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

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The Joint Advanced Materials and Structures Center of Excellence

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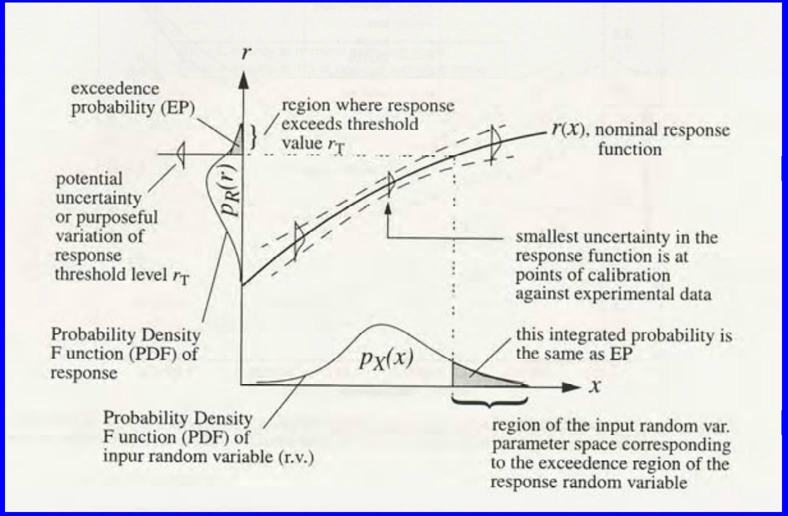
Motivation and Key Issues

- Variation (over time) of local structural characteristics might lead to a major impact on the global aeroservoelastic integrity of flight vehicle components.
- Sources of uncertainty in composite structures: damage, delamination, environmental effects, joint/attachment changes, etc.
- Nonlinear structural behavior: delamination, changes in joints/attachments stiffness and damping, as well as actuator nonlinearities may lead to nonlinear aeroelastic behavior such as Limit Cycle Oscillations (LCO) of control surfaces with stability, vibrations, and fatigue consequences.
- Modification of control laws later in an airplane’s service can affect dynamic loads and fatigue life.

Uncertainty Propagation:
Uncertain Inputs, Uncertain System



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

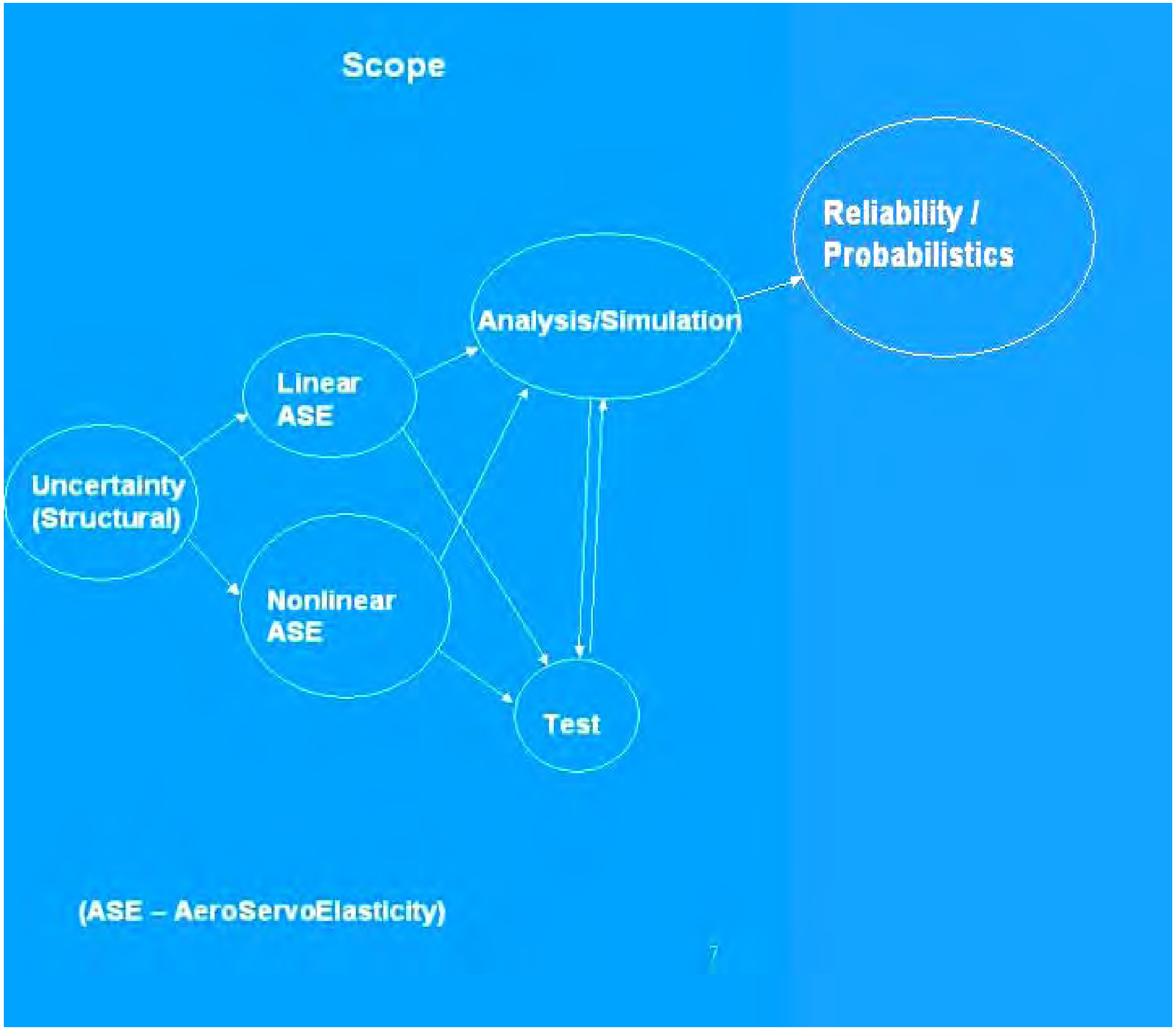
Objectives

- Develop computational tools (validated by experiments) for automated local/global linear/nonlinear analysis of integrated structures/ aerodynamics / control systems subject to multiple local variations/ damage.
- Develop aeroservoelastic probabilistic / reliability analysis for composite actively-controlled aircraft.
- Link with design optimization tools to affect design and repair considerations.
- Develop a better understanding of effects of local structural and material variations in composites on overall Aeroservoelastic integrity.
- Establish a collaborative expertise base for future response to FAA, NTSB, and industry needs, R&D, training,and education.

Approach

– Work with realistic structural / aeroelastic models using industry-standard tools.
– Build a structural dynamic / aeroelastic testing capability and carry out experiments.
– Integrate aeroelasticity work with work on damage mechanisms and material behavior in composite airframes.
– Use sensitivity analysis and approximation techniques from structural / aeroelastic optimization (the capability to run many simulations efficiently) as well as reliability analysis to create the desired analysis / simulation capabilities for the linear and nonlinear cases.

Approach


Scope
Reliability / Probabilistics
Analysis/Simulation
Linear ASE
Uncertainty (Structural)
Nonlinear ASE
Test
(ASE – AeroServoElasticity)
7

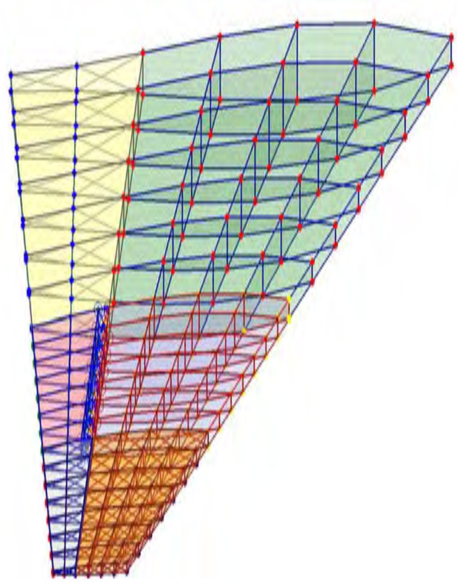
Approach

- Efficient simulation of linear aeroservoelastic behavior to allow rapid reliability assessment:
  - Dedicated in-house tools development (fundamentals, unique features, innovations)
  - Integrated utilization of industry-standard commercial tools (full scale commercial aircraft)
- Efficient simulation of nonlinear aeroservoelastic behavior, including limit cycle oscillations (LCO):
  - Tools development for basic research and physics exploration: simple, low order systems
  - Tools development for complex, large-scale aeroelastic systems with multiple nonlinearities
- Reliability assessment capability development for linear and nonlinear aeroservoelastic systems subject to uncertainty.
- Aeroservoelastic reliability studies with resulting guidance for design and for maintenance.
- Structural dynamic and future aeroelastic tests of aeroelastically scaled models to support aspects of the simulation effort described above.

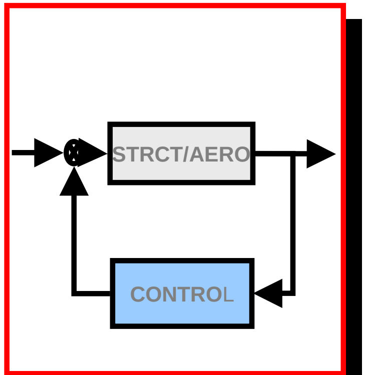
Linear Behavior Simulation: Automated for Carrying Out Fast Repetitive Analyses

Development of an In-House Design Oriented Aeroservoelastic Modeling Capability (May 2005 slide)

Active Aileron



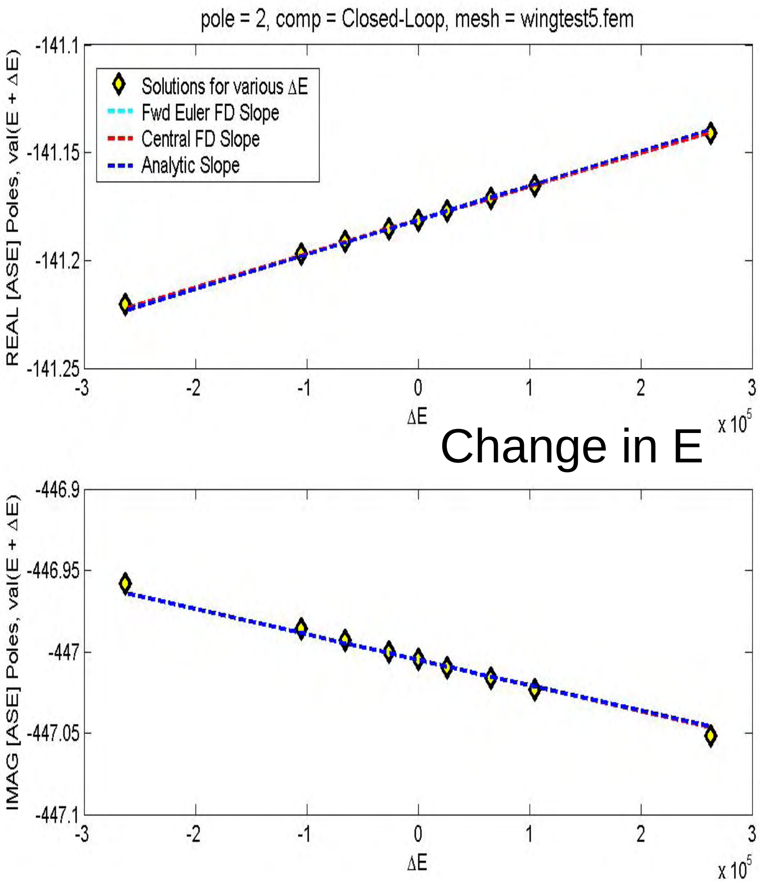
Variable Local Structure: Modulus of Elasticity (E) of certain skin panels



Variation of the Real (damping) And Imaginary (frequency) Parts of a Typical Pole

