Center of Excellence for
AMTAS
Advanced Materials in
Transport Aircraft Structures

# Combined Global / Local Variability and Uncertainty in the Aeroservoelasticity of Composite Aircraft

Eli Livne
Department of Aeronautics and Astronautics

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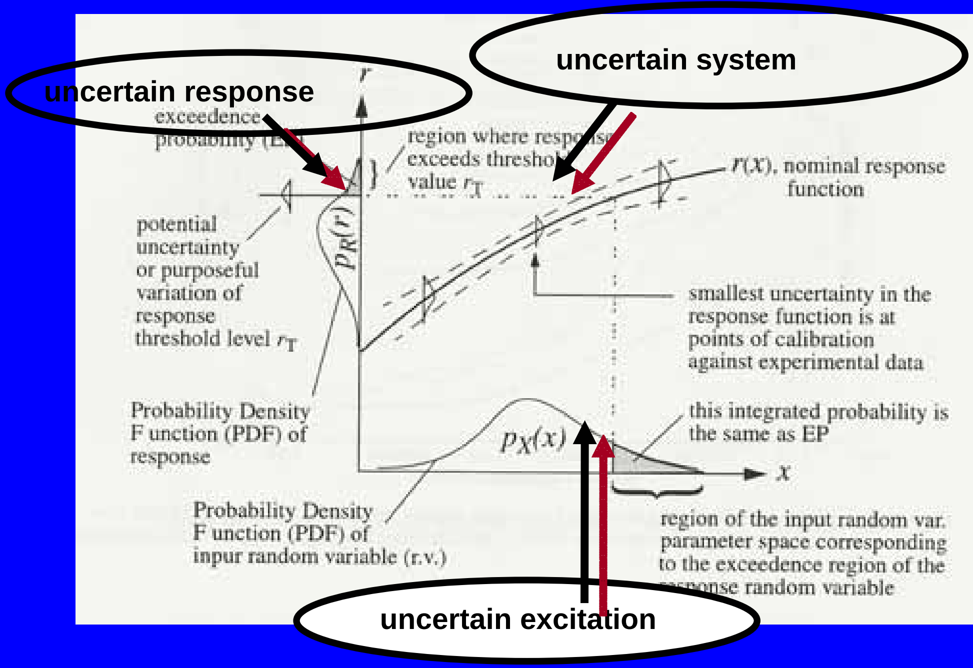
# Uncertainty Propagation : Structural Uncertainty in Composite Airframes → Uncertain Global Aeroservoelastic Behavior

## Uncertainty Propagation: Uncertain Inputs, Uncertain System



V.J.Romero, Sandia National Lab, AIAA Paper 2001-1653

- Motivation and Key Issues
  - Local structural variations in composite airframes due to damage and repair, material changes over time, and nonlinear mechanisms can affect global aeroelastic and aeroservoelastic stability and response.

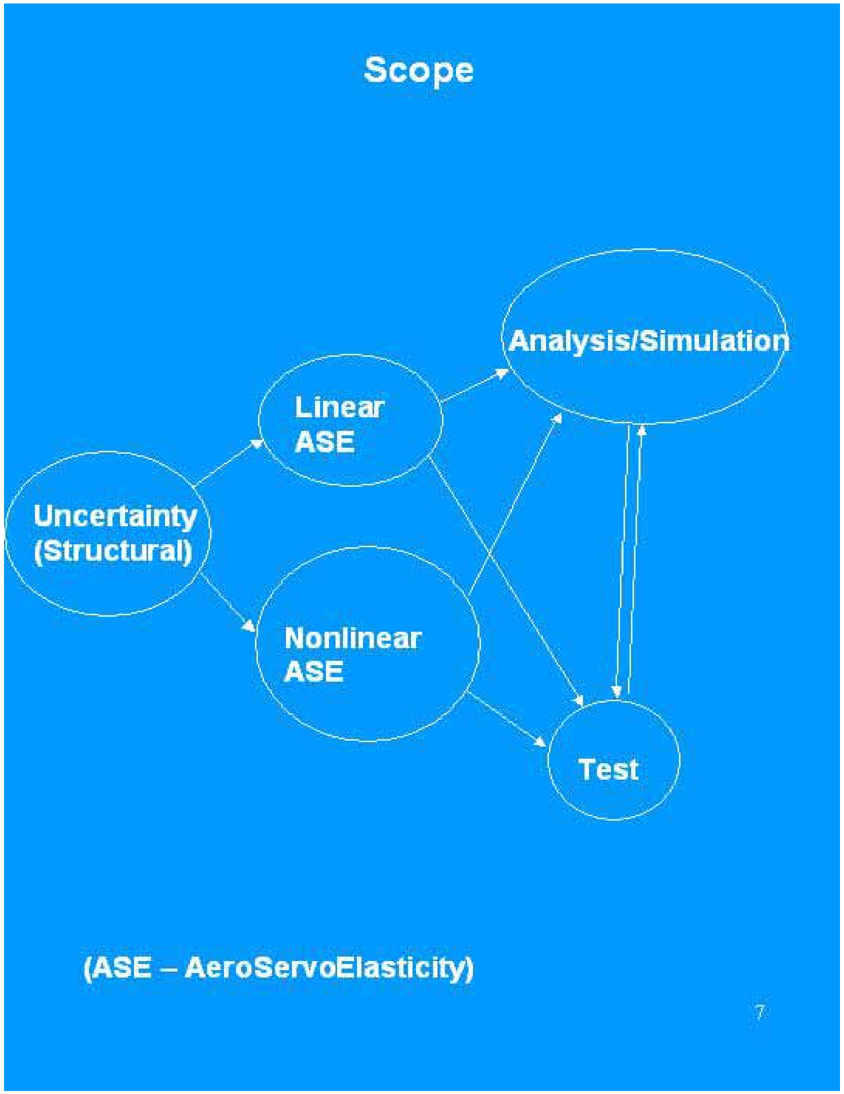
- Objectives
  - Develop computational tools (validated by experiments) for local/global linear/nonlinear analysis of integrated structures/ aerodynamics / control systems subject to multiple local variations/ damage.
  - Establish a collaborative expertise base for future response to FAA, NTSB, and industry needs, R&D, training,and education.
  - Develop a better understanding of effects of local structural and material variations in composites on overall Aeroservoelastic integrity.

