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

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A Center of Excellence
AMTAS
Advanced Materials in Transport Aircraft Structures

FEDERAL AVIATION ADMINISTRATION

Contributors

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    - James Gordon, Associate Technical Fellow, Flutter Methods Development
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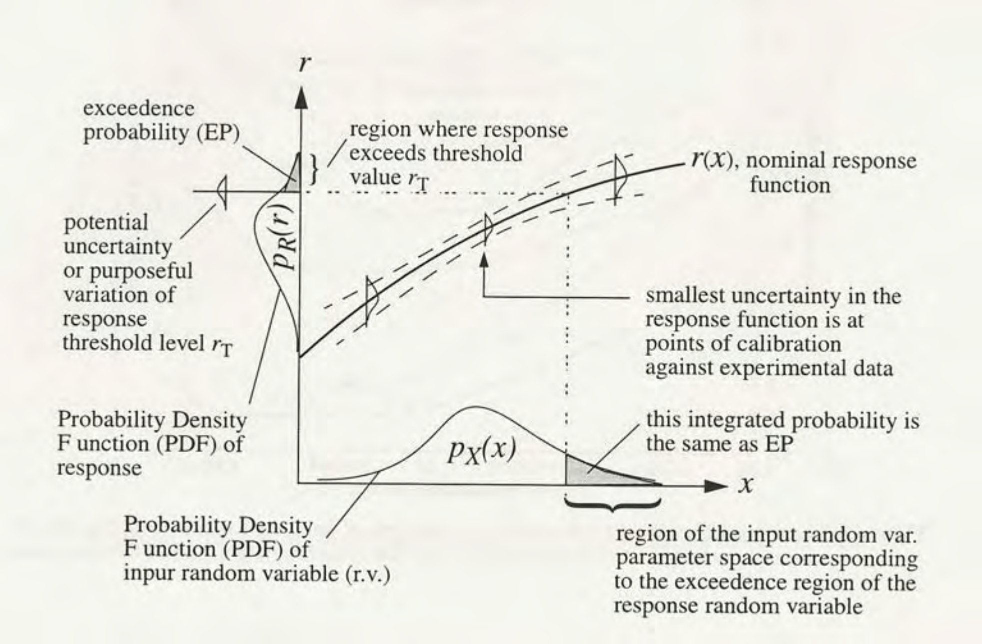
    - Kumar Bhatia, Senior Technical Fellow, Aeroelasticity and Multidisciplinary Optimization
- FAA Technical Monitor
    - Peter Shyprykevich, R&D Manager, FAA/Materials & Structures – *now retired*
    - Curtis Davies, Program Manager of JAMS, FAA/Materials & Structures
- Other FAA Personnel Involved
    - Larry Ilcewicz, Chief Scientific and Technical Advisor for Advanced Composite Materials
    - Gerry Lakin, FAA Transport Airplane Directorate, Standardization Branch

Motivation and Key Issues

Variation (over time) of <u>local</u> Structural characteristics might lead to a major impact on the <u>Global</u> Aeroservoelastic integrity of flight vehicle components.

Uncertainty Propagation:
Uncertain Inputs, Uncertain System



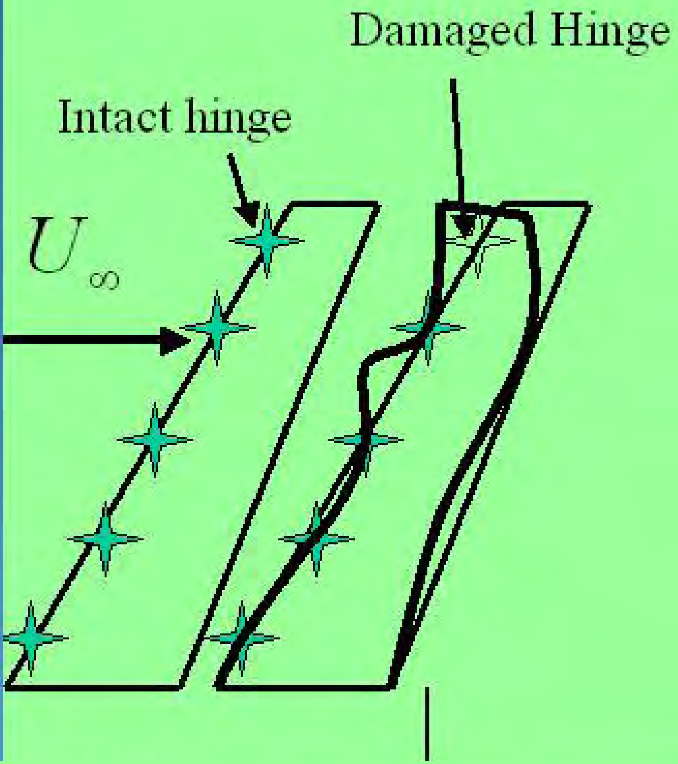
V.J.Romero, Sandia National Lab, AIAA Paper 2001-165

Sources of uncertainty in composite structures: fabrication, damage, environmental effects, service history, maintenance.

Nonlinear structural behavior - example:
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.

