfully suppresses LCO behavior in the aeroelastic environment.**



**Figure 11. The bifurcation diagram illustrates suppression of LCOs and increased operational velocity by NES. Experimental data is shown by symbol.**

## References

- 1) Bunton, R.W., and Denegri, C.M., Jr., "Limit Cycle Oscillation Characteristics of Fighter Aircraft," *Journal of Aircraft*, Vol.37, No. 5, 2000, pp.916-918.
- 2) Denegri, C.M., Jr., "Limit Cycle Oscillation Flight Test Results of a Fighter with External Stores," *Journal of Aircraft*, Vol.37, No.5, 2000, pp.761-769.
- 3) Jacobson, S.B., Britt, R.T., Dreim, D.R., and Kelly, P.D., "Residual Pitch Oscillation (RPO) Flight Test and Analysis on the B-2 Bomber," AIAA Paper 98-1805, 39th AIAA Structures, Structural Dynamics, and Materials Conference, Long Beach, California, April 1998.
- 4) Kim, K. and Strganac, T.W., Nonlinear Responses of a Cantilever Wing with an External Store, AIAA Paper 2003-1708, 44th AIAA Structures, Structural Dynamics, and Materials Conference, Norfolk, Virginia, 2003.
- 5) Beran, P.S., Strganac, T.W. and Kim, K. "Studies of Store-Induced Limit-Cycle Oscillations Using a Model with Full System Nonlinearities," *44th AIAA Structures, Structural Dynamics, and Materials Conference*, AIAA Paper 2003-1730, 2003.
- 6) Crespo da Silva, M.R.M. and Glynn, C.C., "Nonlinear Flexural-Flexural-Torsional Dynamics of Inextensional Beams - I. Equations of Motions", *Journal of Structural Mechanics*, Vol.6, No.4, 1978, pp.437-448.

### **Personnel Supported**

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### **Publications (peer review)**

1. Lee, Y.S., Kerschen, G., McFarland, D.M, Hill, W. J., Nichkawde, C., Strganac, T.W., Bergman, L.A, and Vakakis, A.F., Suppressing Aeroelastic Instability Using Broadband Passive Targeted Energy Transfers, Part 2: Experiments, *AIAA Journal*, Vol. 45, No. 10, October 2007, pp. 2391-2400.
2. Beran, P.S. and Strganac, T.W., Kim, K. and Nichkawde, C., "Studies of Store-Induced Limit Cycle Oscillations Using a Model with Full System Nonlinearities", *Nonlinear Dynamics*, No. 37, 2004, pp. 323-339.
3. Thompson, D.E., Jr. and Strganac, T.W., "Nonlinear Studies of Aircraft Store-Induced Limit Cycle Oscillations", *Nonlinear Dynamics*, No. 39, 2005, pp. 159-178.
4. Platanitis, G. and Strganac, T.W., "Suppression of Control Reversal Using Leading and Trailing Edge Control Surfaces", *Journal of Guidance, Control and Dynamics*, Vol. 28, No. 3, 2005, pp. 452-460.
5. Gargoloff, J., Cizmas, P., Strganac, T.W., and Beran, P.S., "A Parallel Multigrid Algorithm for Aeroelasticity Simulations", *AIAA Journal*, in review.

## **Interactions and Transitions**

1. Kim, K. and Strganac, T.W., The Effects of External Stores on Nonlinear Aeroelastic Responses, AIAA Paper 2004-1942, 45th AIAA Structures, Structural Dynamics, and Materials Conference, Palm Springs, California, 2004.
2. Beran, P., Hur J., Soni, B., Snyder, R., and Strganac, T., Static Nonlinear Aeroelastic Analysis of a Blended-Wing Body, AIAA Paper 2005-1944, 46th AIAA Structures, Structural Dynamics, and Materials Conference, Austin, Texas, 2005.
3. Silva, W., Strganac, T., and Hajj, M., Higher- Order Spectral Analysis of a Nonlinear Pitch and Plunge Apparatus, AIAA Paper 2005-2013, 46th AIAA Structures, Structural Dynamics, and Materials Conference, Austin, Texas, 2005.
4. Strganac, T., Cizmas, P., Nickkwade, C., Gargoloff, J., and Beran, P., Aeroelastic Analysis for Future Air Vehicle Concepts Using a Fully Nonlinear Methodology, AIAA Paper 2005-2171, 46th AIAA Structures, Structural Dynamics, and Materials Conference, Austin, Texas, 2005.
5. Nickkawde, C., Strganac, T.W. and Beran, P.S., "Nonlinear Aeroelastic Analysis of a Wing in Nonzero Trim", AIAA Paper 2006-1637, 47th AIAA / ASME / ASCE / AHS / ASC Structures, Structural Dynamics, and Materials Conference, Newport, Rhode Island, 2006.
6. Hill, J., Strganac, T.W., Nickkawde, C., McFarland, D.M., Kerschen, G, Lee, Y., and Vakakis, A.F., and Bergman, L. A., "Suppression of Aeroelastic Instability with a Nonlinear Energy Sink: Experimental Results", AIAA Paper 2006-1848, 47<sup>th</sup> AIAA / ASME / ASCE / AHS / ASC Structures, Structural Dynamics, and Materials Conference, Newport, Rhode Island, 2006.
7. Gargoloff, J., Nickkawde, C., Cizmas, P., and Strganac, T.W., "Parallel Algorithm for Fully Nonlinear Aeroelastic Analysis", AIAA Paper 2006-2073, 47<sup>th</sup> AIAA / ASME / ASCE / AHS / ASC Structures, Structural Dynamics, and Materials Conference, Newport, Rhode Island, 2006.
8. Hill, J., Strganac, T.W., Nickkawde, C., McFarland, D.M., Kerschen, G, Lee, Y., and Vakakis, A.F., and Bergman, L. A., "Suppression of Aeroelastic Instability with a Nonlinear Energy Sink: Experimental Results", AIAA Paper 2006-1848, 47<sup>th</sup> AIAA / ASME / ASCE / AHS / ASC Structures, Structural Dynamics, and Materials Conference, Newport, Rhode Island, 2006.
9. Gargoloff, J., Cizmas, P., Strganac, T.W., and Beran, P.S., "A Parallel Multigrid Algorithm for Aeroelasticity Simulations", AIAA-2007-330, 45th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, Jan. 8-11, 2007.
10. AFRL/AFSEO Workshop on Aircraft Store-Clearance and Related Aeroelastic Phenomenon, May 2006, Scottsdale, AZ.

**Consultative functions to laboratories**

Forwarded to AFRL/VA (Dr. Philip S. Beran)

1. CFD mesh generating tool
2. NoLiBeam Package: Aeroelastic code for wings modeled by a nonlinear beam with a quasi-steady aerodynamic model, User Guide-Version 0.1, July 4, 2007.

**new inventions or patent disclosures**

no patents to report

**honors / awards**

no awards external to the university