# Boeing Control Surface Freeplay Effort - Plan

- Develop nonlinear flutter analysis for control surfaces
  - Nonlinearities
    - Control surface freeplay
    - Coulomb friction (about control surface hinge line)
    - Add composite structures structural nonlinearities
  - Unsteady aerodynamic terms converted to time domain with RFA for
    - Linear or nonlinear aerodynamics
    - Time domain solutions (state space formulation and/or time integration)
  - Solution Methods
    - Describing function
    - Direct time integration
- Obtain limit cycle amplitude and frequency at different flight conditions

- Apply to test problems and compare with test data
  - 3DOF typical section with control surface freeplay
  - Elevator with freeplay
  - Elevator tab limit cycle oscillation
- Incorporate the nonlinear freeplay capability in the standard Boeing flutter process

# Approach- Two Complementary Thrusts: Uncertainty in Linear and in Nonlinear Aeroelastic Systems



Scope

Uncertainty (Structural)

Linear ASE

Nonlinear ASE

Analysis/Simulation

Test

(ASE – AeroServoElasticity)

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# FAA Sponsored Project Information

- Principal Investigators & Researchers
    - Prof. Eli Livne
    - Dr. Luciano Demasi – Uncertain Linear Aeroservoelastic Systems
    - Dr. Andrey Styuart (25%) – Uncertain Nonlinear & Linear Systems / Probabilistic
    - Mr. Levent Coskuner, PhD student – Uncertain Nonlinear Aeroelastic Systems
- FAA Technical Monitor
    - Peter Shyprykevich
- Other FAA Personnel Involved
    - Dr. Larry Ilcewicz - Composites
    - Gerry Lakin – Flutter
    - Curtis Davies
- Industry Participation
    - Boeing Commercial, Seattle
        - Mr. Carl Niedermeyer – Flutter & Loads
        - Dr. Kumar Bhatia – Aeroservoelasticity and Multidisciplinary Optimization
        - Mr. James Gordon – Flutter & Dynamic Loads

Part I

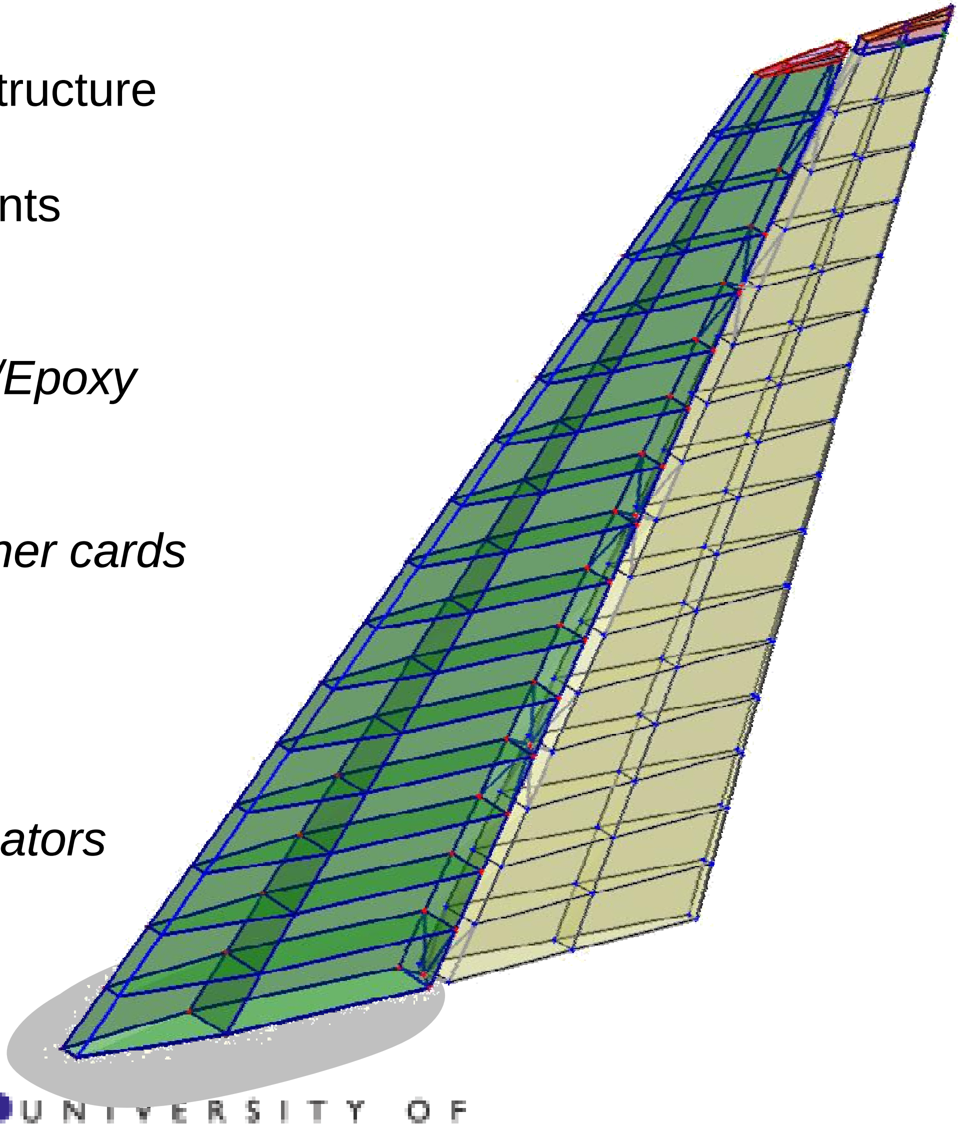
# Aeroservoelastic Sensitivity and Uncertainty in Composite Aircraft