Motivation



Reliability – Uncertainty

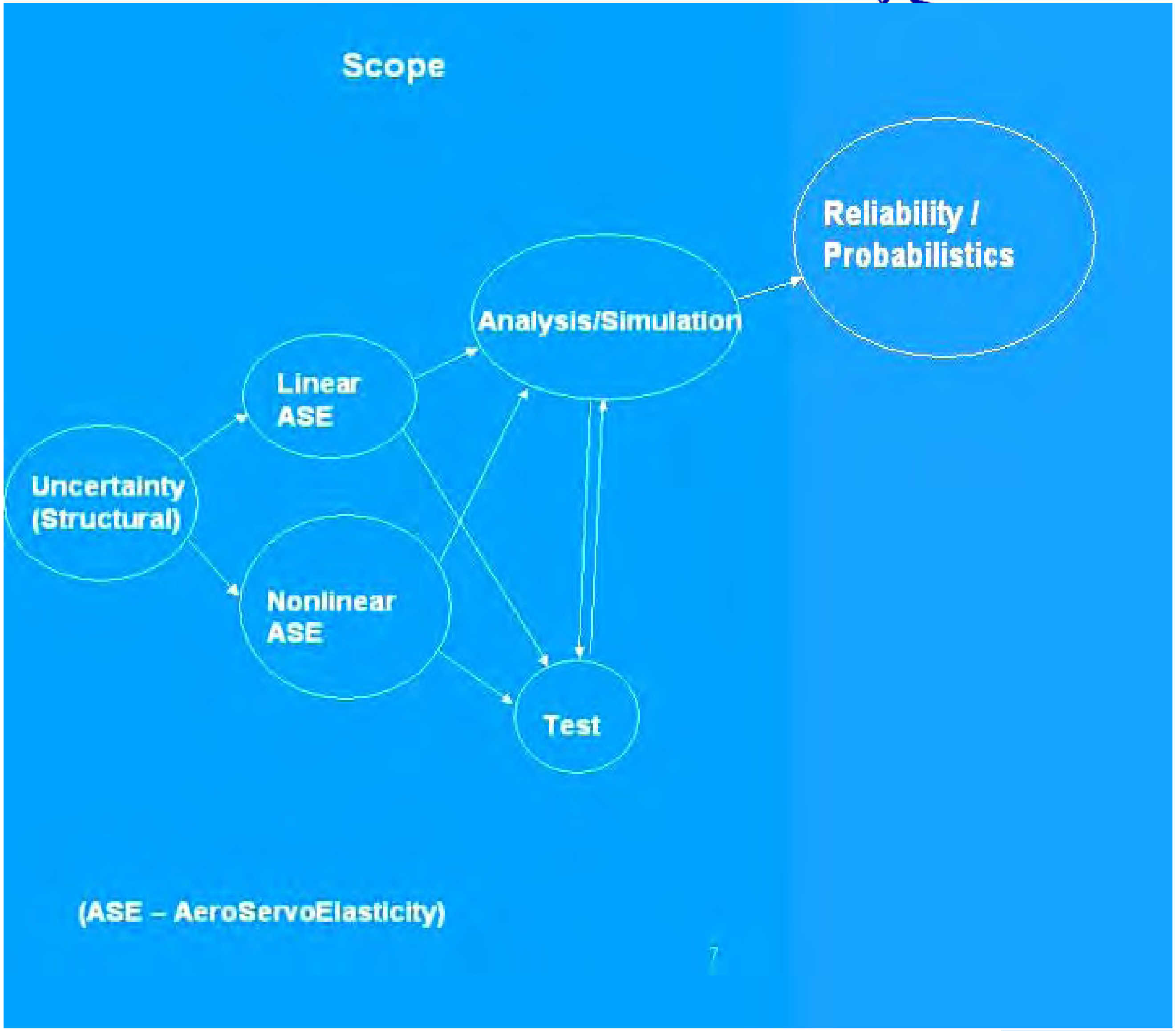
Worst-case scenarios

Effect on design

Effect on maintenance

Approach

Strategy:
From fundamentals
to models & tools
capable of addressing
industry-level
size and complexity



Scope

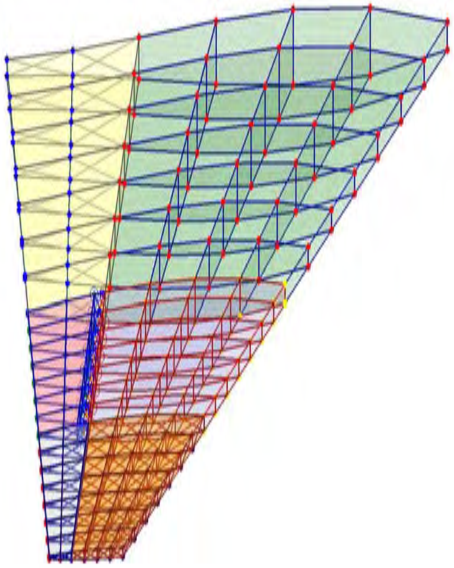
(ASE – AeroServoElasticity)