σ

ω

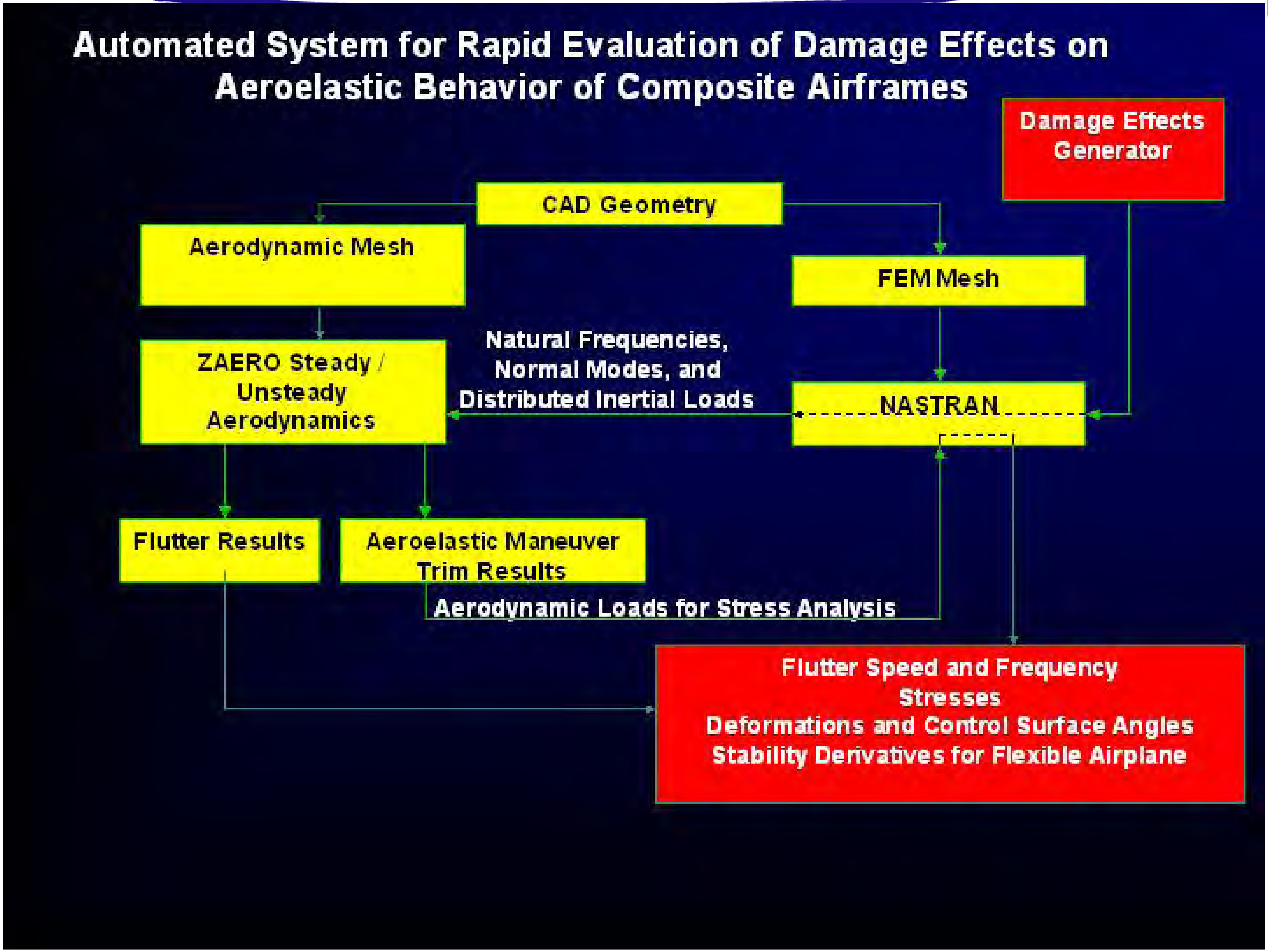


Change in E

Development of an In-House Design Oriented Aeroservoelastic Modeling Capability (June 2006)

- Development of the in-house capability continues:
- Extensions under development:
  - Linear buckling analysis (and sensitivities).
  - Non-linear structural behavior (local nonlinearities due to damage or wear, large structural deformations).
- Complete control of the simulation software is necessary for:
  - Studies of non-standard approximation techniques (used for accelerating the large number of repeated analyses needed to cover structural uncertainties).
  - Insight.
  - Better integration with an array of different commercial packages.
  - Creating a comprehensive design optimization / reliability assessment tool that will also allow development of best repair practices and fleet retrofits, if needed.

Linear Aeroelasticity of Full Scale Composite Aircraft: Computational Array using Commercial Codes

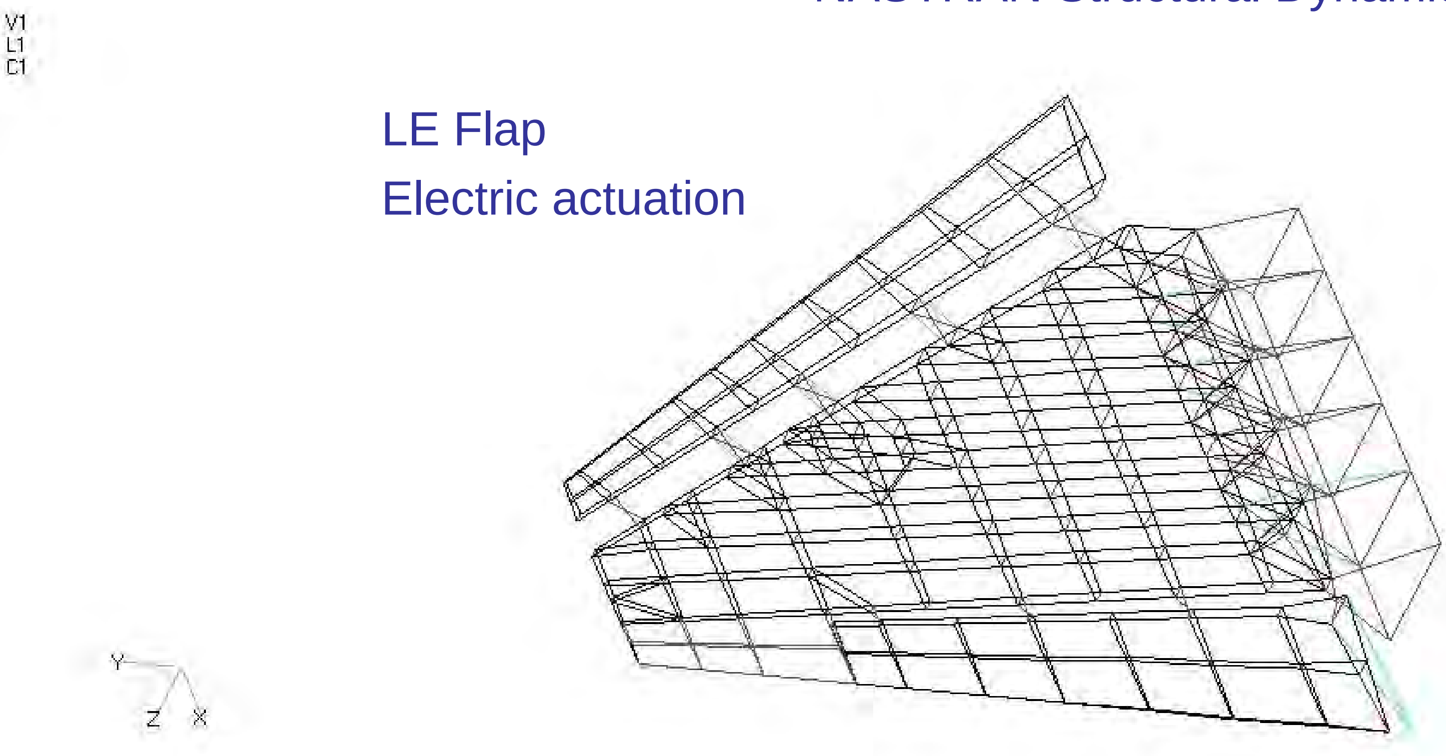


Modeling Case: The Fighter-Type Wing with Control Surfaces

NASTRAN Structural Dynamic Mesh

LE Flap

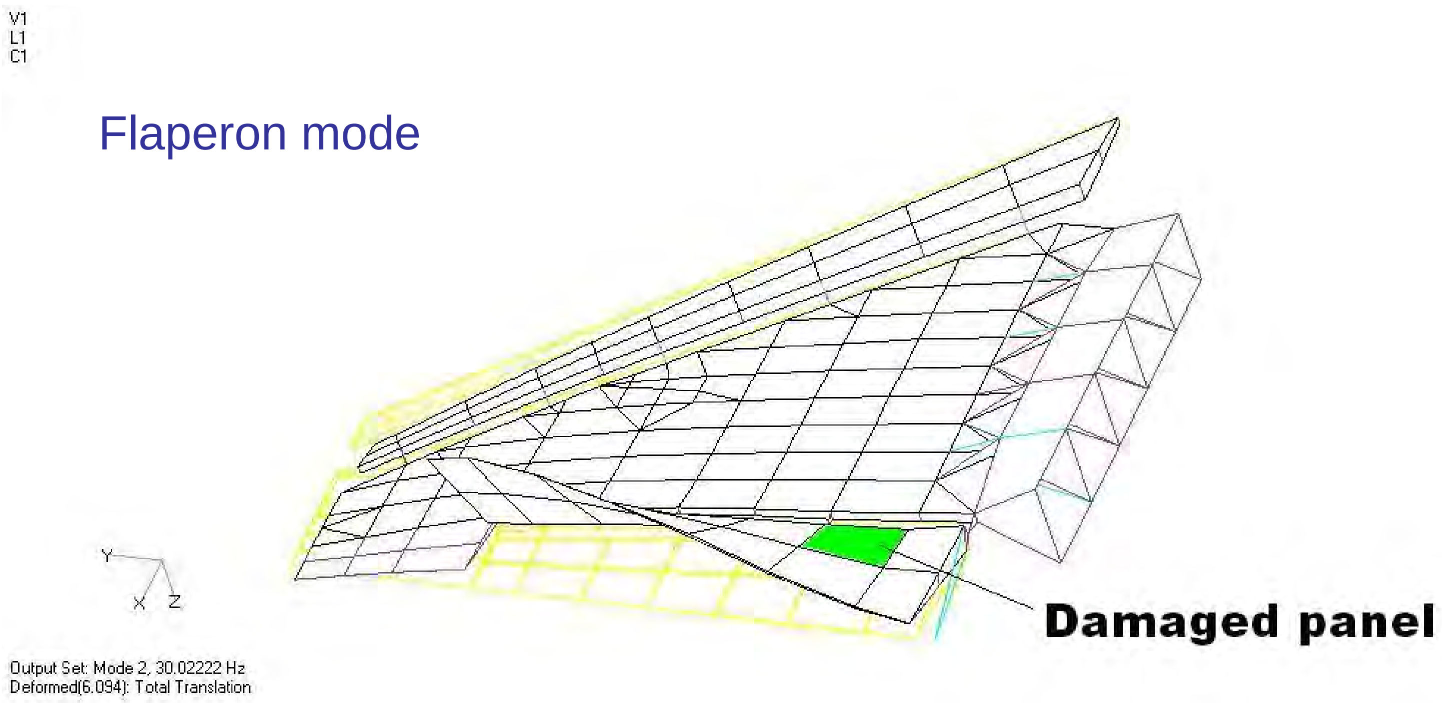
Electric actuation



TE flaperon

Servo-hydraulic actuation

Modeling Case: The Fighter-Type Wing with Control Surfaces



- Panel damage → 7% reduction in flutter speed
- Added mass near trailing edge due to repair → 6% flutter speed reduction (added mass at TE: 1% of TE mass)

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Modeling Case: The UW Low-Speed Dynamically-Scaled All Composite Supersonic Business Jet (SSBJ) UAV

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Length=9.5 ft

Span=4.5 ft

Weight=26 lbs

Structure=13 lbs

Structure: →

Kevlar/Epoxy Skins

Graphite/Epoxy Frames

Kevlar/Graphite/Epoxy spars and local reinforcements

Aluminum hard points for landing gear

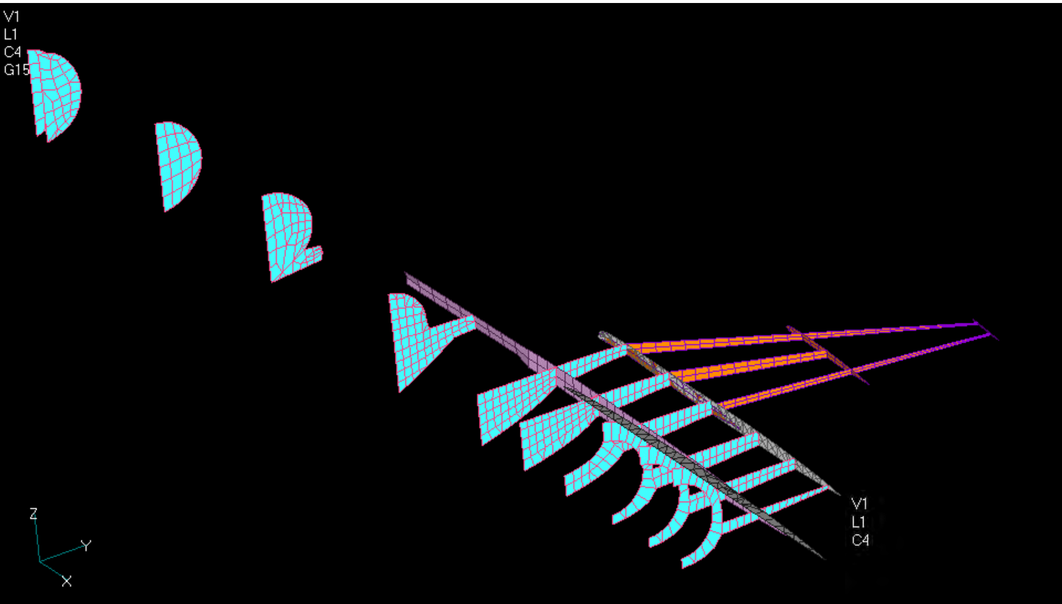
Wood engine mounts

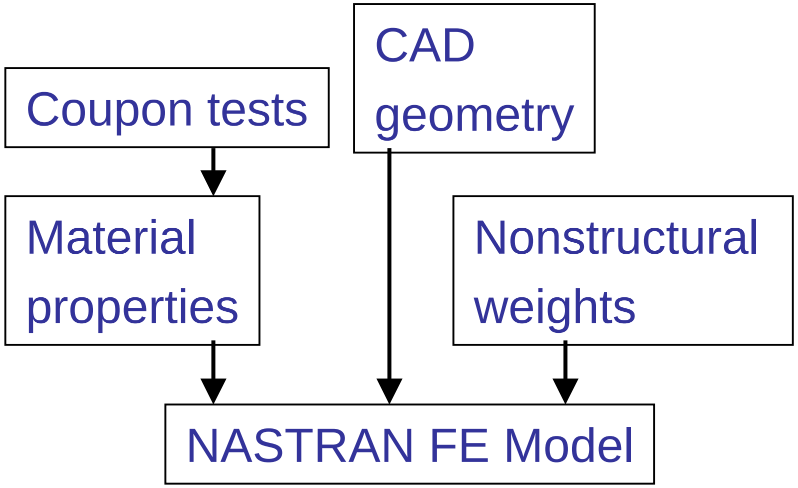
Balsa/Fiberglass canards and horizontal tails