Sensitivity analysis

Local structural variation and global system’s behavior

# Vertical Tail / Rudder FEM

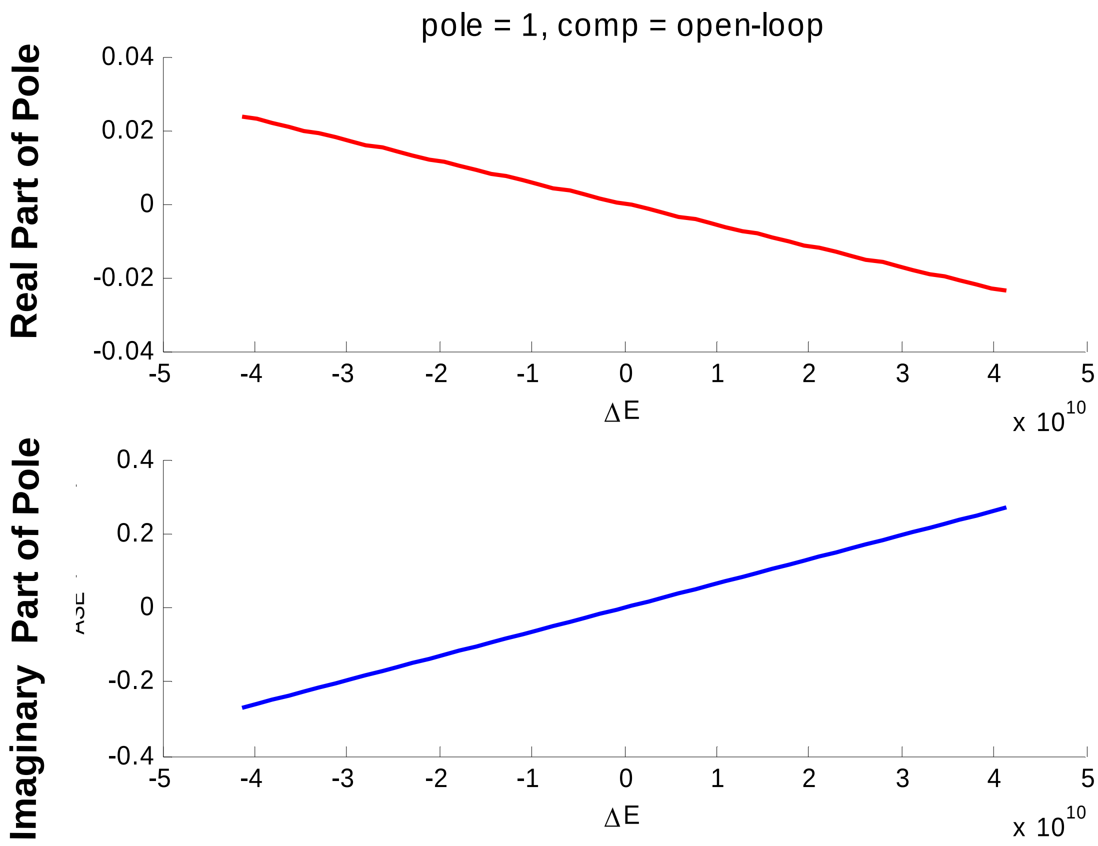
- 767-size vertical tail / rudder structure
- Fixed at root
- Rudder actuated at 5 pivot points along hinge line
- All composite structure:
  *Graphite/Epoxy and E-Glass/Epoxy*
- 11 Property cards:
  *2 skin cards; 4 web cards;*
  *2 caps cards; 2 vertical stiffener cards*
  *1 actuator card*
- 232 Nodes
- 1851 Elements:
  *1308 Membranes; 503 Bars;*
  *35 Rigid Links; 5 Rotary Actuators*