Linear Behavior Simulation: Automated for Carrying Out Fast Repetitive Analyses

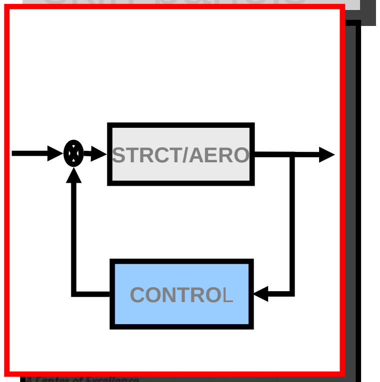
Independently Developed Capability

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

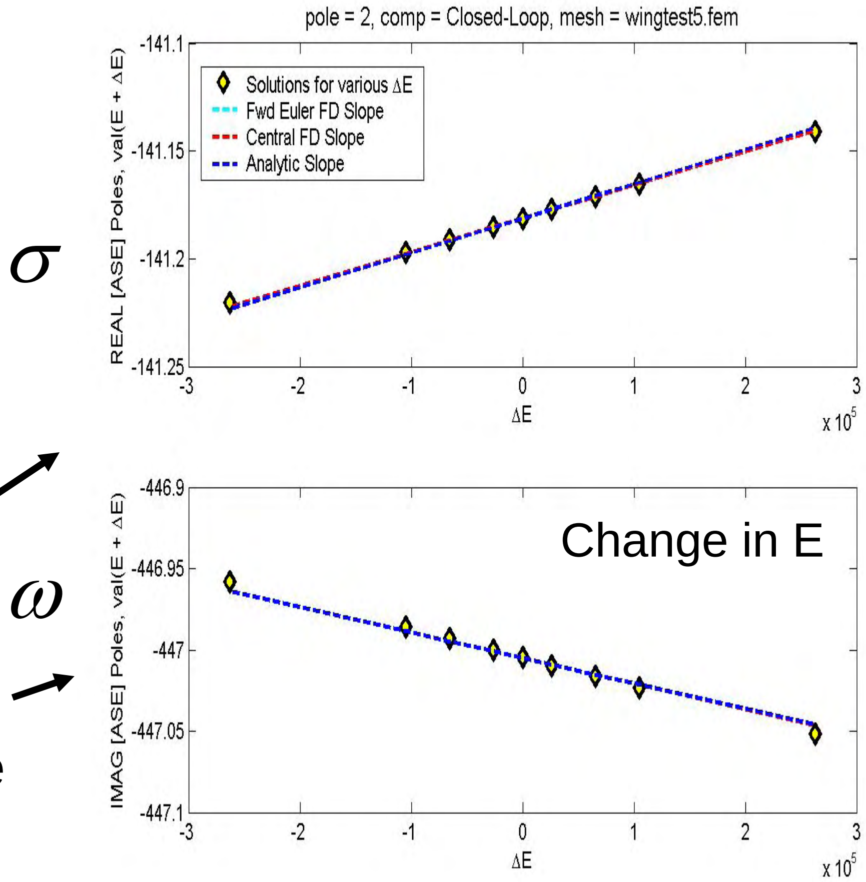
Active Aileron



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



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

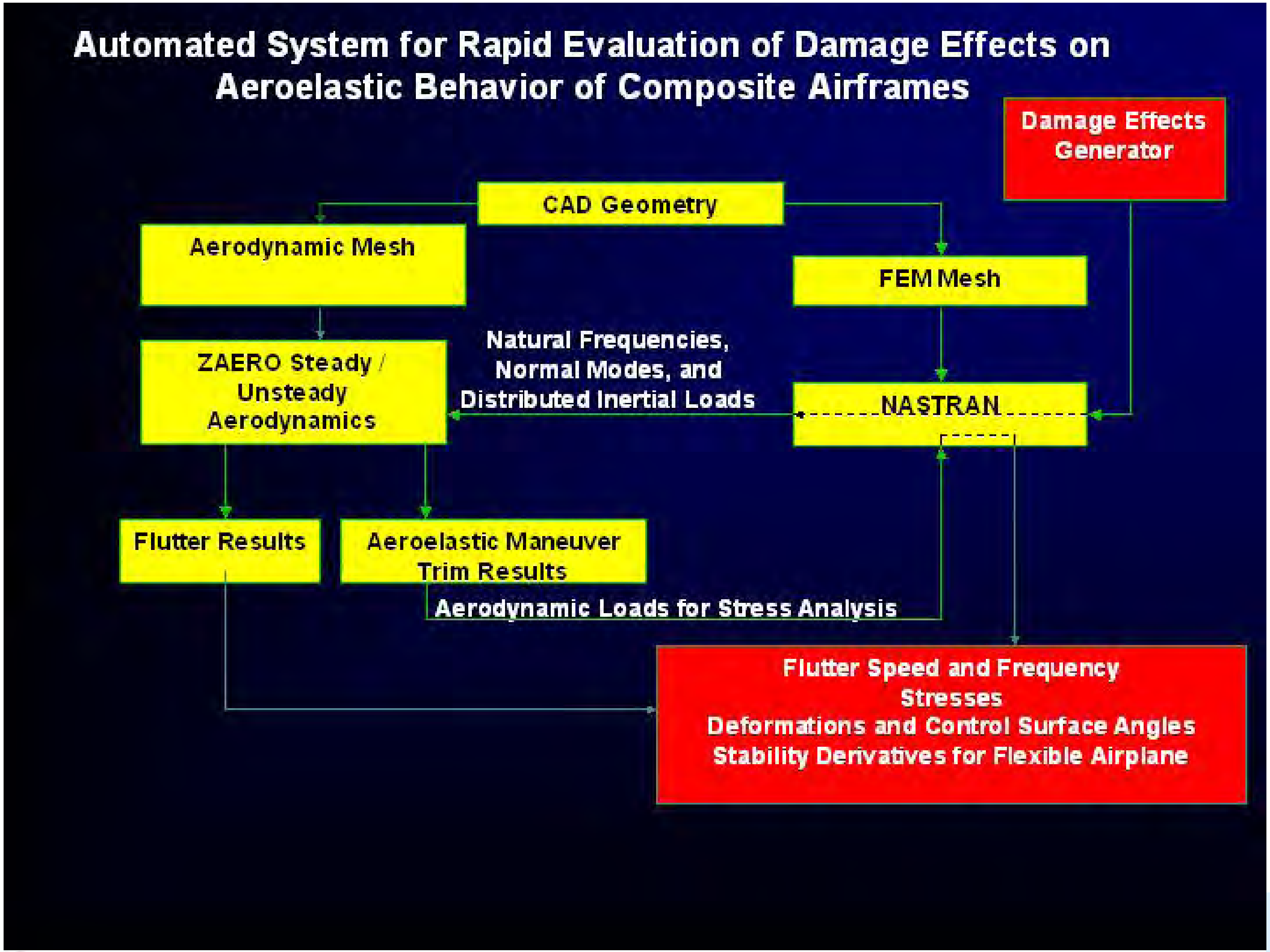


Development of an In-House Design Oriented Aeroservoelastic Modeling Capability (June 2006)

- 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.

Simulation Array based on Commercial Codes

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



Automated System for Rapid Evaluation of Damage Effects on Aeroelastic Behavior of Composite Airframes

Damage Effects Generator

CAD Geometry

Aerodynamic Mesh

FEM Mesh

ZAERO Steady / Unsteady Aerodynamics

Natural Frequencies, Normal Modes, and Distributed Inertial Loads

NASTRAN

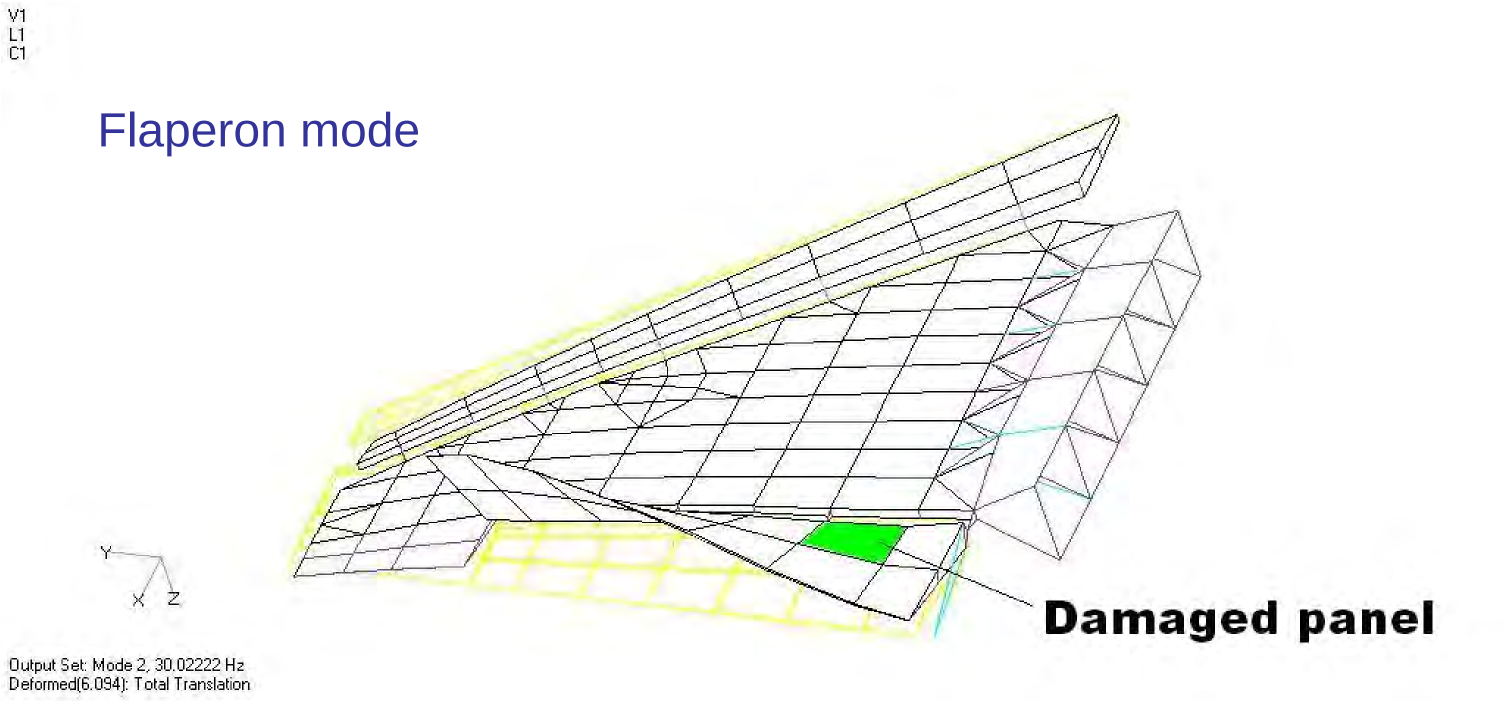
Flutter Results

Aeroelastic Maneuver Trim Results

Aerodynamic Loads for Stress Analysis

Flutter Speed and Frequency
Stresses
Deformations and Control Surface Angles
Stability Derivatives for Flexible Airplane