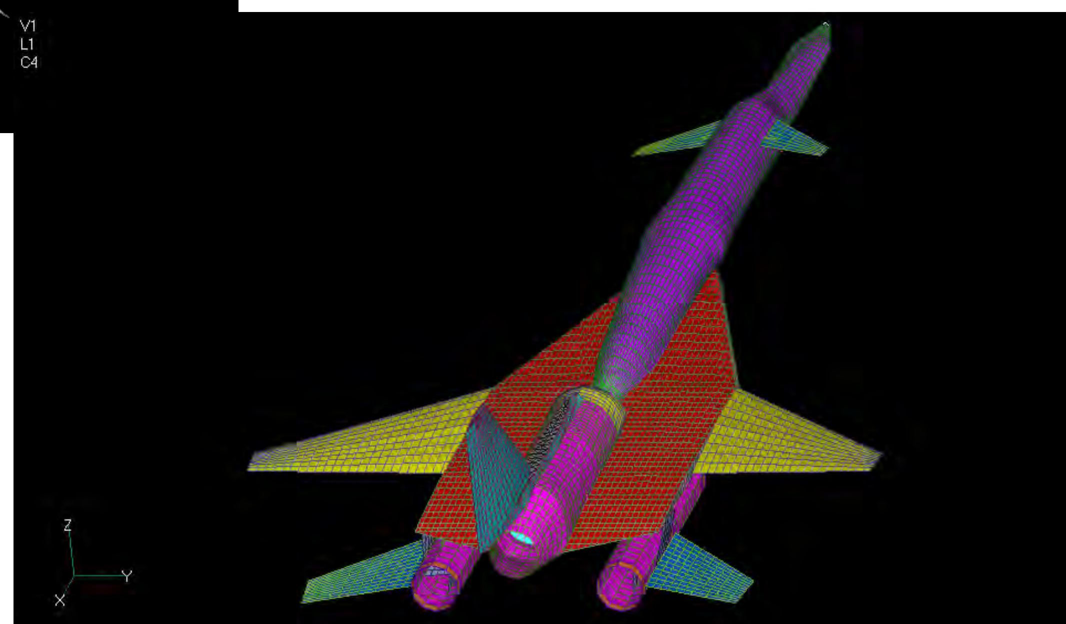
The UW Dynamically Scaled SSBJ UAV

The complete vehicle and selected structural details

Modeling Case: The UW Low-Speed Dynamically-Scaled All Composite Supersonic Business Jet (SSBJ) UAV







Modeling Case: The UW Low-Speed Dynamically-Scaled All Composite Supersonic Business Jet (SSBJ) UAV

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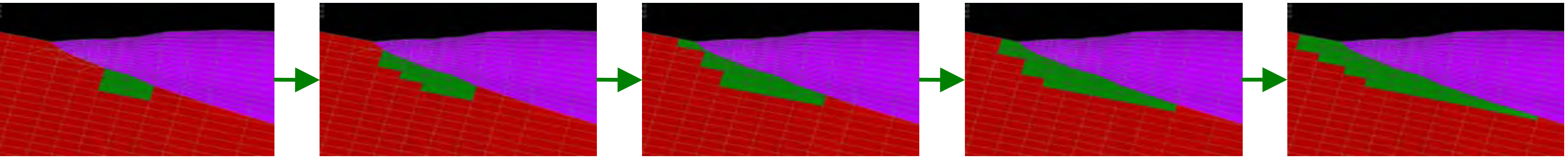
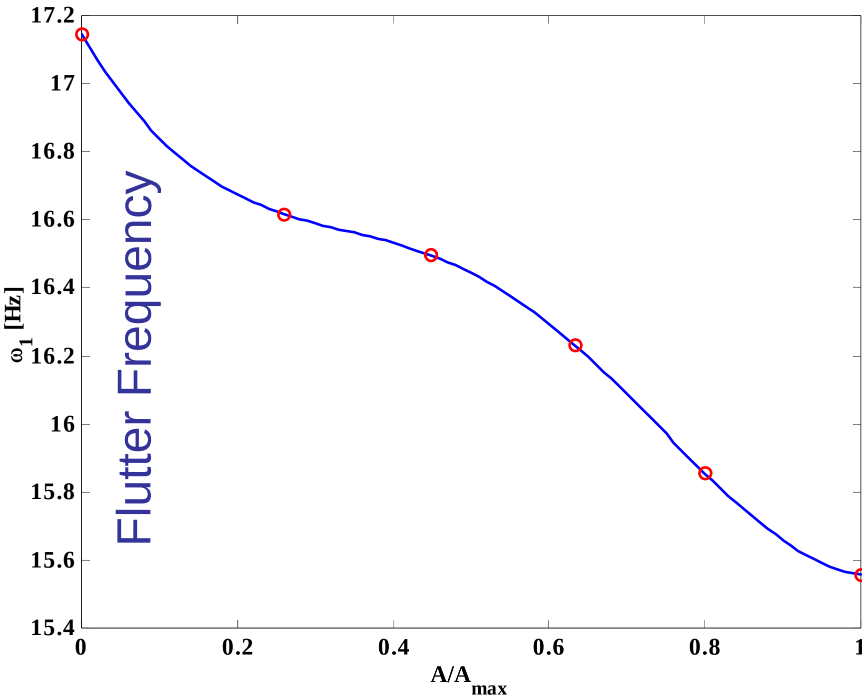
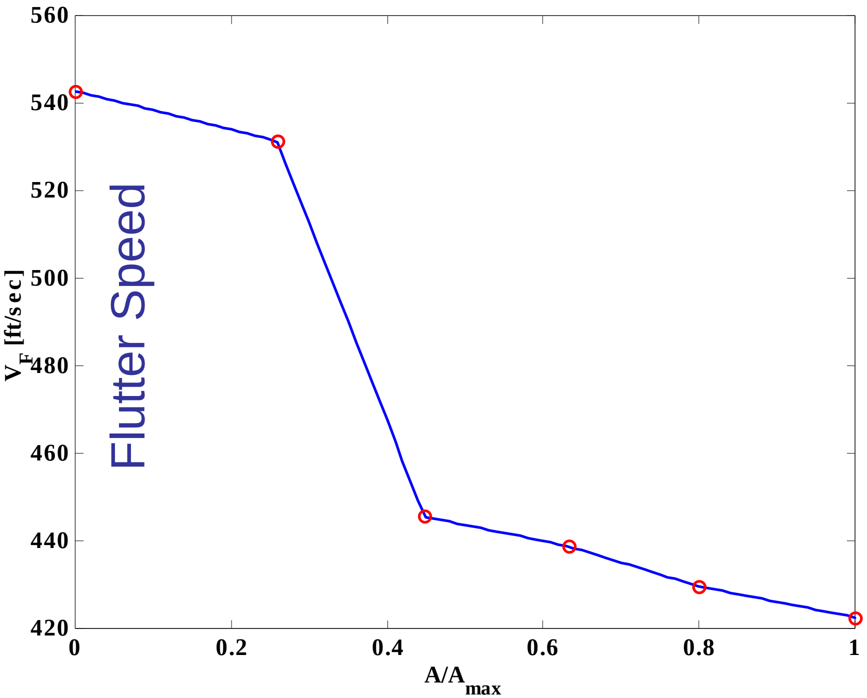
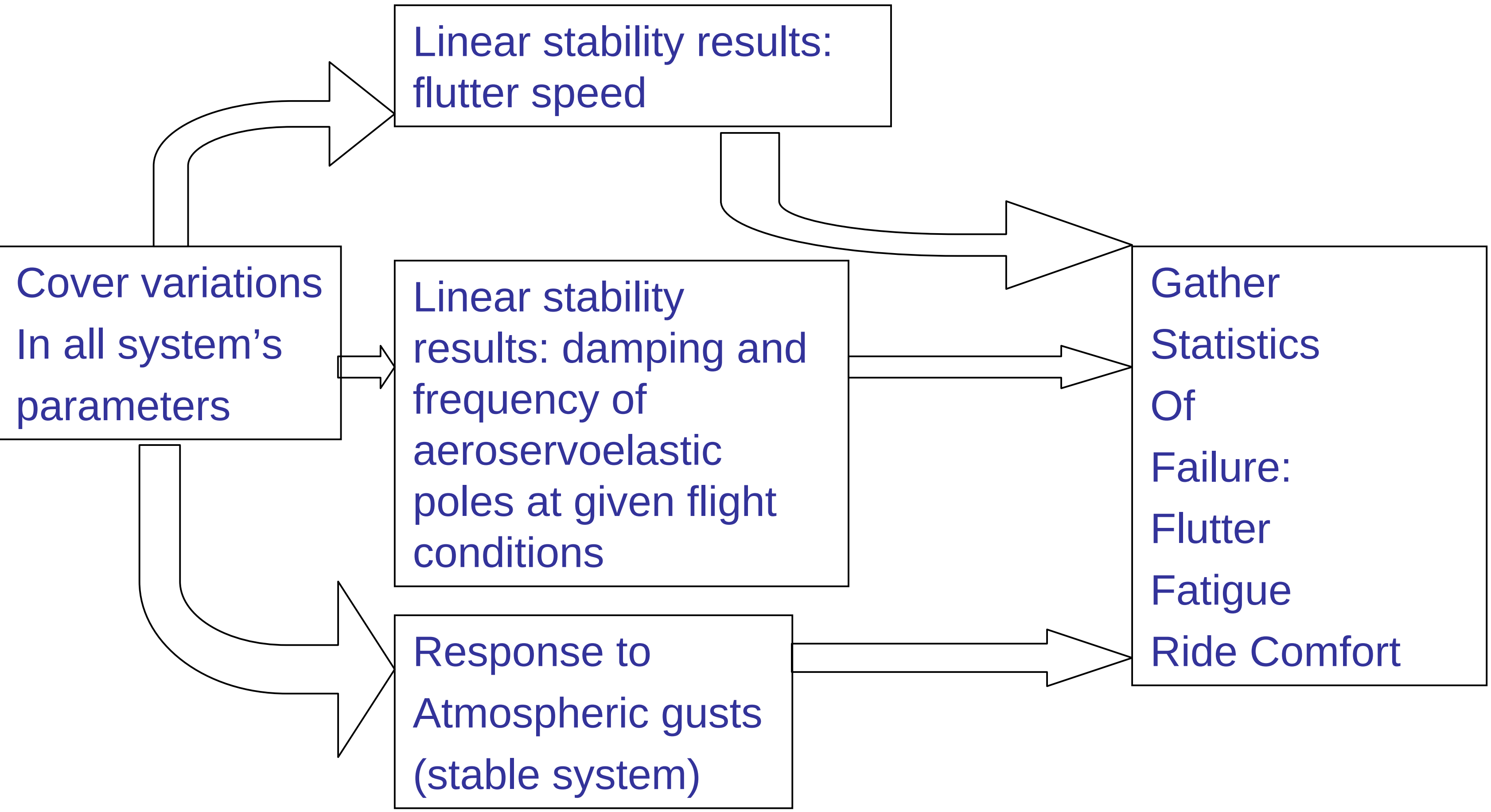






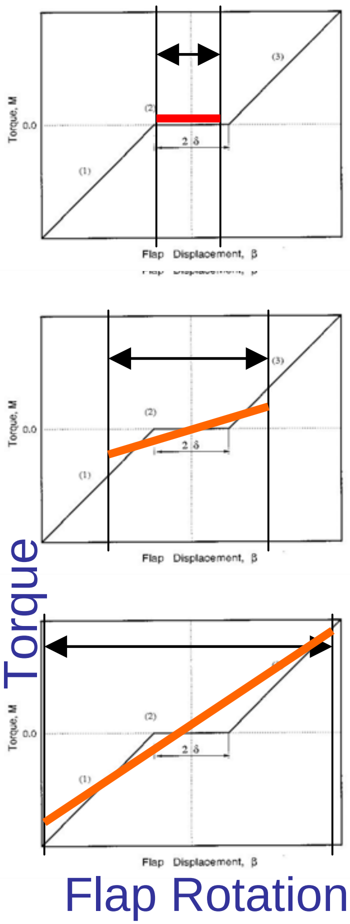
Effect of Damage Size on Flutter Frequency and Speed