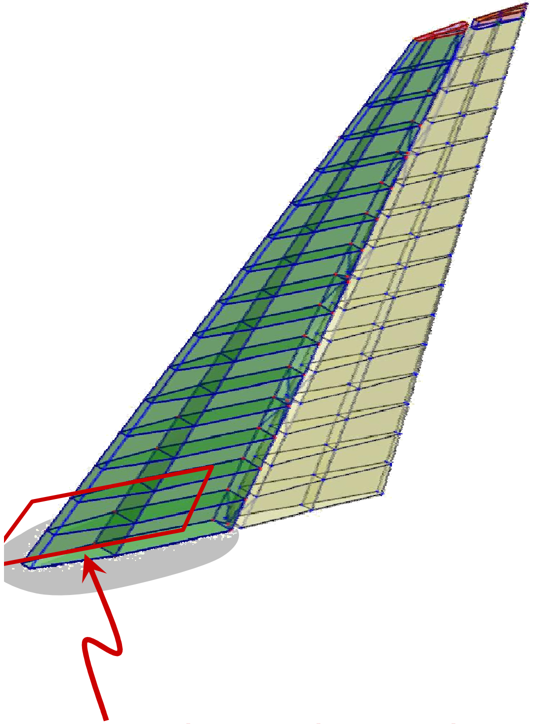


# Effect of Local Material Property Change on Aeroelastic Poles

## (Poles at a given flight condition determine stability of motion)

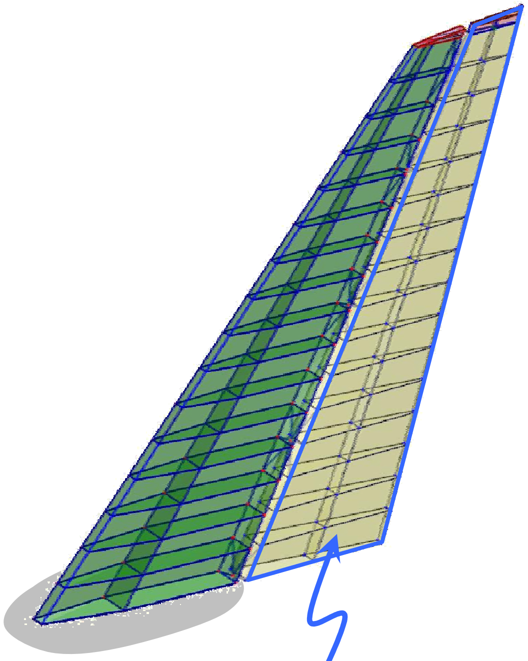
$$\lambda = \lambda_R + j\lambda_I \rightarrow e^{\lambda t}$$



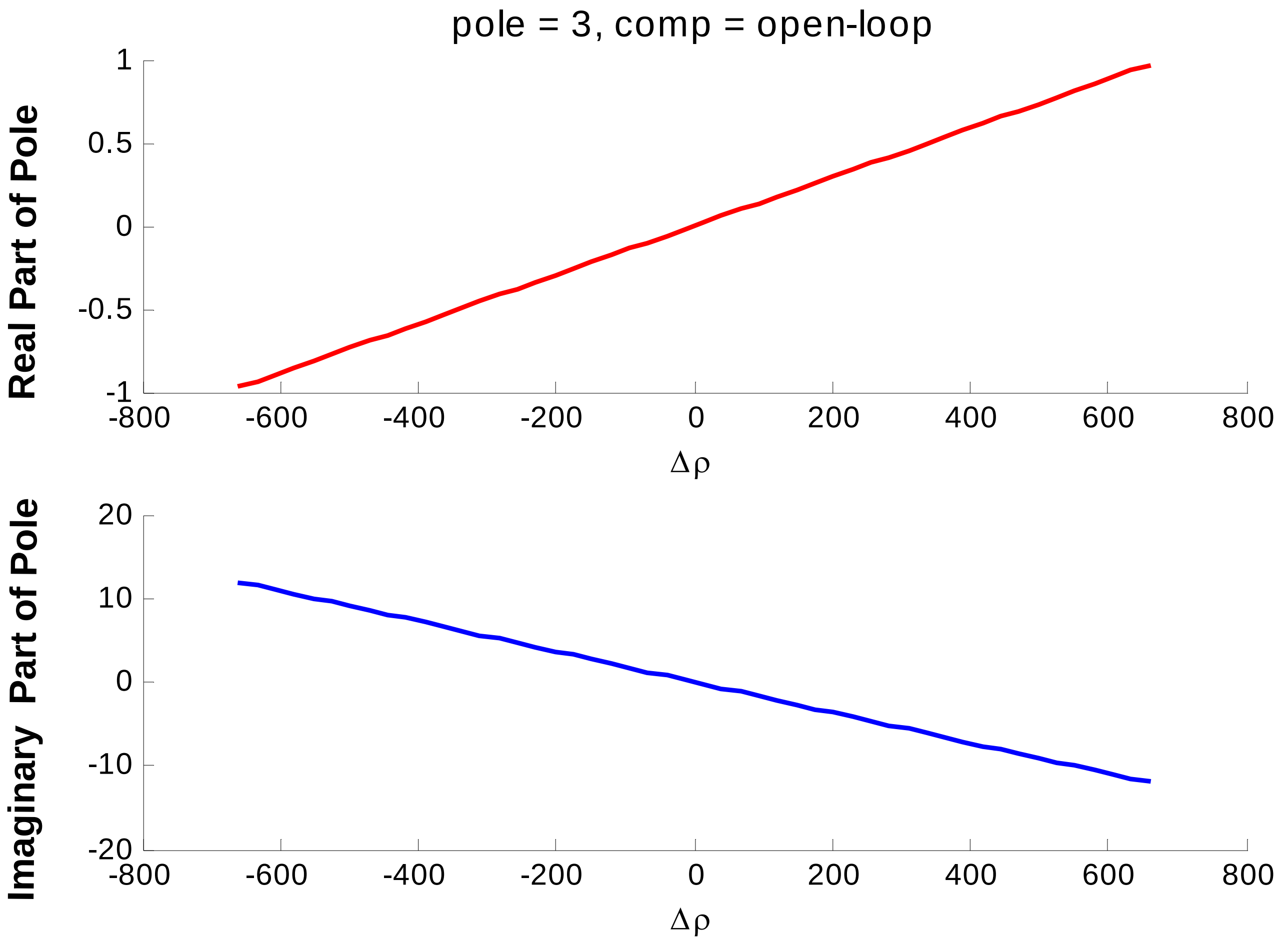


Change in elastic modulus (E) of composite skin panels at root
(all layers [0/90/+45/-45]; both sides)

# Effect of Local Structural Change on Aeroelastic Poles



Change in rudder mass (moisture absorption?)