Modeling Case: The Fighter-Type Wing with Control Surfaces

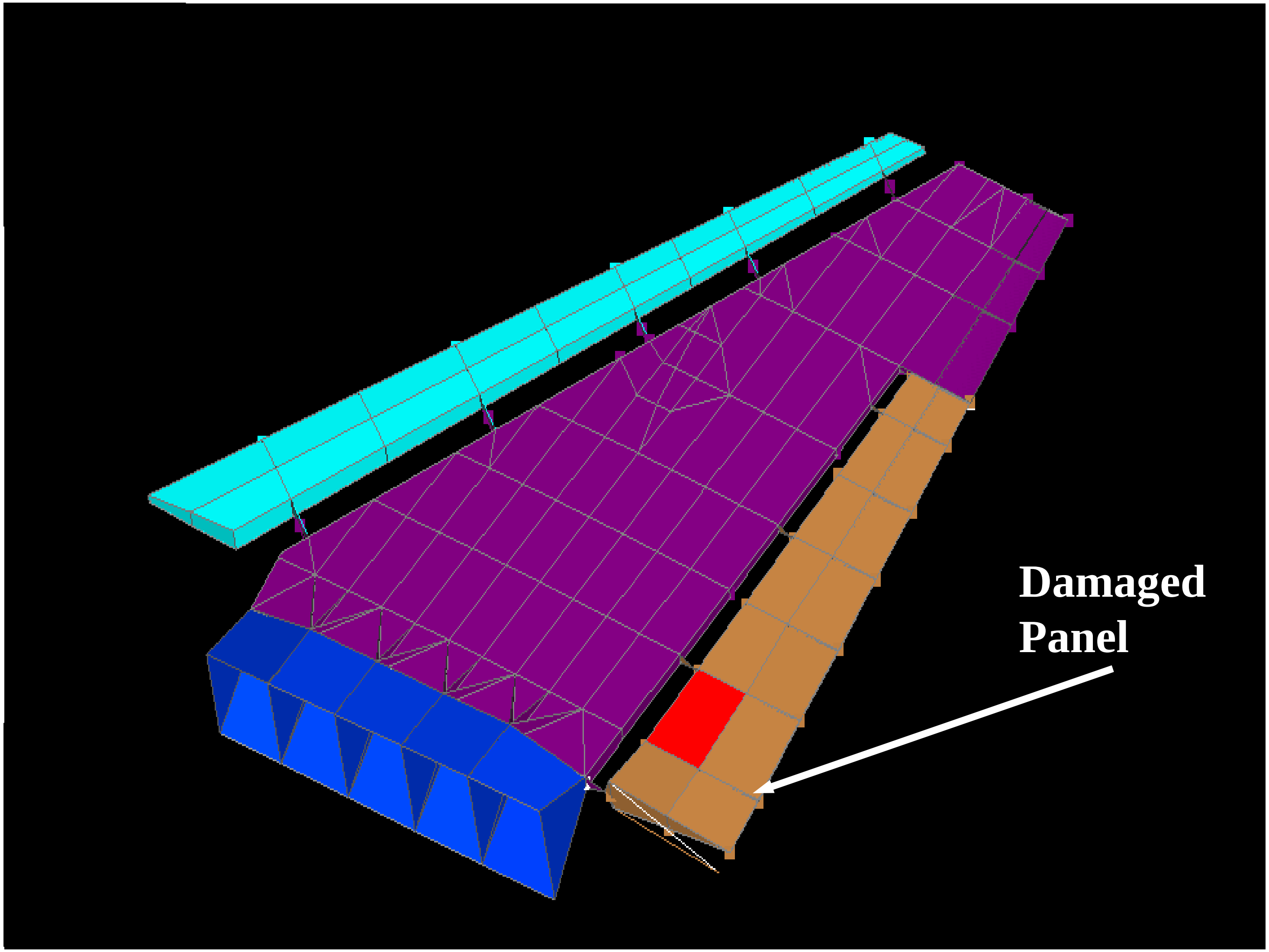


Flaperon mode

Damaged panel

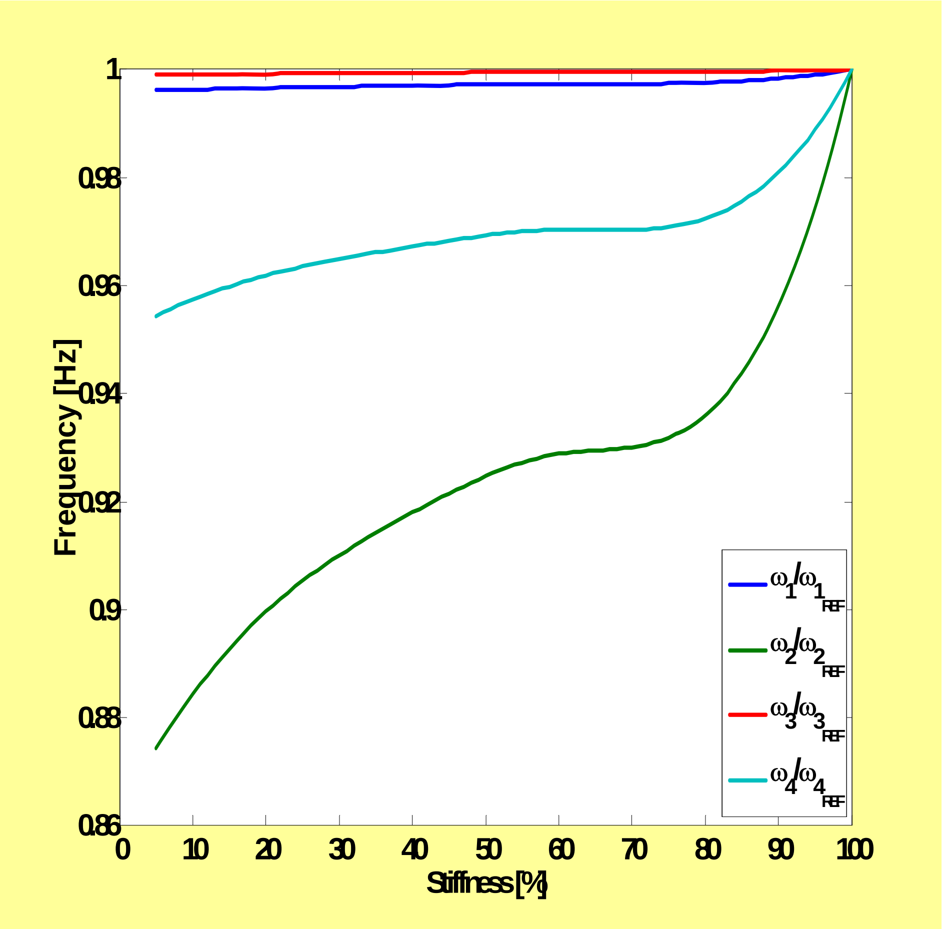
Output Set: Mode 2, 30.02222 Hz
Deformed(6.094): Total Translation

- 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)