Aeroelastic Reliability
Considering Linear Aeroservoelastic Failure Modes

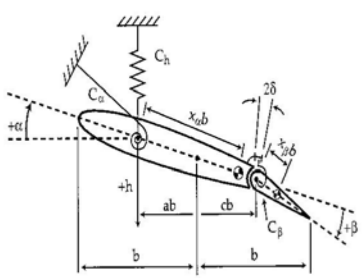


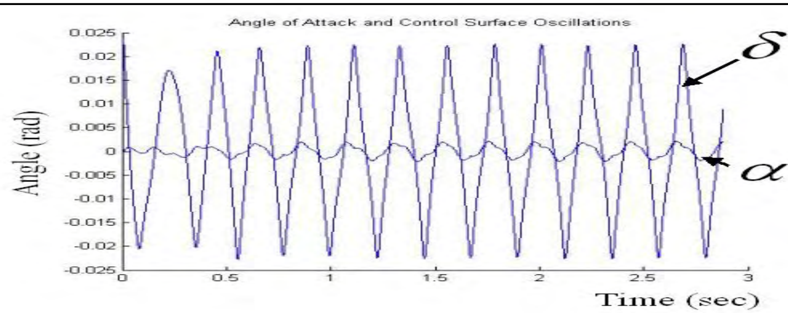
Nonlinear Behavior Simulation: Automated for Carrying Out Fast Repetitive Analyses

Free-Play Induced LCO: Intuitive Concepts



- The amplitude of oscillation determines an equivalent effective linear spring.
- At low oscillation amplitudes stiffness is low, the system can become unstable (in the linear sense) and oscillation begins to grow.
- As oscillation amplitudes build up, the system begins to move against a hardening spring.
- The increased stiffness arrests the oscillations, which now stays steady at some amplitude and frequency.
- Failure due to LCO can be due to structural fatigue. Crew and passenger comfort can also be compromised by high LCO vibration levels / frequencies.





LCO Simulation Methods

- Describing Function Method
  - Solve the aeroelastic equations in the frequency domain.
  - Assume existence of simple harmonic motion. Find the speed, frequency, and amplitude at which it will happen (if at all).
  - Map: LCO amplitude and frequency vs. speed.
  - Method determines if LCO can or cannot exist. Different initial conditions are not used to create the LCO maps.

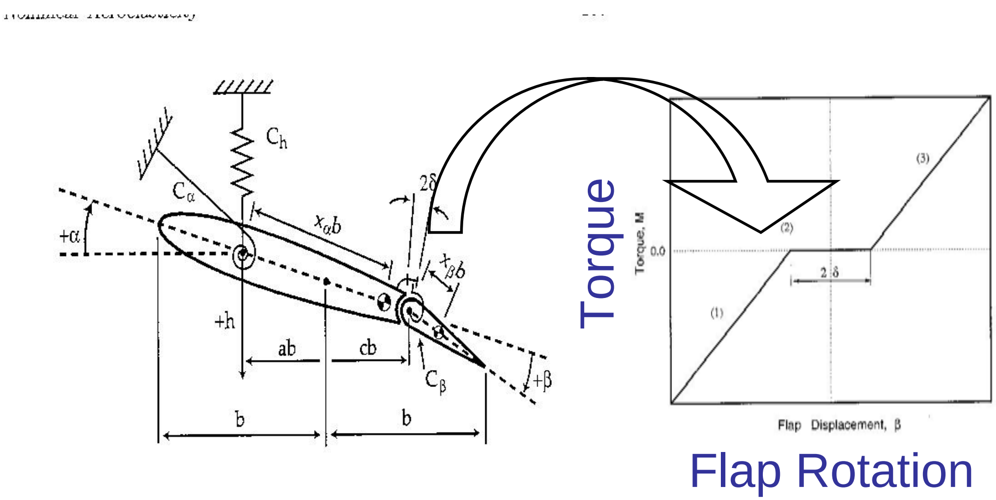
- Time Domain Simulation
  - Solve the aeroelastic equations in the time domain.
  - Obtain time histories.
  - In theory: there is a need to cover all possible initial conditions and excitations to get a complete map of all possible aeroelastic time responses.

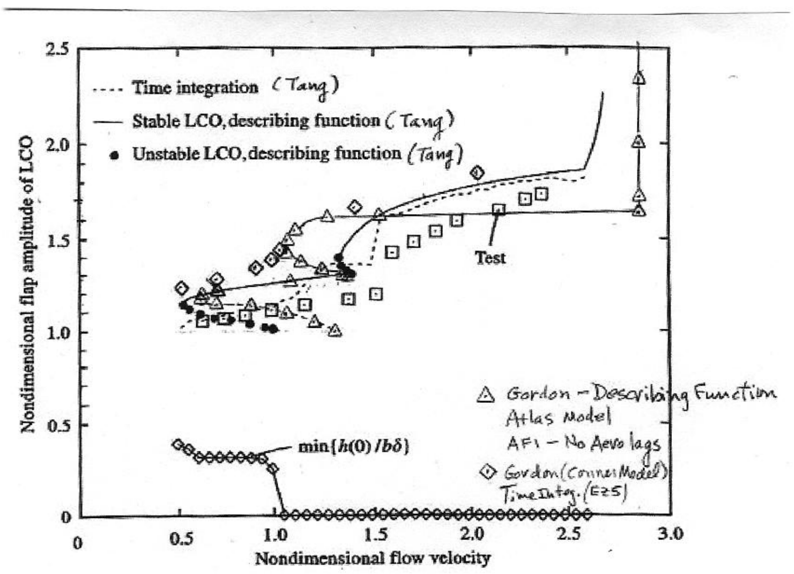
Boeing: Development of Limit Cycle Oscillations (LCO)

Simulation Tools

- Computational tools for both Describing Function frequency-domain simulations and time domain simulations were developed and validated using a simple case: The Tang-Dowell 2D 3dof airfoil / aileron low-speed aeroelastic model.

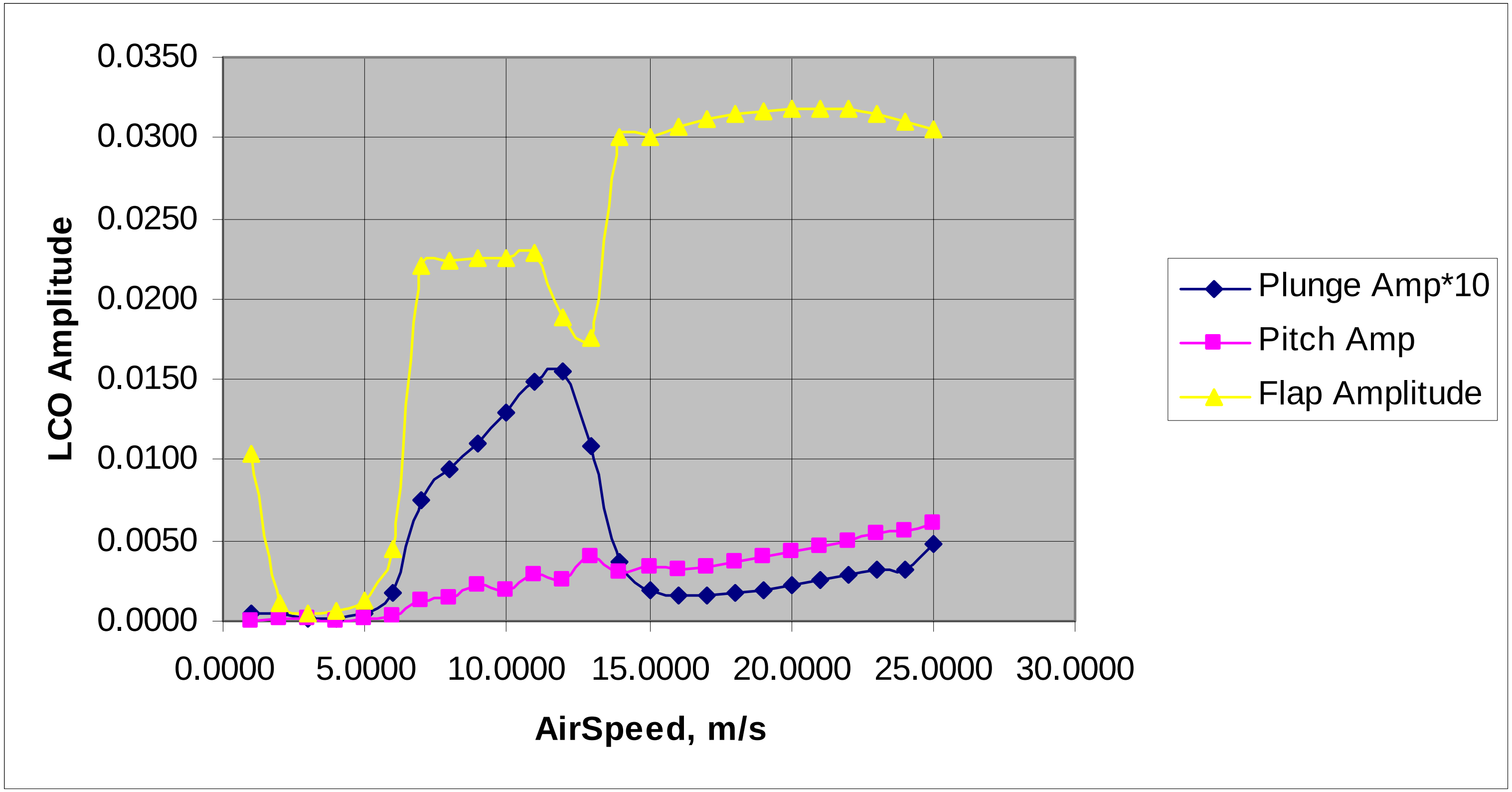
- Describing Function results were also validated using independent University of Washington simulation results.





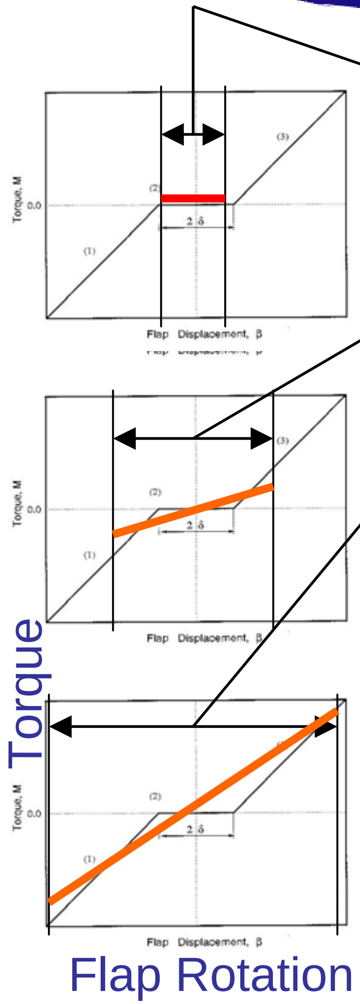
LCO Amplitudes for the Tang-Dowell Airfoil / Flaperon 3dof System

All system parameters: nominal values



Note: abrupt changes in LCO amplitudes (with speed) can correspond To change on oscillation frequency also.

Describing Function LCO Analysis in the Case of Control Surface Free-Play: Concept



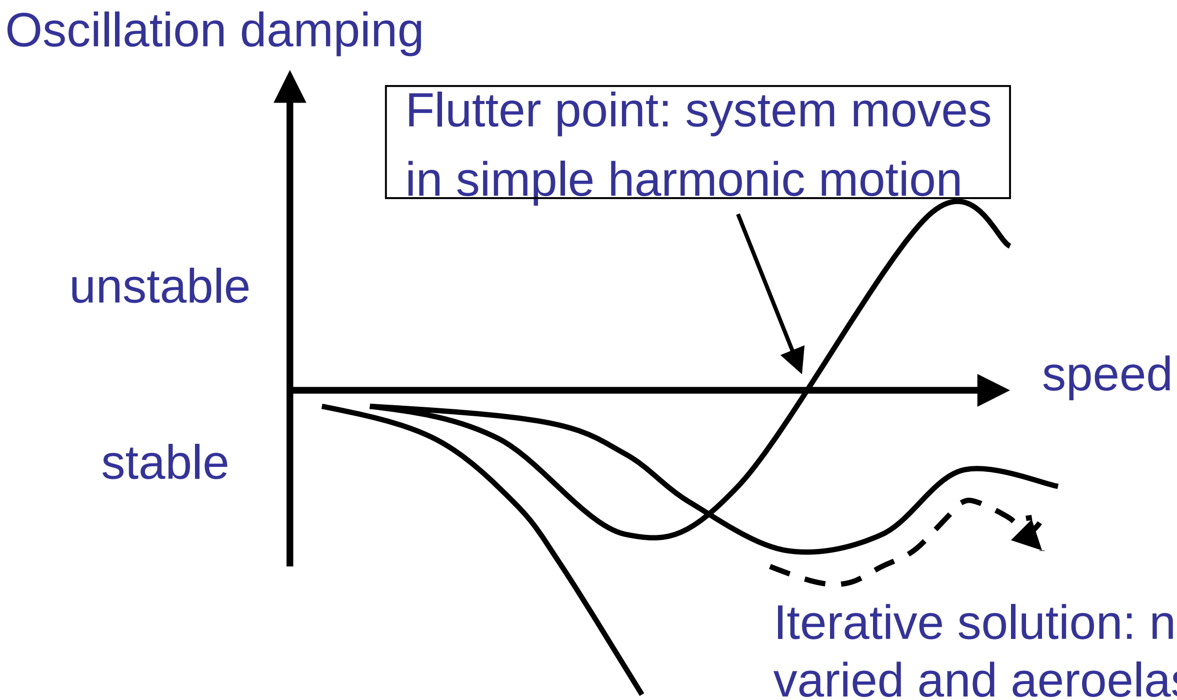
Amplitude of oscillation determines an equivalent effective linear spring.