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# Status – Uncertainty of Linear ASE Systems

- The UW code SMART was used to design a simple model composite vertical tail
- Sensitivity analysis was demonstrated with SMART: sensitivity of aeroelastic poles with respect to structural material changes
- Analysis & sensitivity results can be used to create approximate behavior surfaces representing behavior variation due to structural variation for usage in reliability analysis
- Progress was made on the SMART – NASTRAN interfaces and on improvements in SMART.
- An in-depth assessment of the NASTRAN-based aeroservoelastic optimization capability at the Polytechnic of Milan (considered as a potential NASTRAN-based capability to adopt) was completed
- A NASTRAN model of a realistic vertical tail / empennage – has not been received yet

Part II

# Control Surface Limit Cycle Oscillations

Nonlinear structural effects in actuator / composite control surface assemblies

Methods development

Validation

# The Benchmark 2DOF Airfoil / Flap System

**Freeplay** $\pm\delta$

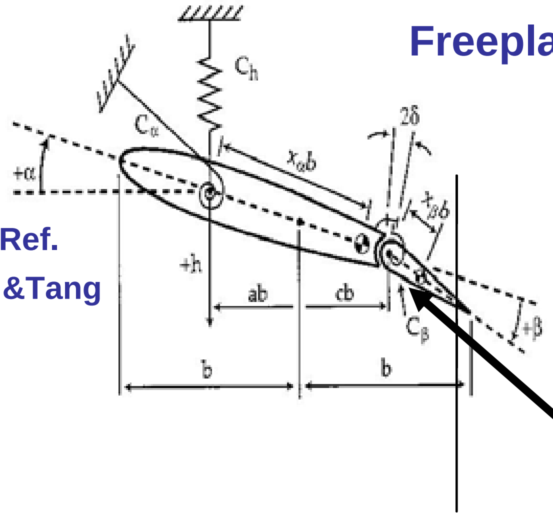
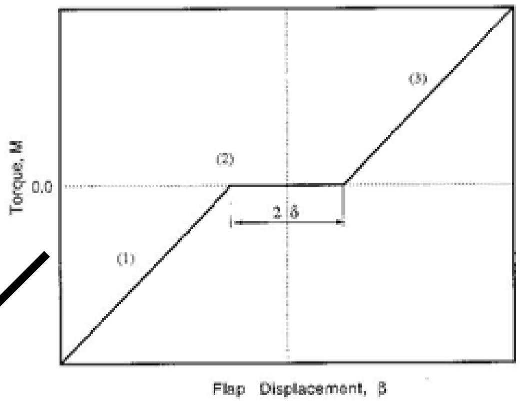


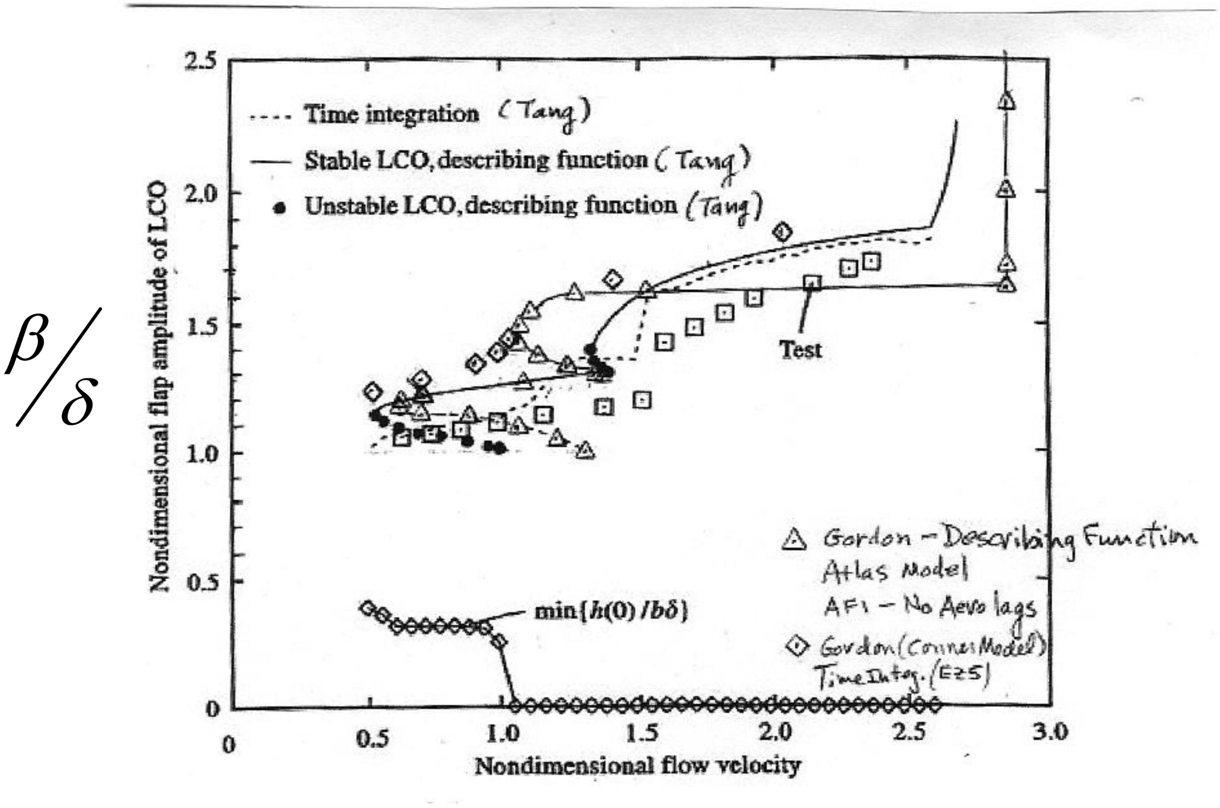
**Fig.Ref.**
**Dowell&Tang**



**Nonlinear Spring**

# Boeing / UW LCO Prediction Methods Correlation with Duke University Analysis and Test Results

Amplitude of control surface limit-cycle oscillations (normalized by free-play amplitude) as a function of speed