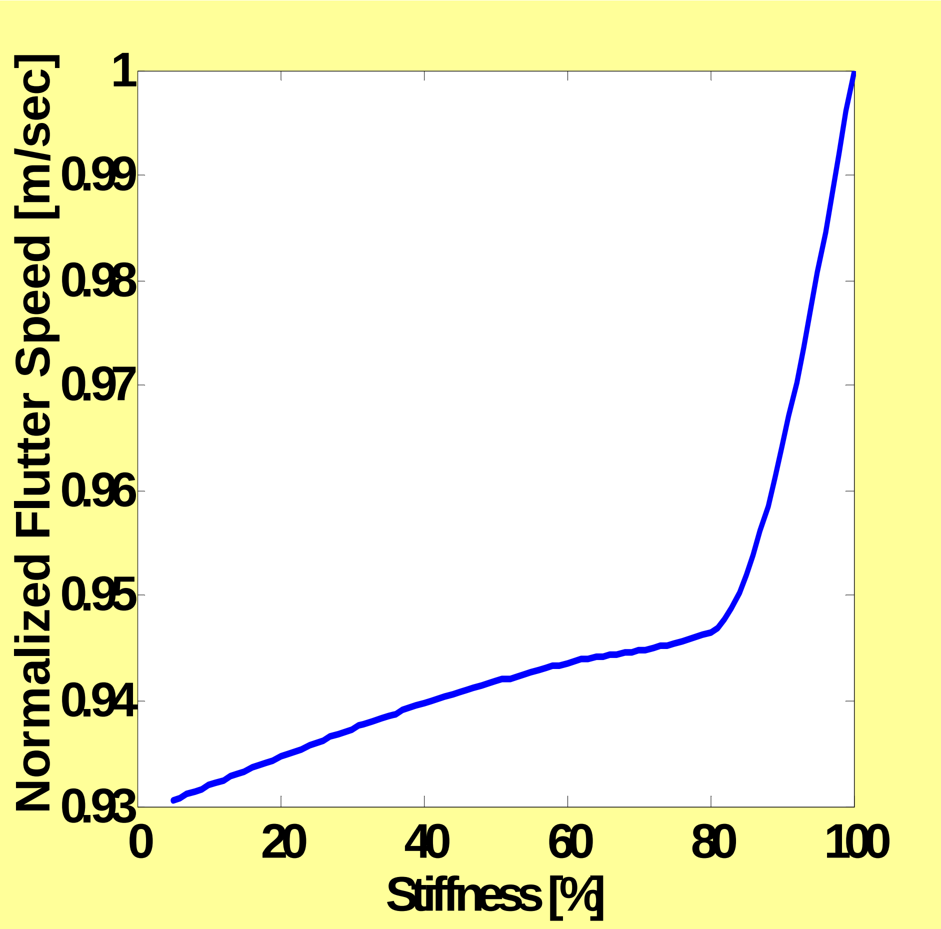


Damaged Panel

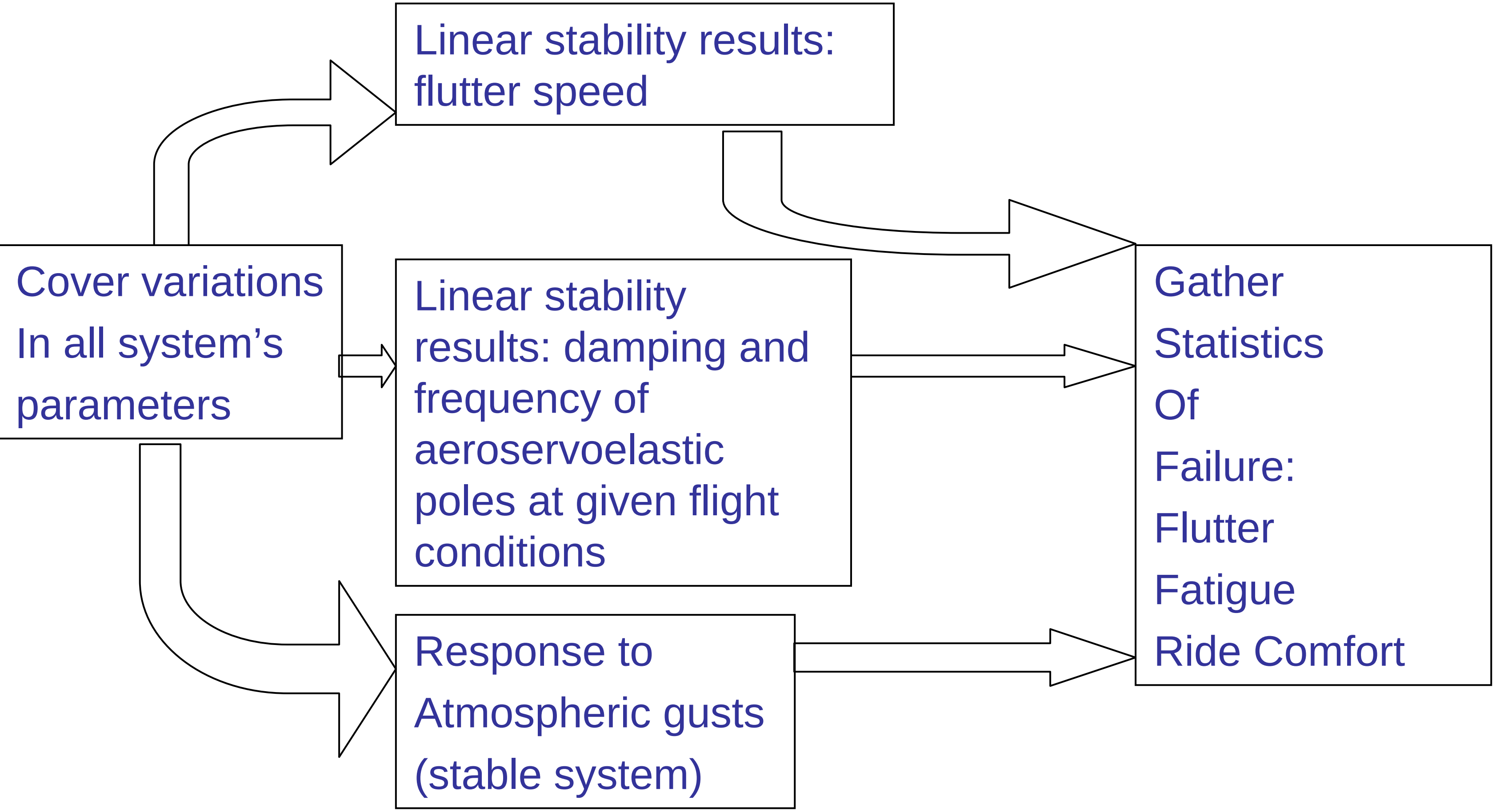
Frequency Behavior vs. Local Stiffness



Flutter Behavior vs. Local Stiffness



Aeroelastic Reliability
Considering Linear Aeroservoelastic Failure Modes



Cover variations
In all system's
parameters

Linear stability results: flutter speed

Linear stability results: damping and frequency of aeroservoelastic poles at given flight conditions