Carry out linear flutter analysis for that spring value
And find flutter speed(s) and frequency(ies).

Linear flutter solutions correspond to the system oscillating in simple harmonic motion, with the flaperon moving on its hinge with the assumed amplitude (used to determine the equivalent spring).

Create a map of possible simple harmonic oscillation amplitudes
Versus speeds and frequencies that allow them.

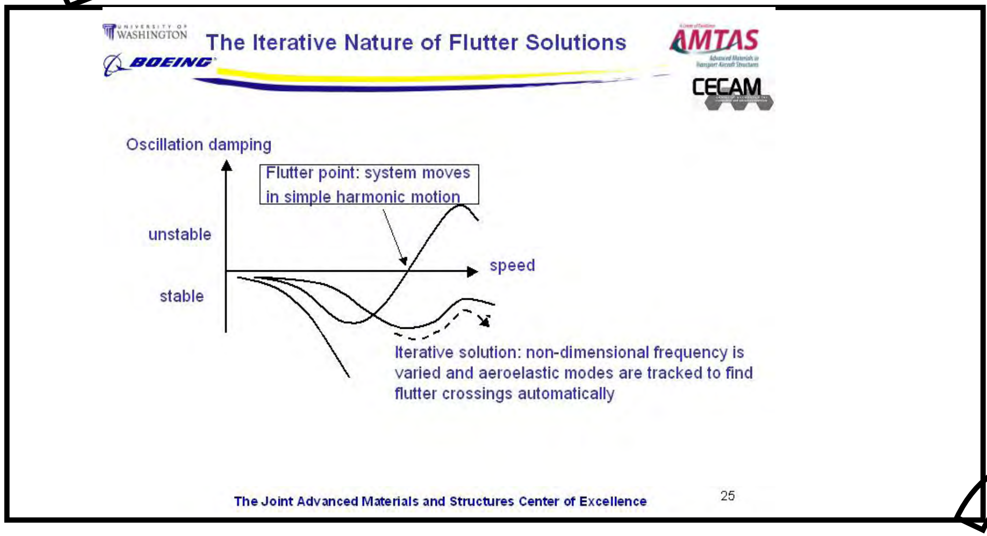
The Iterative Nature of Flutter Solutions



Iterative solution: non-dimensional frequency is varied and aeroelastic modes are tracked to find flutter crossings automatically

The Double-Iterative Nature of Free-Play LCO Flutter Solutions

Vary assumed stiffness to model different levels of oscillation



Find possible LCO speeds and frequencies

Track LCO speeds and frequencies vs. oscillation amplitudes
To create LCO maps and identify the most critical LCO conditions

Aeroelastic Reliability
Considering LCO-Related Failure Modes

Cover variations
In all system's
parameters

LCO results –
Describing Function
Maps

LCO results –
Extract amplitudes /
frequencies
From Time Histories of
Response to excitation
And initial conditions

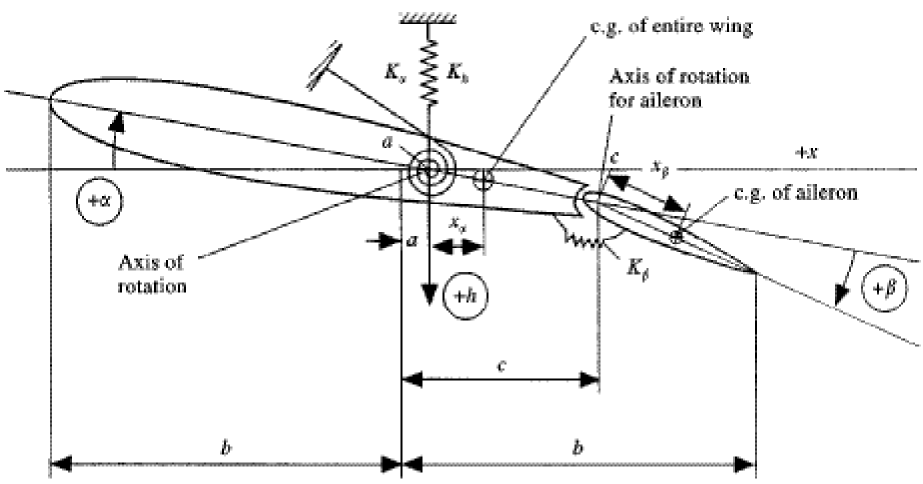
Assess failure
Modes: fatigue,
Ride comfort,
Possibility of
Destructive
Linear flutter

Gather
Statistics
Of
Failure

3DOF aeroelastic system – Probabilistic Analysis

Damage may lead to:

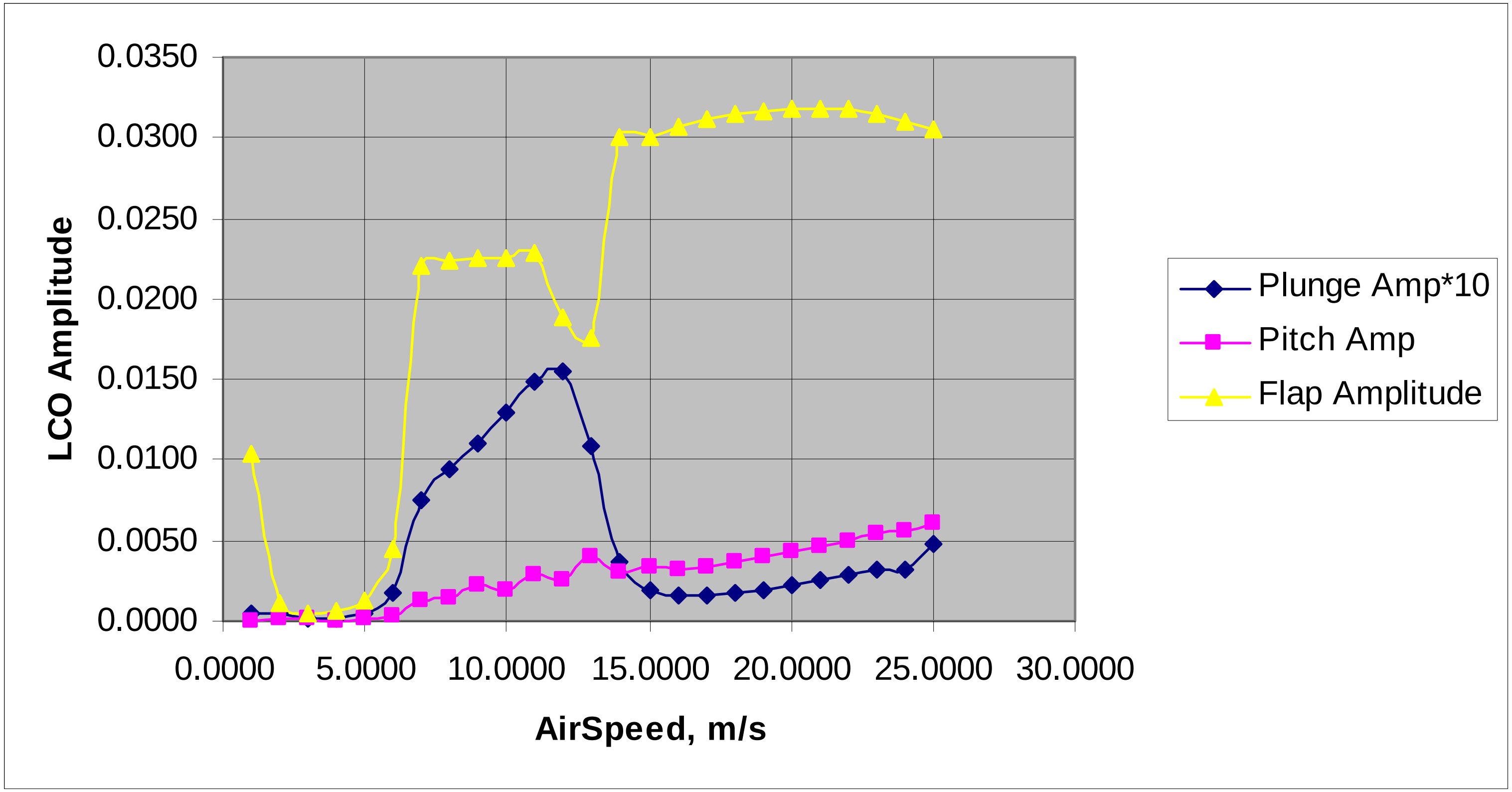
- reduction of stiffness
- moisture absorption and possible changes in properties
- changes in stiffness and inertia properties after damage repair
- irreversible properties degradation due to aging



Random Simulation

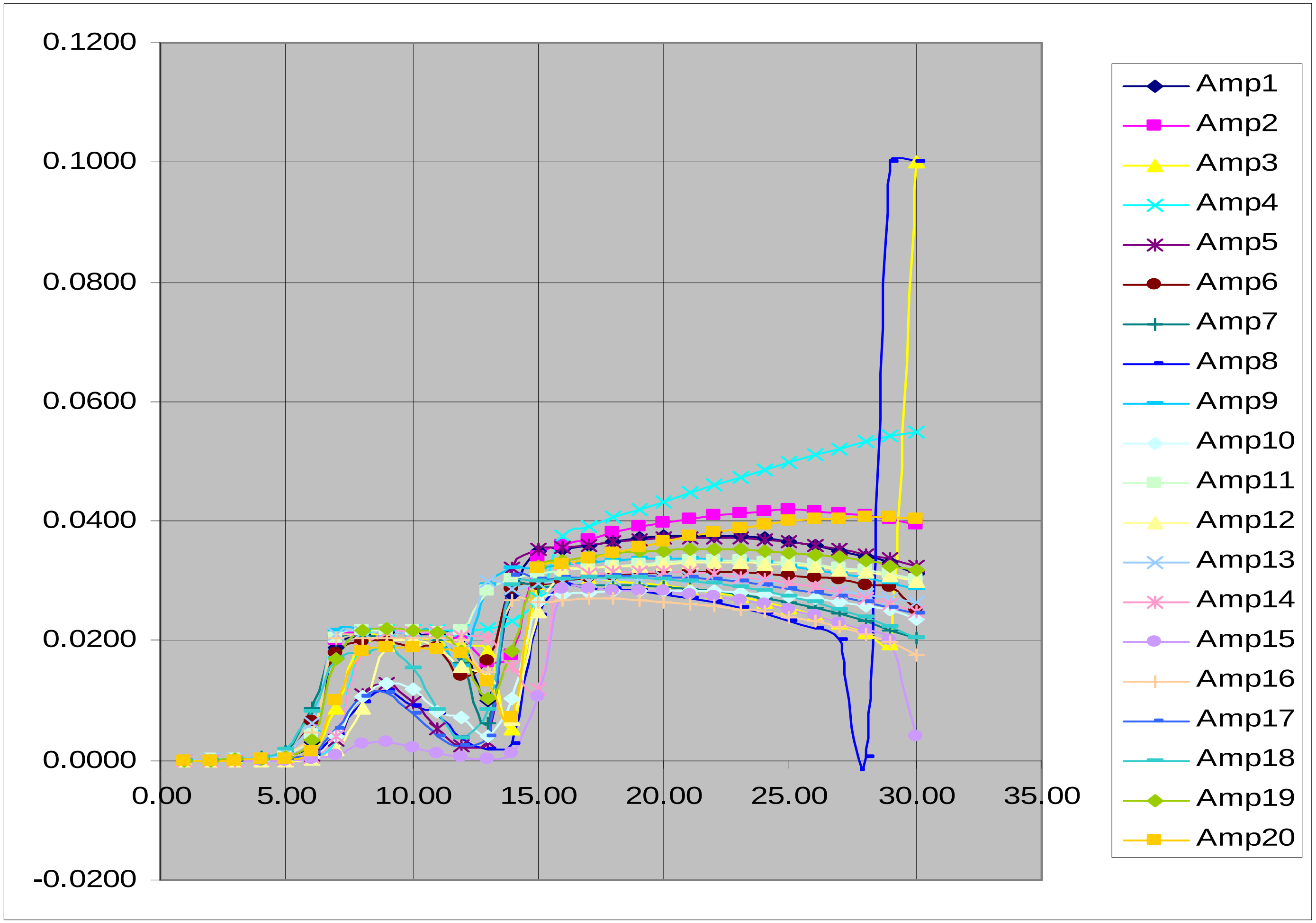
- 5 geometrical parameters
- 6 inertia parameters
- 4 stiffness parameters
- 3 structural damping parameters
- 2 free-play parameters
- air density, airspeed, discrete gust velocity