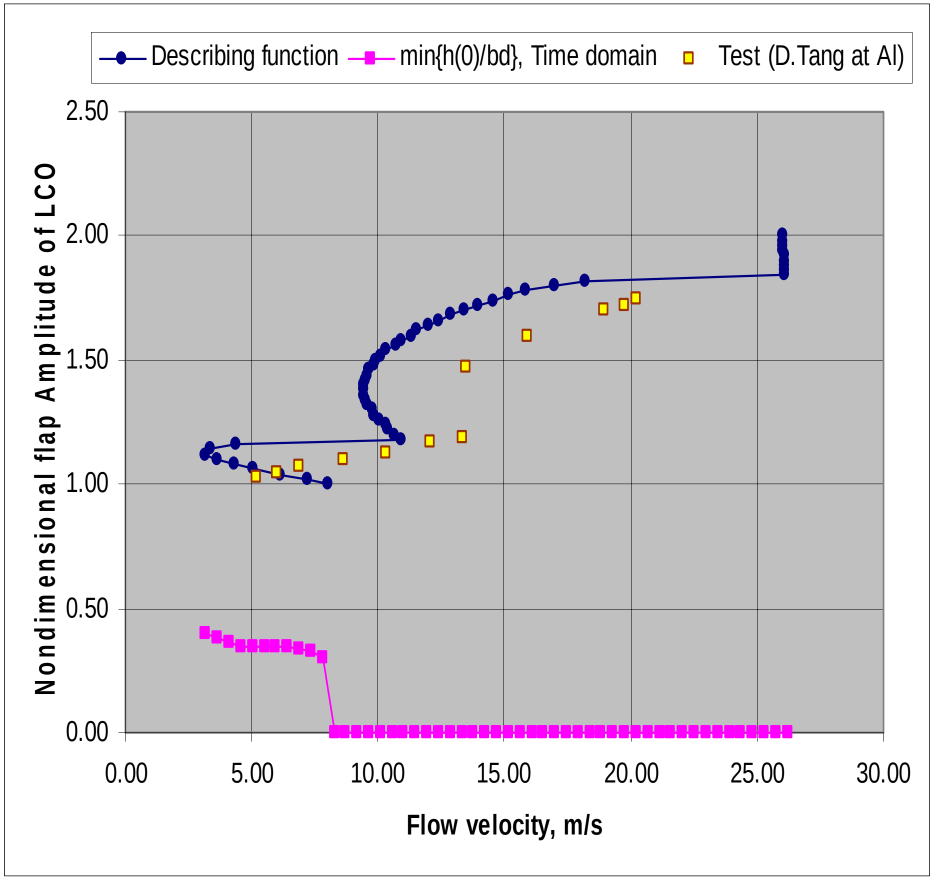
# Two Approaches to LCO Simulation

- A frequency domain approach: assume harmonic oscillation and search for the amplitude & frequency and the flight speed at which such harmonic oscillation will happen; use describing function approach to reduce nonlinear task to linear.

- A time domain approach: solve the nonlinear state space equations of the system for different flight conditions and initial conditions

# Automated LCO Simulation in the Frequency Domain for Uncertain Systems

- **Frequency Domain Analysis Module features:**
  - **Theodorsen aerodynamics**
  - **Describing function for non-linearity**
  - **V-g-ω flutter analysis**
  - **Fair comparison with tests**
- **Issues**
  - **Resolution of problems and completion of the automated LCO frequency-domain capability for 2D airfoil-flap systems is still a work in progress**



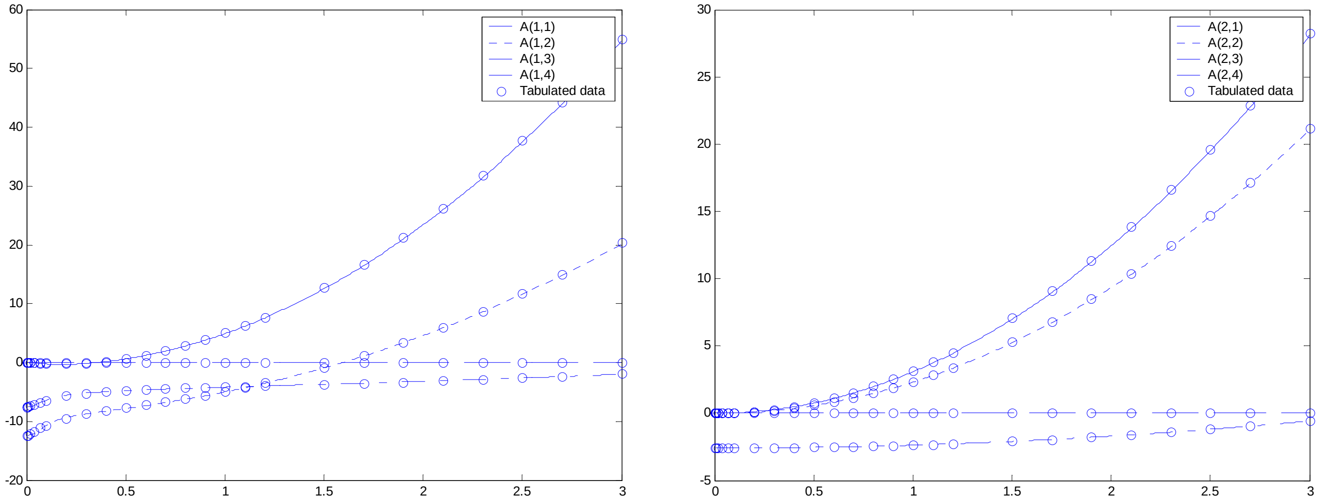
# Automated LCO Simulation in the Time Domain for Uncertain Systems

- Method

The conversion from frequency domain to time domain is done via the use of Roger's Approximation (Roger Fitting). It expresses the unsteady generalized force matrix as a rational function of the Laplace variable as follows:

$$[A(s)] = [A_0] + s[A_1] + s^2[A_2] + \frac{s}{s+\beta_1}[A_3] + \frac{s}{s+\beta_2}[A_4] + \ldots$$

The [*A*] matrices are fitted to tabulated data obtained in the frequency domain. This is done using a least-square fit.