Response to
Atmospheric gusts
(stable system)

Gather
Statistics
Of
Failure:
Flutter
Fatigue
Ride Comfort

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Nonlinear Behavior Simulation: Automated for Carrying Out Fast Repetitive Analyses

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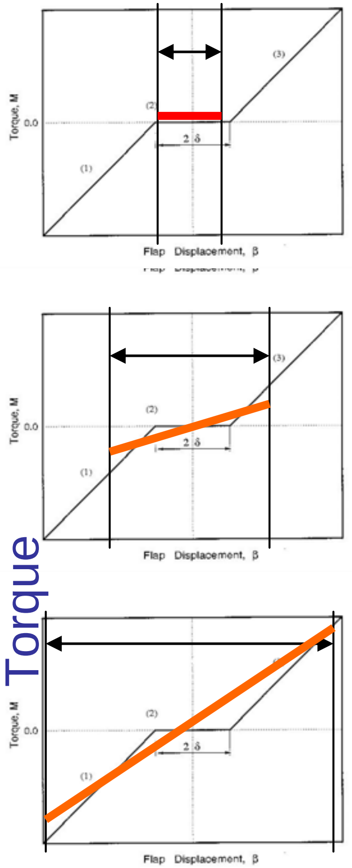
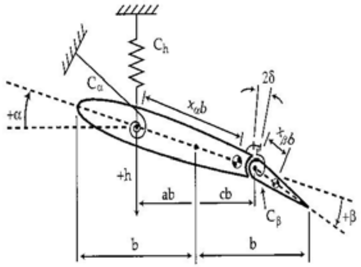
Federal Aviation Administration

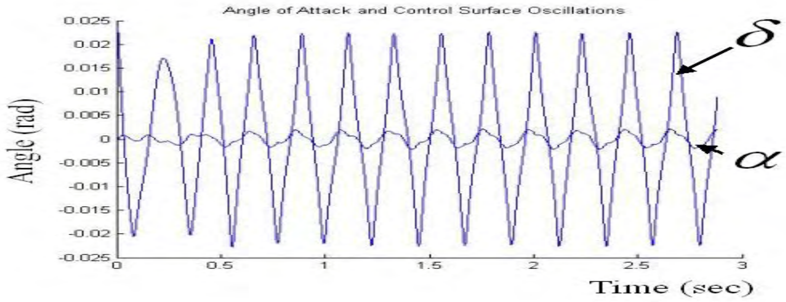
Free-Play Induced LCO: Intuitive Concepts

- 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.



Flap Rotation



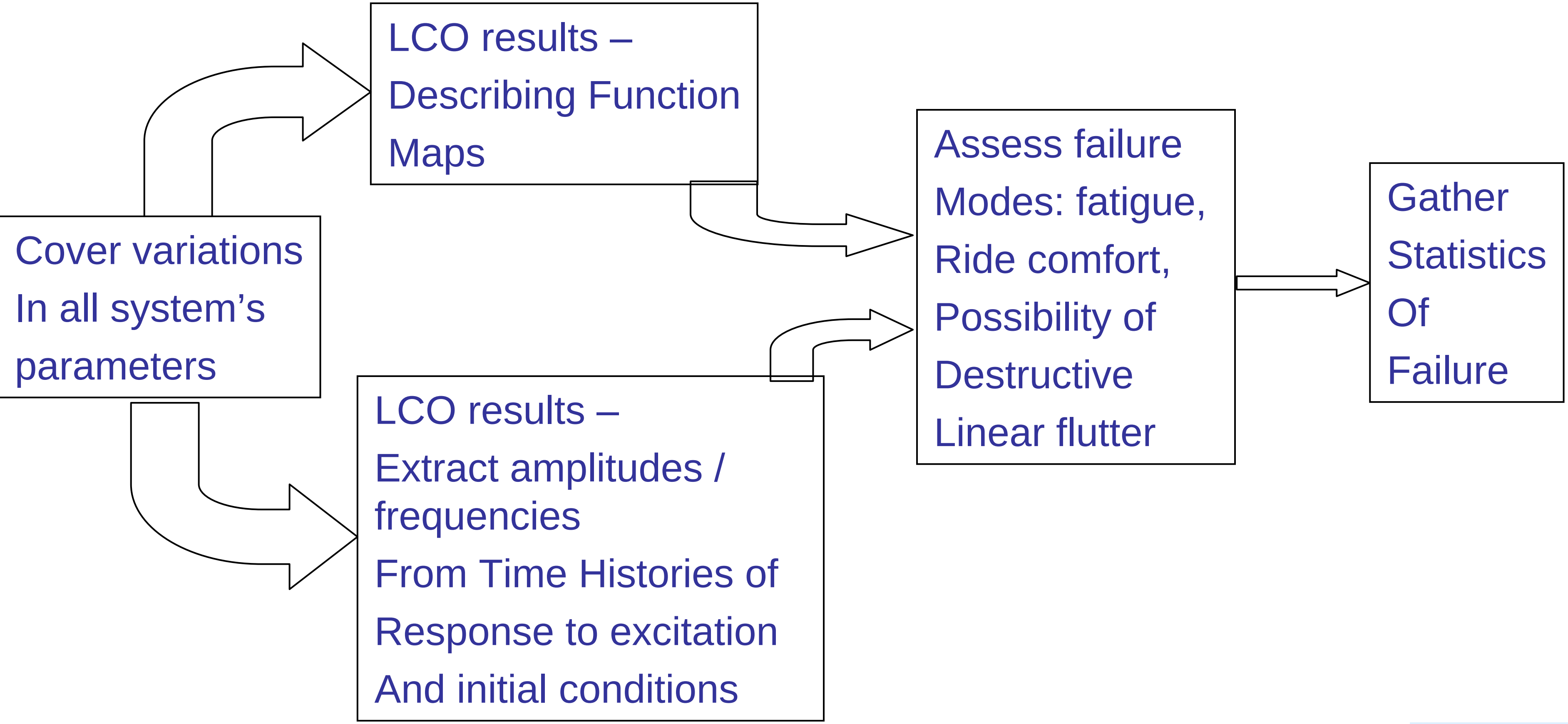


LCO Simulation Methods

- 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.