Nominal parameters (LCO results obtained from response time histories)

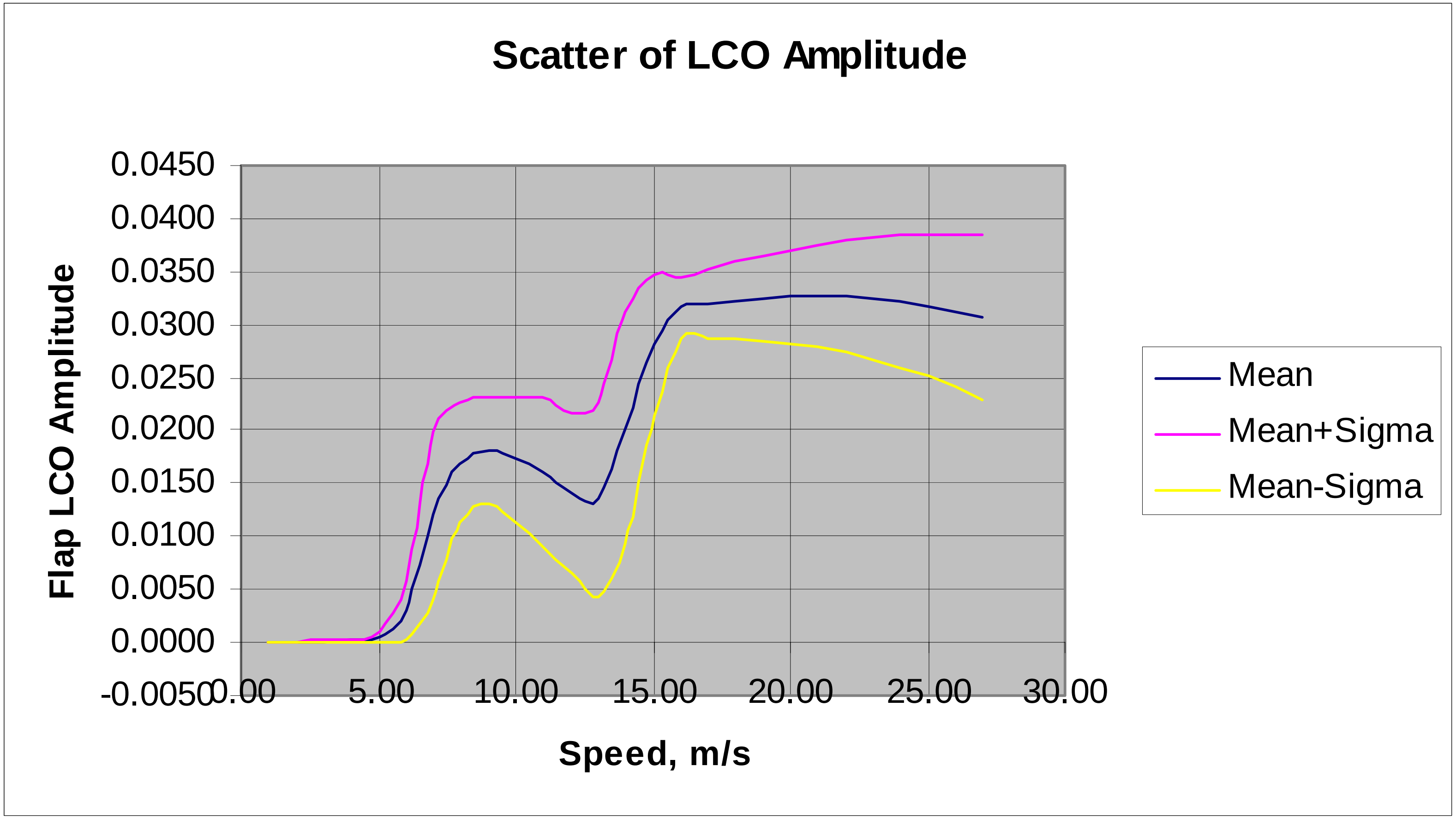


Note: the response amplitudes are normalized

Monte-Carlo Simulation Results (obtained from response time histories)



Scatter band



A Probabilistic Approach to Aeroservoelastic Reliability Estimation

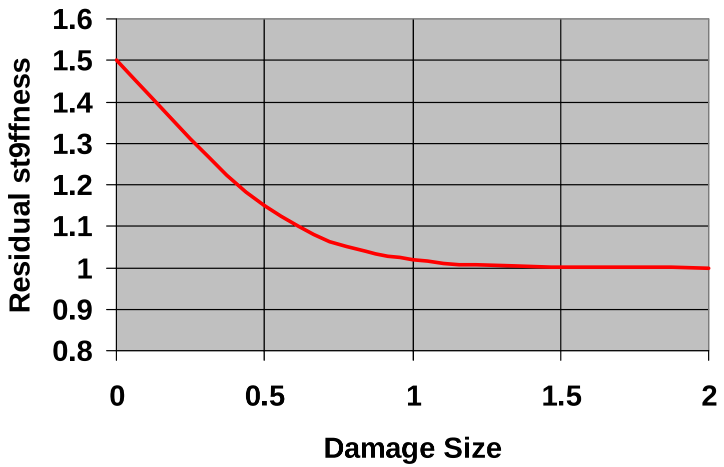
General

The Next Step – Link Statistical Variability Models with Variability and Damage Models of Actual Aircraft

- With capabilities to rapidly find statistics of aeroelastic behavior and failure due to variability of system's parameters, add:
  - Models of actual damage types
  - Information regarding damage variability for actual aircraft in service
- Develop tools for assessing aeroelastic reliability measures
- Use the statistics of the resulting behavior to evaluate aeroelastic reliability
- Use the technology to affect design practices, maintenance procedures, and optimal retrofits

Deterministic Approach

- For normal conditions without failures, malfunctions, or adverse conditions: no aeroelastic instability for all combinations of altitudes and speeds up to max design conditions + 15%
- In case of failures, malfunctions, and adverse conditions: no aeroelastic instability within operating conditions + 15%
- Parametric studies used extensively to find and cover all worst case scenarios
- A damage tolerance investigation shows that the maximum extent of damage assumed for the purpose of residual strength evaluation does not involve complete failure of the structural element.
- Extension of damage tolerance concepts to aeroelasticity: residual stiffness in the presence of damage and no catastrophic aeroelastic failure.



General probabilistic approach

Probability of failure on conditions of aeroelasticity is expressed by the integral:

$$P_f = \int_0^{\infty} (1 - F_{Va}(V))\, f_{Vf}(V)\, dV$$

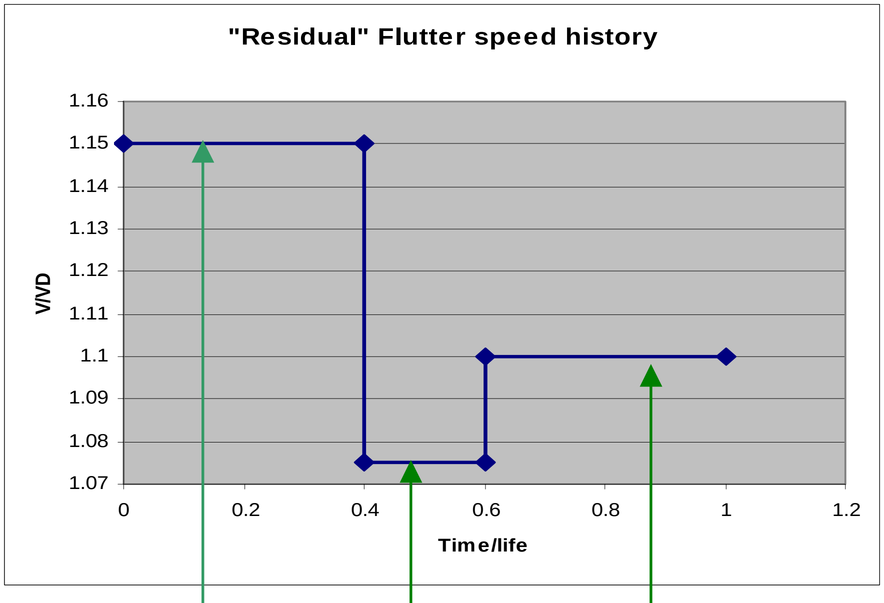
F_{Va} is a Cumulative Probability Function of maximum random airspeed per life

f_{vf} is Probability Density Function of the random flutter speed

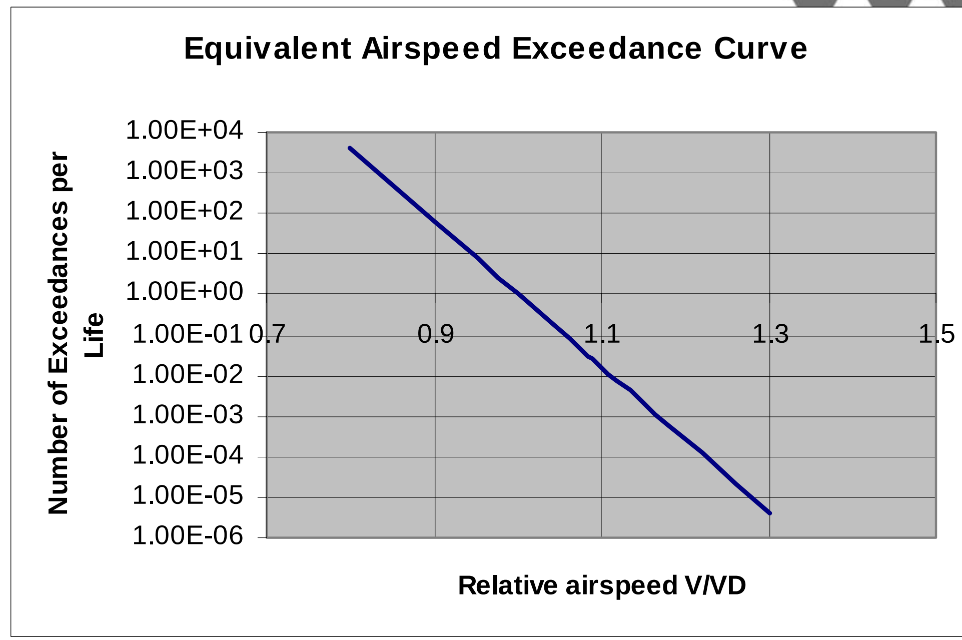
Failure types considered

- Excessive deformations
- Flutter: airspeed exceeds the flutter speed of damaged structure
- High amplitude limit cycle oscillations: the acceptable level of vibrations is exceeded

Probability of Failure Formulation 1



Before Damage | With Damage | After Repair
Flutter speed



Interval #	Probability of Failure
1 (new structure)	8.0E-04
2 (damaged structure)	8.9E-03
3 (repaired structure)	6.33E-03
Total POF =	1.60E-02

$$P_f = 1 - \prod_{i=1}^{N=3} [1 - P_f(V_i, t_i)]$$

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Probability of Failure Formulation 2