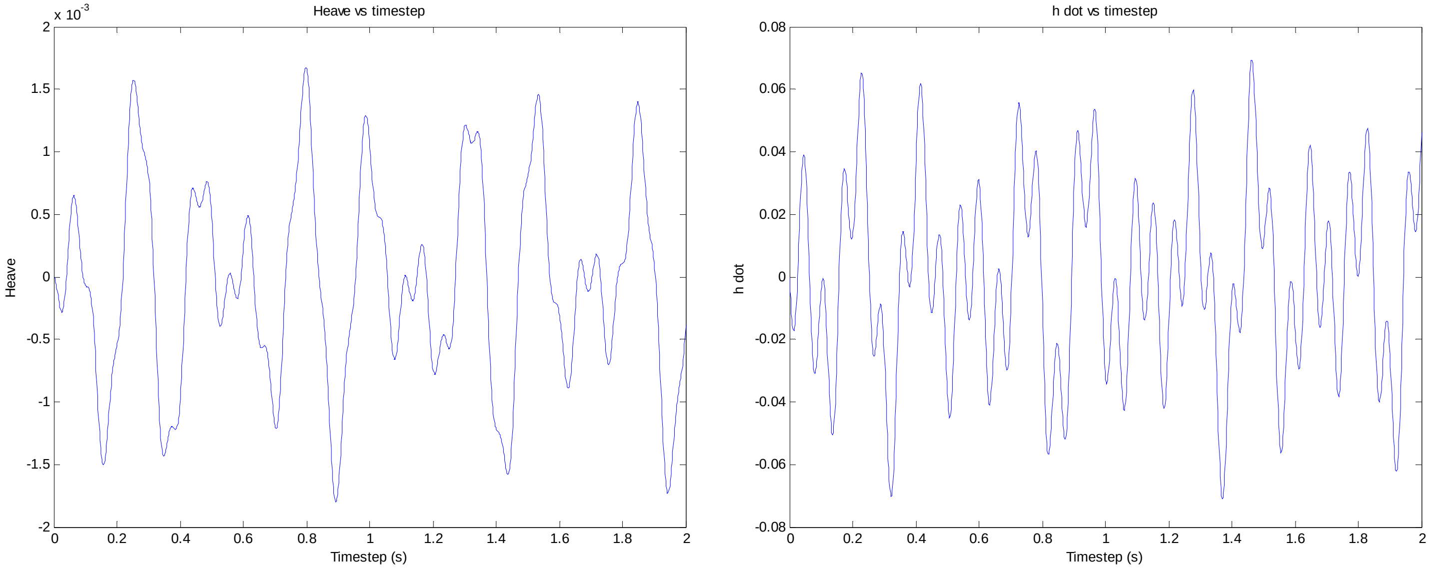
**Sample of Roger Fitting, 4 DOF Airfoil, Flap and Tab System**

# Automated LCO Simulation in the Time Domain for Uncertain Systems

Once a satisfactory Roger Fit is obtained, a state space system can be constructed for the time domain solution.

- Time Domain Solution

A working time domain code has been implemented and some preliminary LCO results are available.



**Sample LCO result for 3 DOF Airfoil and Flap System**

# Automated LCO Simulation in the Time Domain for Uncertain Systems

- **Issues**

  Obtaining verifiable results, particularly with consistent damping modeling is still a work in progress.

- **Future Work**

  Once verifiable results are obtained, the LCO simulation will be extended to an actual airplane (wing-body) model, expanding work from the current 2-D, 3 DOF airfoil system.

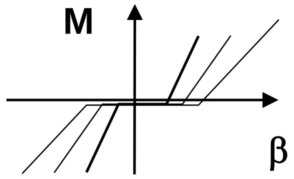
# Methods of probabilistic stability analyses

- <u>Stochastic equations</u> - equations where the coefficients of the equations are random variables or random fields. This leads to nonlinear problem from the statistical point of view. The structure of stochastic equations is usually different from that for solving the corresponding deterministic problem. The solver is a kind of “black box” with internal structure which is very different from mechanical model.
- Methods where <u>mechanical model is separated from probabilistic one</u>: Simulation Methods, Perturbation Methods and their combinations. An example software utilizing these methods: NASA IPACS, SWRI NESSUS. They typically use the pure deterministic mechanical solver like NASTRAN, ABAQUS, etc. It is invoked many times with various input parameters.