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

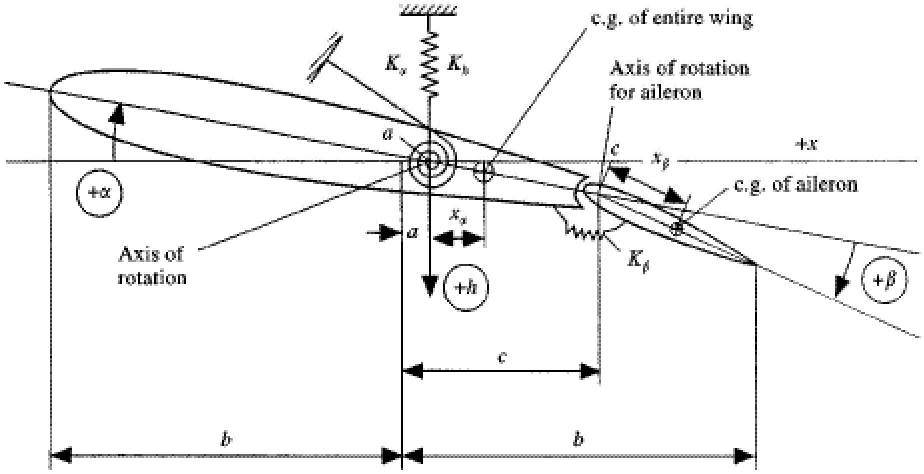
Assess failure
Modes: fatigue,
Ride comfort,
Possibility of
Destructive
Linear flutter

Gather
Statistics
Of
Failure

3DOF aeroelastic system – Probabilistic Analysis

Damage may lead to:

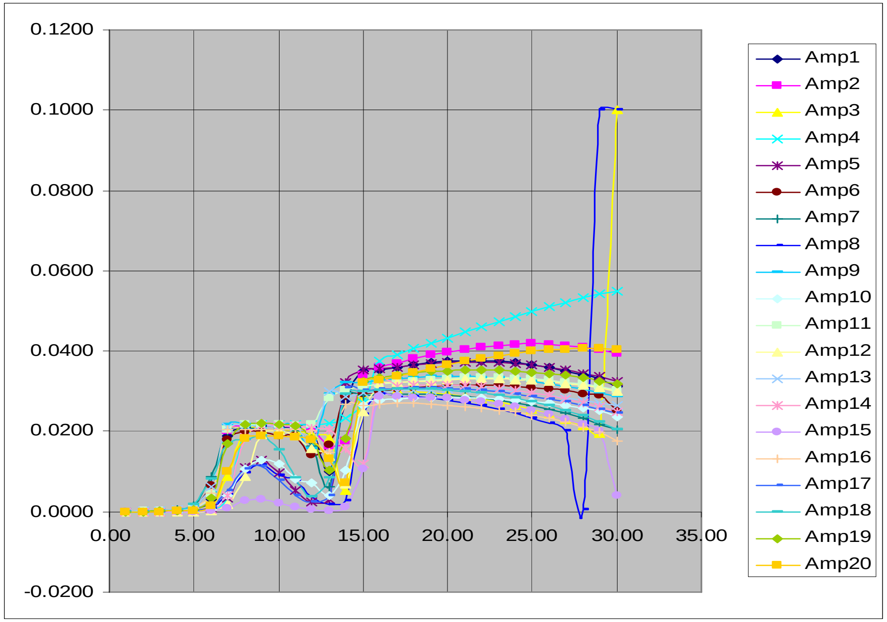
- reduction of stiffness
- moisture absorption and possible changes in properties
- changes in stiffness and inertia properties after damage repair
- irreversible properties degradation due to aging



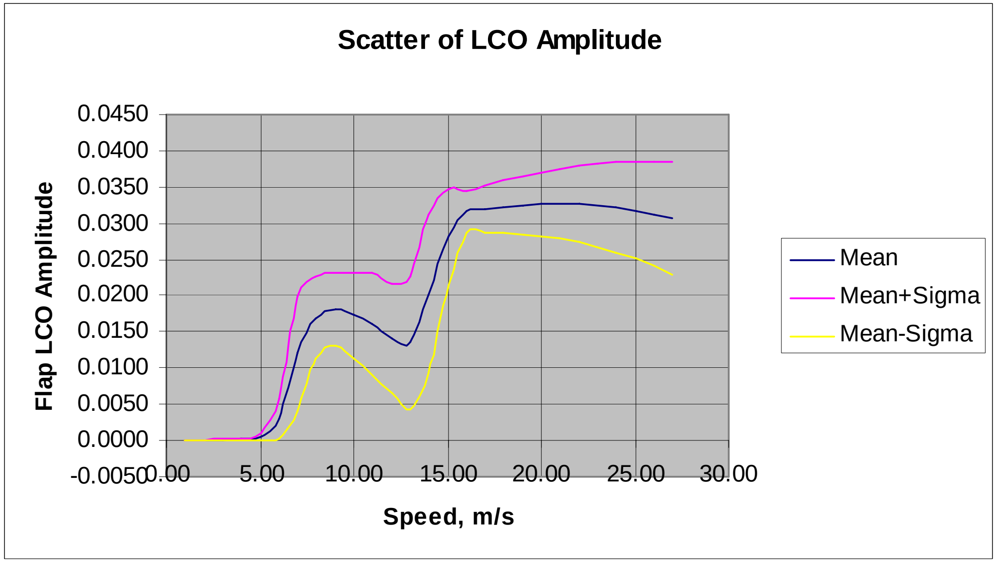
Random Simulation

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

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



Scatter band



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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

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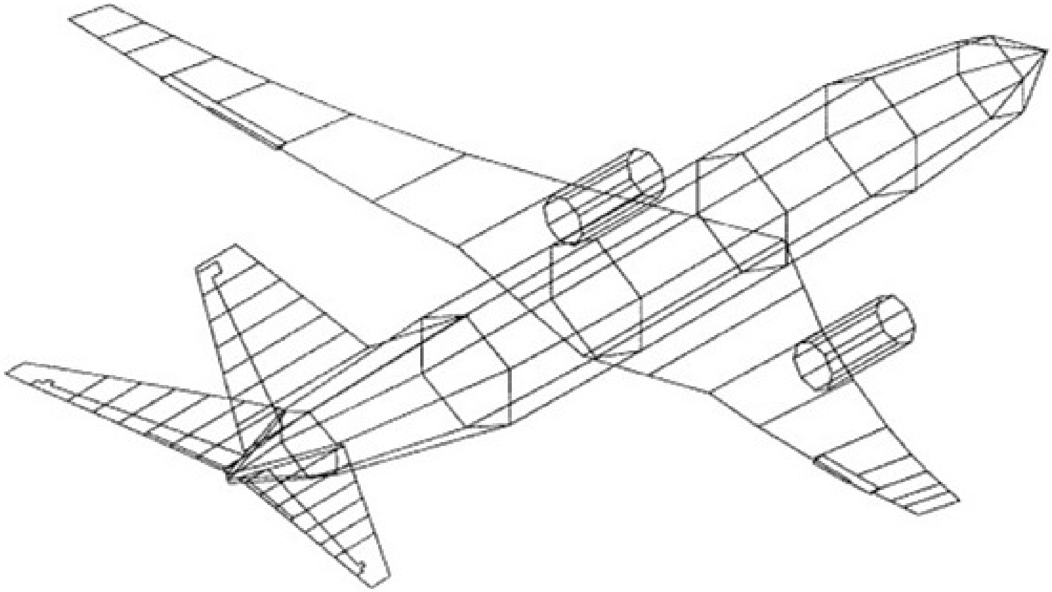
Test-Case Aircraft Used for LCO Studies