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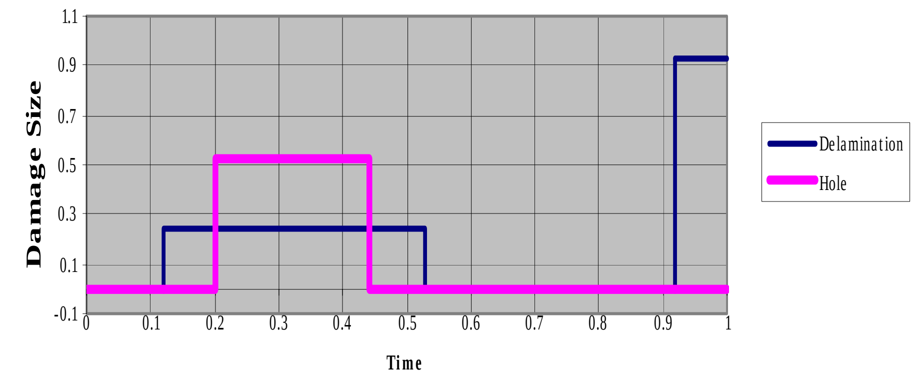
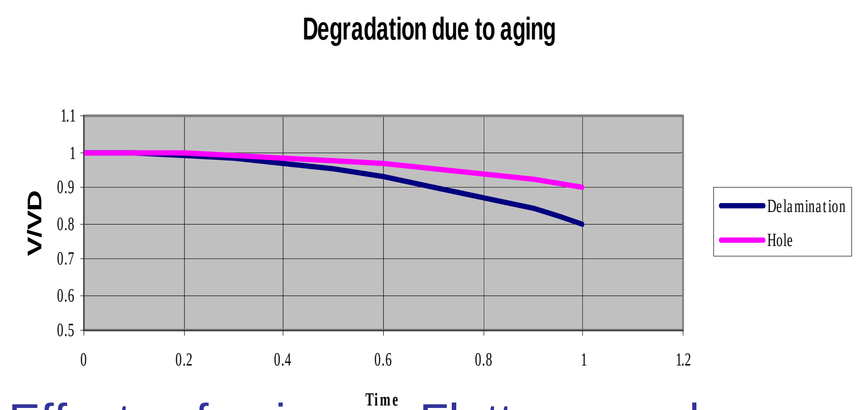
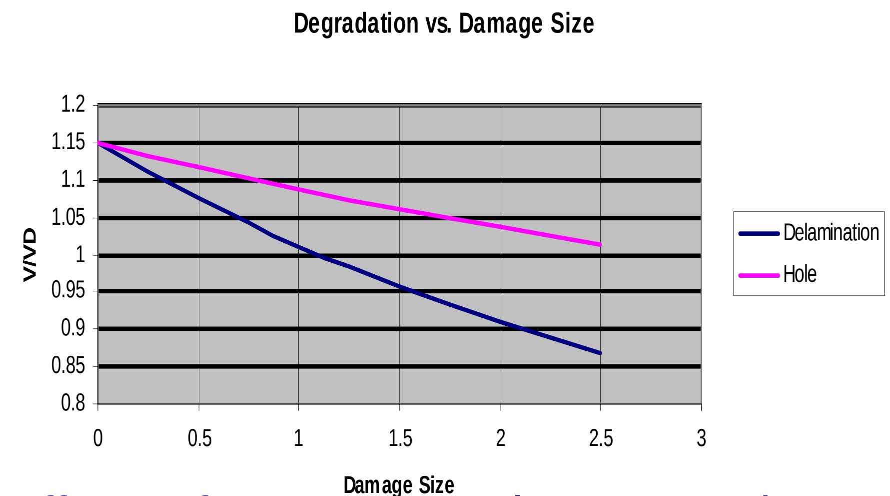


Multiple damages / times / repairs

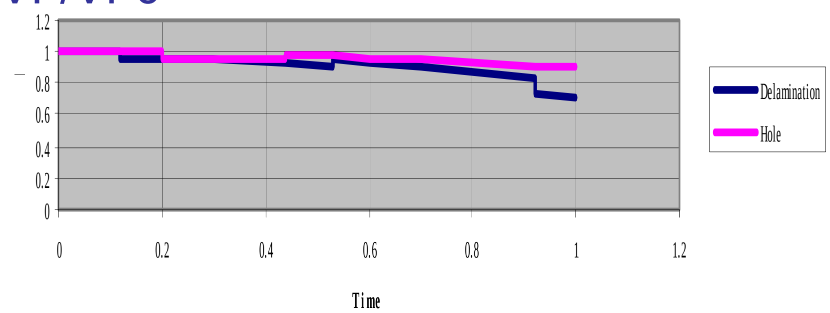


Effects of aging on Flutter speed



Effects of Damage on Flutter Speed

Total degradation for both damages VF/VF0



Probabilistic Model

Combine statistics of flutter speed (due to damage and structural changes, as simulated by the aeroelastic modeling capabilities described here) with statistics of speed excursions.

The methodology is built on:

Lin, K., and Styuart, A.,
"Probabilistic Approach to Damage Tolerance Design of Aircraft Composite Structures",
AIAA-2006-2156, 47th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Newport, Rhode Island, May 1-4, 2006

extended to include Aeroelastic failure modes.

Describing Function Analysis of Multi-Degree of Freedom Aircraft

The step from a simple 3 dof system to the case of a complete passenger airplane

Describing Function Analysis of Multi-Degree of Freedom Aircraft

- The step from a simple 3 dof system to the case of a complete passenger airplane makes the problem more complex by orders of magnitude:
  - Many more modes of vibration must be included in the aeroelastic analysis in order to capture all global and local motions of importance
  - Many limit cycles are possible
  - Automation of the analysis process is challenging
  - A major challenge: Automation of probabilistic analysis / LCO simulations of systems covering large numbers of possible system variations

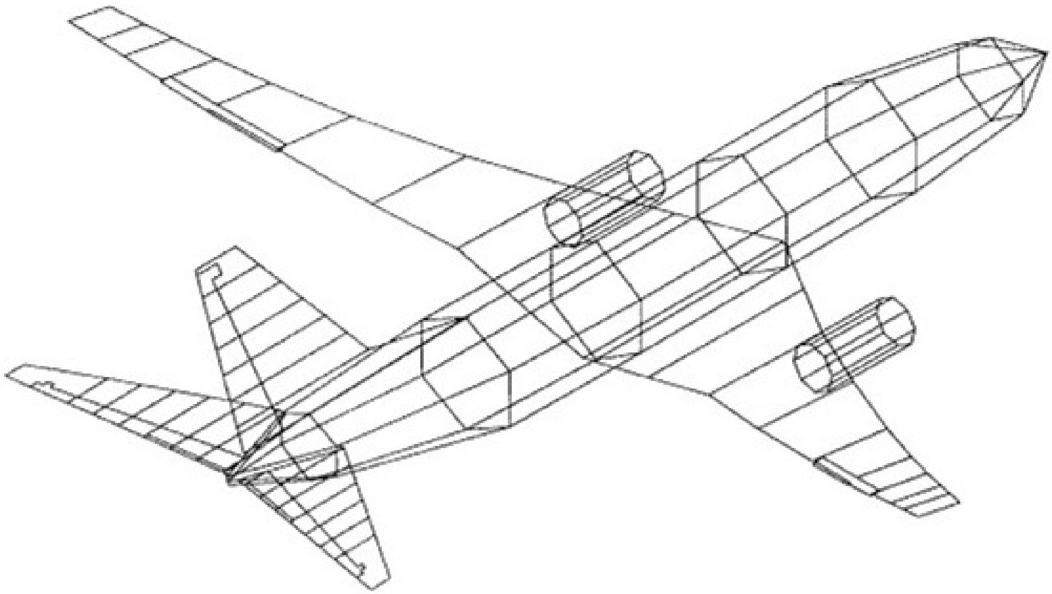
Boeing Test Case Study

- **Test case uses representative airplane model with associated real-world complexity**
- **Test case does not reflect any service configuration / flight conditions**
- **Test case used freeplay values far in excess of any maximum in-service limits**

The Boeing Development of Describing Function Tools for MDOF Aircraft

- Full size non-symmetric test-case passenger aircraft study
- 153 modes used
- Free-play allowed in one trim tab (only one side of the aircraft)
- Unsteady aerodynamics adjusted by wind tunnel data
- Algorithms and tools for automated determination of flutter speeds / frequencies in the case of large, densely packed, modal bases
- Algorithms and tools for automated parametric studies of effects of structural variation on flutter speeds / frequencies and LCO response
- Correlation of simulation results with flight test results

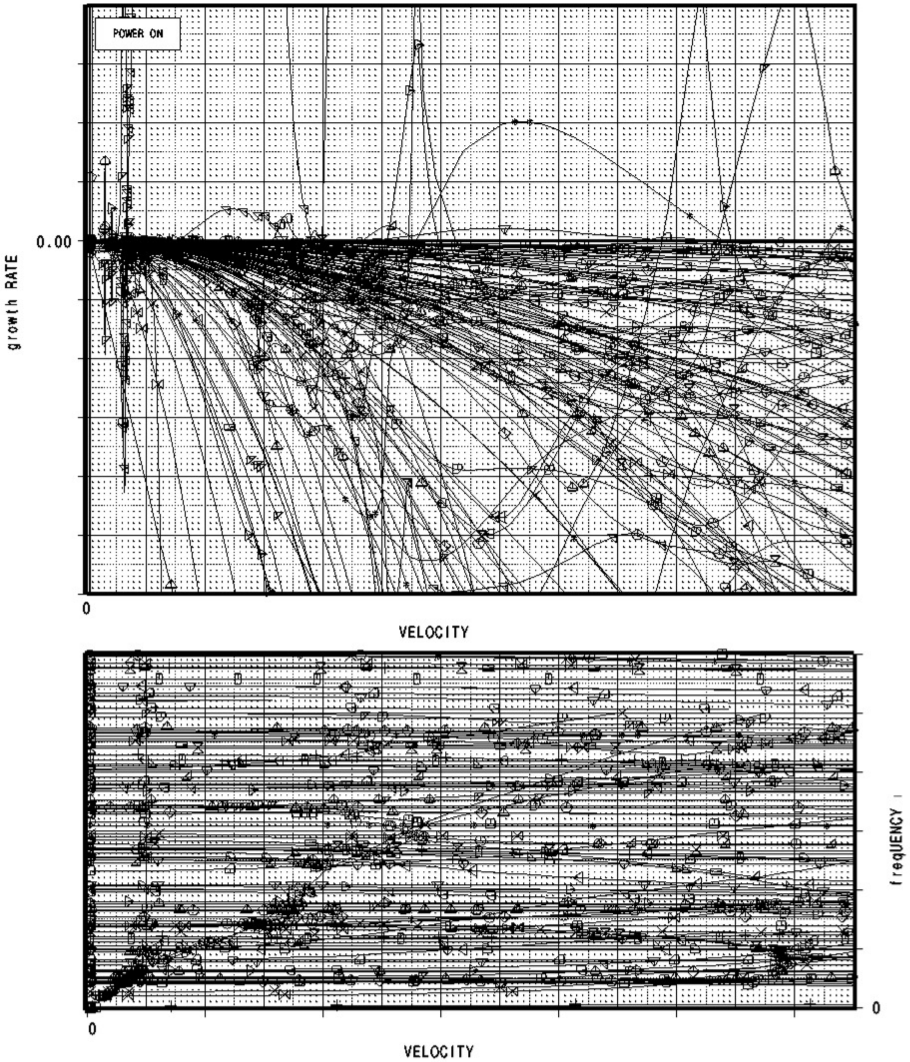
Test-Case Aircraft Used for LCO Studies



Note: the test-case aircraft used and conditions tested
do not correspond to any actual airplane / service cases