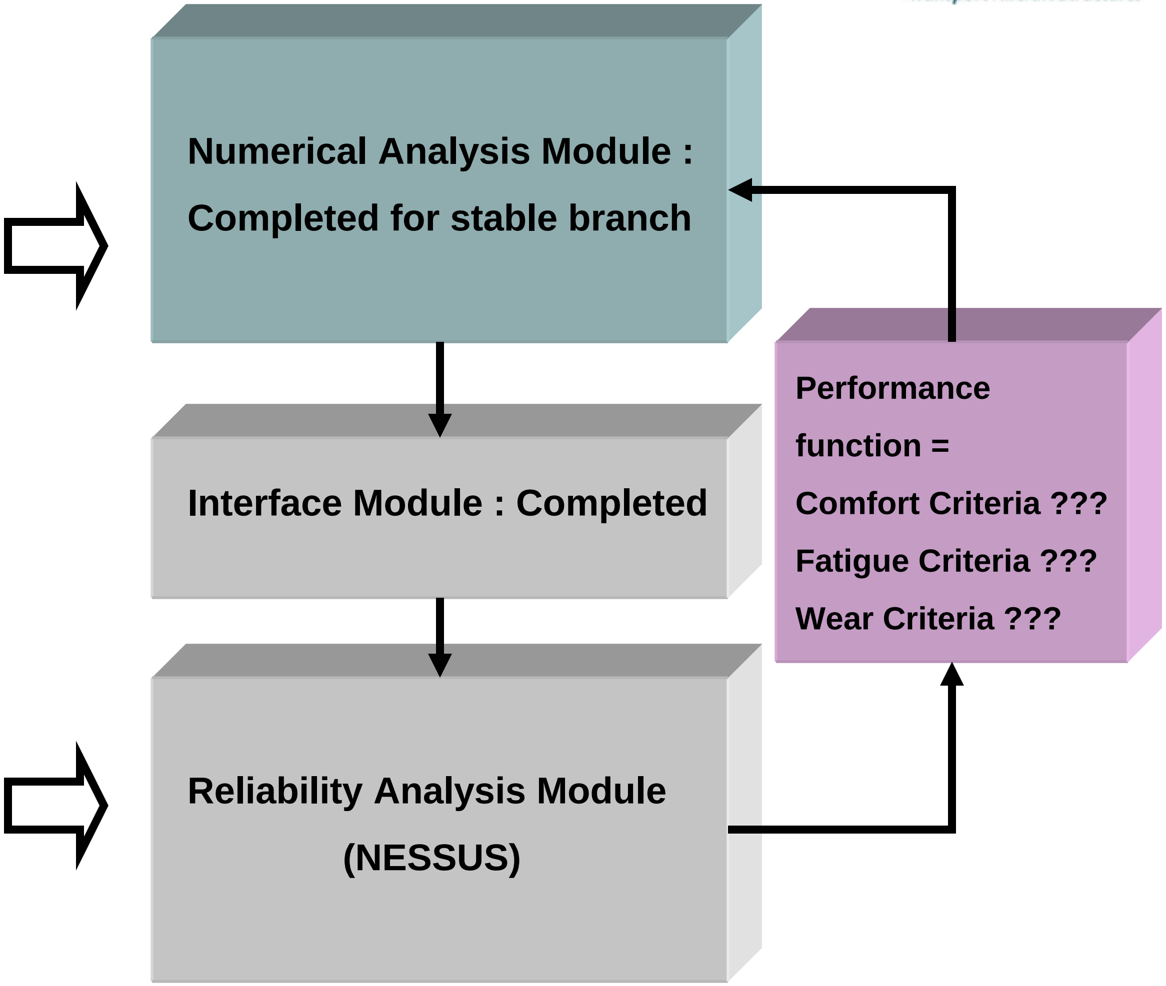
*<u>We are going to use these methods</u>*

# Integration of LCO Simulation Capabilities with a Reliability Analysis Code

**Simulated Uncertainties**



- β/δ uncertainty
- Mass uncertainty
- h, α stiffness uncertainty
- C.G. uncertainty
- Airspeed uncertainty
- β/δ excitation uncertainty



**Numerical Analysis Module : Completed for stable branch**

**Interface Module : Completed**

**Reliability Analysis Module (NESSUS)**

**Performance function =**
**Comfort Criteria ???**
**Fatigue Criteria ???**
**Wear Criteria ???**

# Status

- **Frequency domain LCO prediction**
  - ✓ Numerical Analysis Module 3-4 DOF (describing functions): completed
  - ✓ Comparison with test results: Fair

- **Time domain LCO prediction**
  - ✓ working time domain LCO simulation code has been constructed, and verification with available data is in progress. In the near future, the current time domain LCO simulation will be extended to a 3 dimensional, multi degree of freedom model.

- **Reliability / Uncertainty Analysis**
  - ✓ Numerical Analysis Module completed for stable branch
  - ✓ Interface with NESSUS completed
  - ✓ NESSUS license acquired

# Planned Progress

- Resolution of problems and completion of the automated LCO frequency-domain capability for 2D airfoil-flap systems
- Completion of the time domain LCO prediction Capability for 2D airfoil-flap systems
- Extension of frequency and time domain LCO simulation methods to the general 3D case for real aircraft
- Integration with Reliability / Uncertainty prediction capabilities
- Study of ACTUAL mechanisms that lead to uncertainty / nonlinearity in composite airframes

# Information / Data Needed

- Statistical data on actual distribution of free-play and other structural variations / nonlinearities in airframes (maintenance data)

- A detailed Finite Element model of a realistic airframe structure (to be used to evaluate effects of uncertainty / nonlinearity on global aeroelastic behavior)

# A Look Forward

- Benefit to Aviation
- a. Technology for design optimization of composite aircraft - accounting for variation in airframe characteristics early in the design process of a new vehicle, and leading to designs that will be robust with respect to such changes but not over-conservative.
- b. The capability to guide structural and control system <u>modifications</u> of <u>existing</u> airplanes to minimize or totally eliminate adverse effects on the reliability, fatigue, and damage tolerance of the airframe.
- c. The capability to quantify the reliability of composite airframes accounting for material degradation and local damage, to update reliability estimates based on scheduled maintenance checks, and to guide maintenance decisions based on this information.
- d. Better understanding of control surface limit cycle oscillations sources in composite airframes and resulting engineering-based maintenance guides.
- E. A university center of expertise for commercial aircraft aeroservoelasticity – meeting FAA & NTSB needs, and contributing to research, education, and training.

# A Look Forward

## Next Steps

Link sensitivity / approximation analysis to models of local damage and local structural variation

Develop probabilistics / reliability analysis for structurally linear and nonlinear composite aircraft.

Extend nonlinear aeroelastic modeling / simulations to 3D real systems and link models of structural uncertainty of structure and attachments to variation in nonlinear global aeroelastic behavior

Build structural dynamic / flutter test system and use in a series of tests to support damaged / uncertain composite structures simulations and flutter predictions