The Challenging Case of Many Dofs and closely-spaced Frequencies

Effective tab rigid rotation stiffness = 0

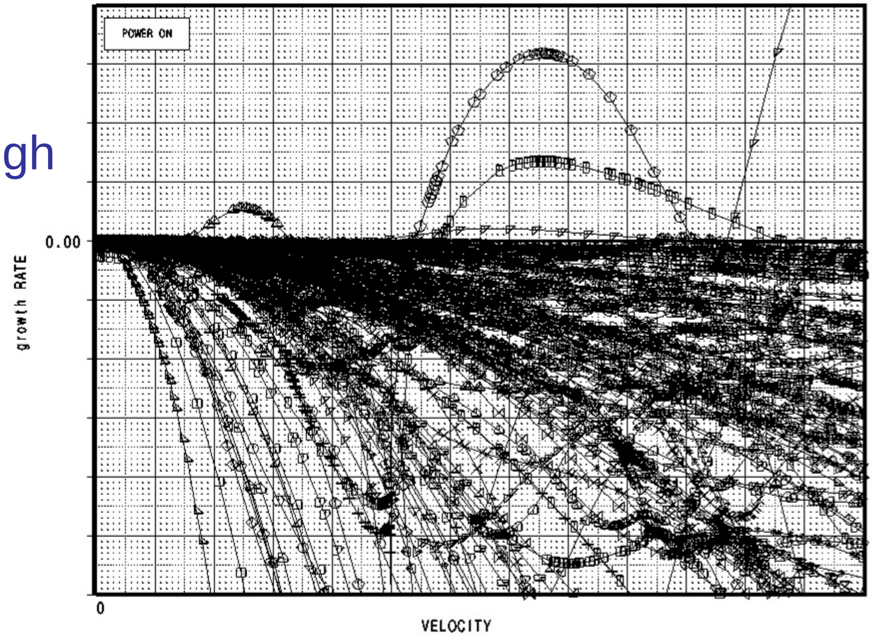


Growth Rate vs Velocity

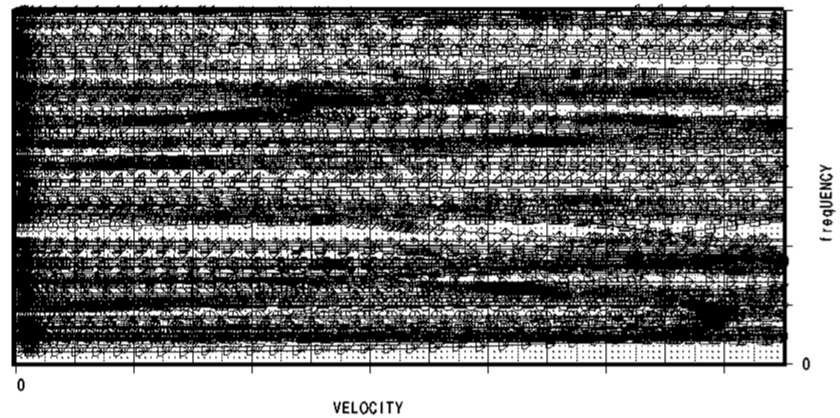
Frequency vs Velocity

The Challenging Case of Many Dofs and closely-spaced Frequencies

Effective tab rigid rotation stiffness - High



Growth Rate vs Velocity

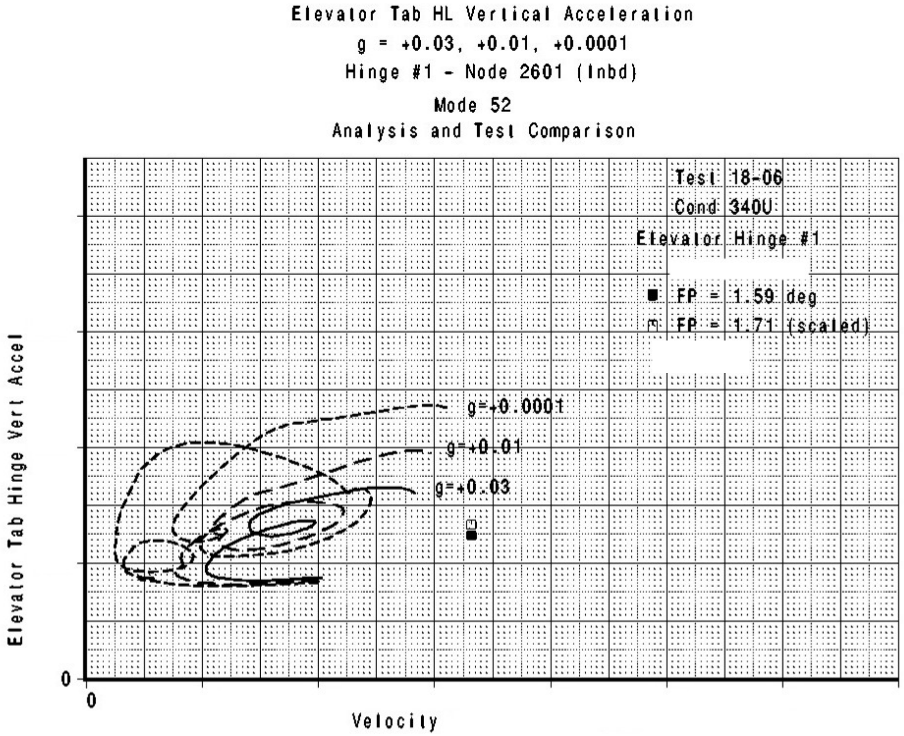


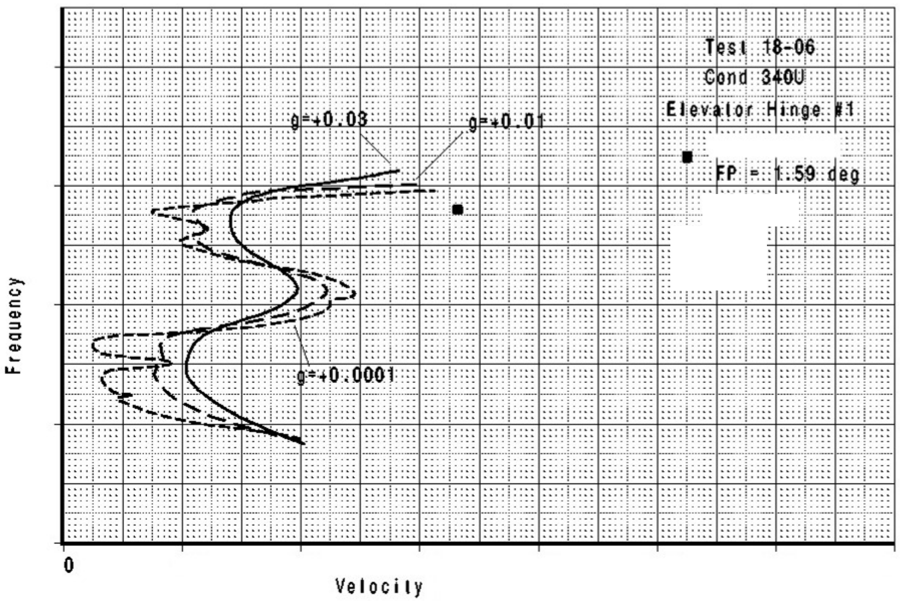
Frequency vs Velocity

Representative Describing Function Limit Cycle Predictions and Flight Test Results

$\delta_{fp} = \pm 1.71$ deg

$0 < g < +0.03$

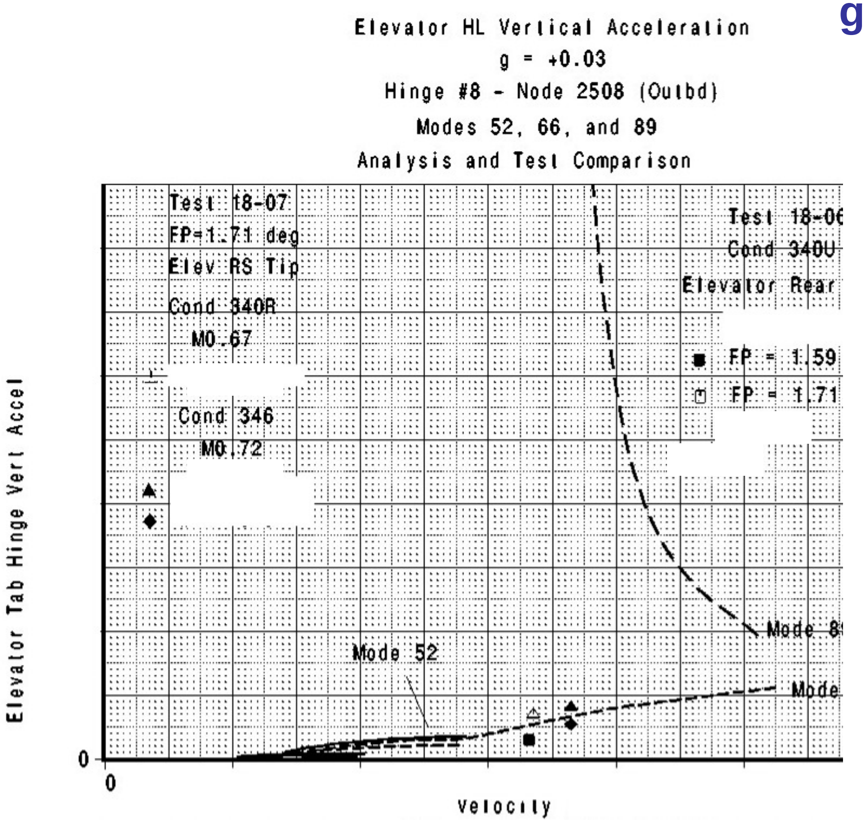


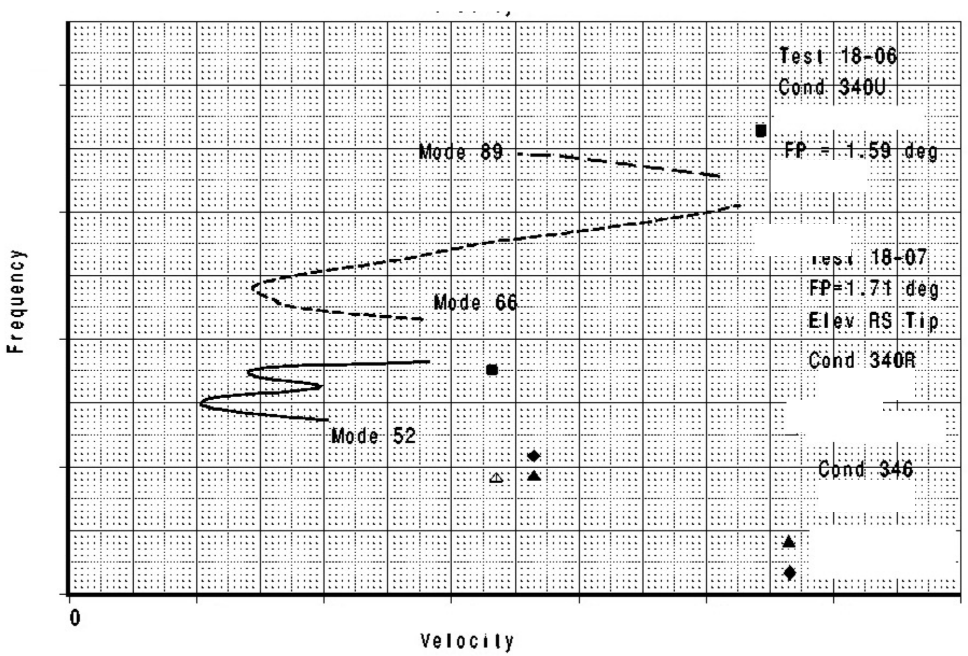


Representative Describing Function Limit Cycle Predictions and Flight Test Results

$\delta_{fp} = \pm 1.71$ deg

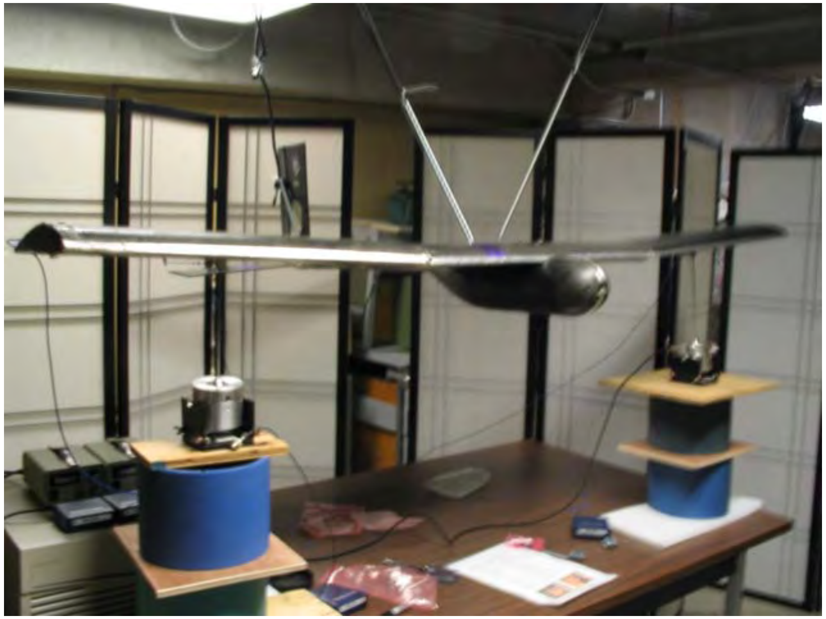
g = +0.03





Development of Experimental Capabilities

- New Modal testing system: arrived and installed.
- Training: June-July 2006.
- Test articles: small composite UAVs & components: nominal and with different types and level of damage.



UNIVERSITY OF WASHINGTON

Conclusion

A Center of Excellence AMTAS Advanced Materials in Transport Aircraft Structures

CECAM center of excellence for composites and advanced materials

- Progress in all major areas of this R&D effort:
  - Efficient simulation tools for uncertain airframes covering flutter and LCO constraints
  - Automated systems for rapid simulations of large number of systems' variations, needed for probabilistic / reliability analysis
  - A mix of in-house capabilities (allowing studies non-standard techniques and flexibility in tools development) and industry-standard commercial capabilities (for improved interaction with industry)
  - Experimental capability: Equipment arrives; Up to speed in the next few weeks.
  - Formulation of a comprehensive approach to the inclusion of aeroelastic failures in the reliability assessment of composite aircraft, and resulting benefits to both maintenance and design practices.

Plans

- Flutter
  - Continue development of the UW in-house simulation capability to include buckling (geometric nonlinearity) effects.
  - Continue development of the integrated NASTRAN / ZAERO simulation environment:
    - test using models with complexity representative of real passenger aircraft, and
    - improve automation of analysis and computational speed to allow efficient execution of the large number of simulations needed for probabilistic studies.
  - Use sensitivity analysis and approximations to utilize design optimization technology to address issues of reliability and optimal maintenance.

Plans

- LCO
  - Extend time-domain LCO simulation capability to complete airplanes and their finite element model.
  - Integrate with probabilistic / reliability analysis.
  - Continue development of LCO simulation tools for large-scale aeroelastically complex flight vehicles.
  - Develop a probabilistic approach to nonlinear LCO problems using Describing Function simulation techniques.
  - Design nonlinear small scale models (with different sources of service life and damage-related nonlinearity), carry out numerical simulations, correlate with structural dynamic tests, and prepare for aeroelastic wind tunnel tests.

Plans

- Probabilistics & Reliability
  – Link structural variation over time and damage modes to structural stiffness and inertia variations (including statistics).
  - Develop a comprehensive reliability methodology for composite airframes (with design and maintenance consequences) covering aeroelastic / aeroservoelastic failure modes.