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

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

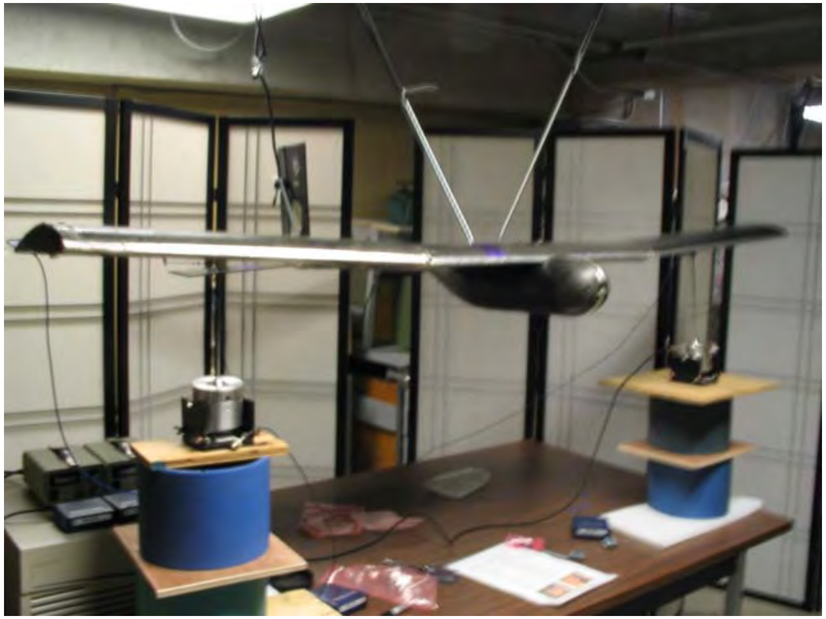
The Boeing Development of Describing Function Tools for MDOF Aircraft

- 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

Development of Experimental Capabilities

- New Modal testing system: arrived and installed.

- Test articles: small composite UAVs & components: nominal and with different types and level of damage.



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

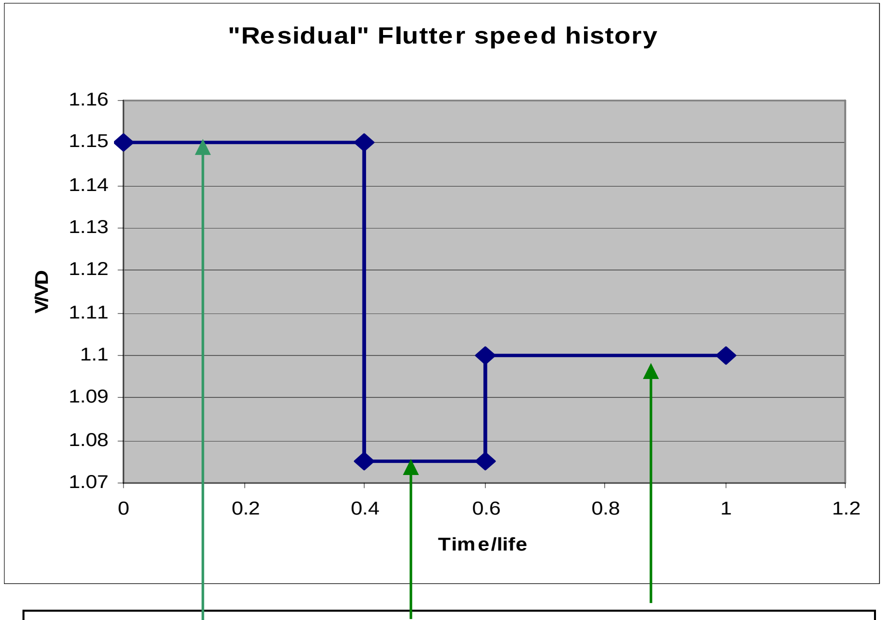
- Use the statistics of the resulting behavior to evaluate aeroelastic reliability

- Use the technology to affect design practices, maintenance procedures, and optimal retrofits

Failure types considered

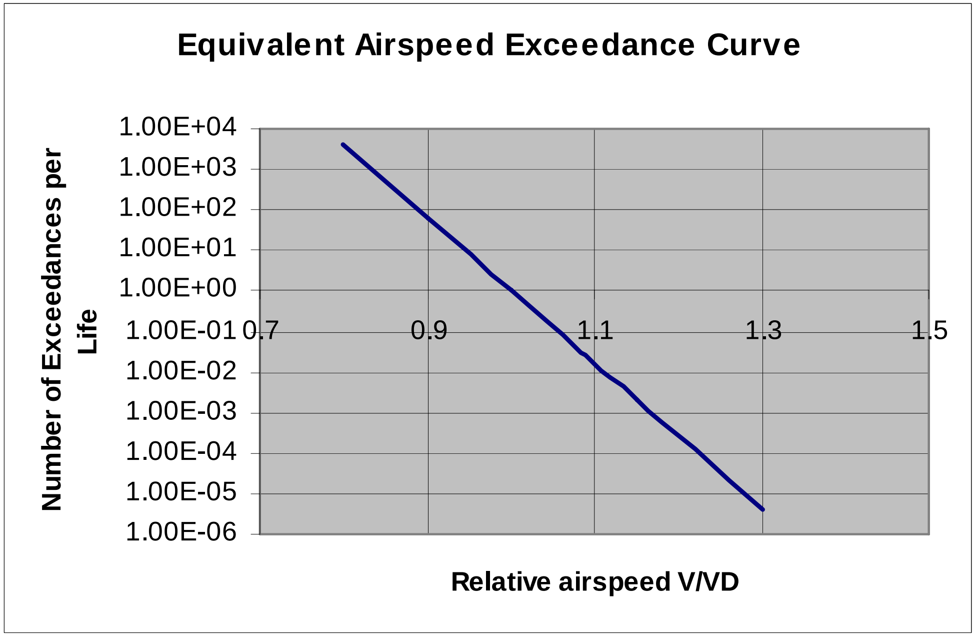
- Excessive deformations
- Flutter: airspeed exceeds the flutter speed of damaged structure
- High amplitude limit cycle oscillations: the acceptable level of vibrations is exceeded

Probability of Failure Formulation 1



Before Damage | With Damage | After Repair

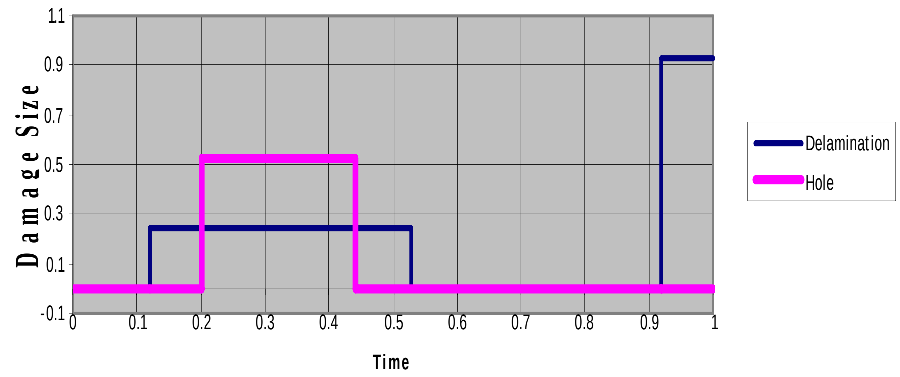
Flutter speed



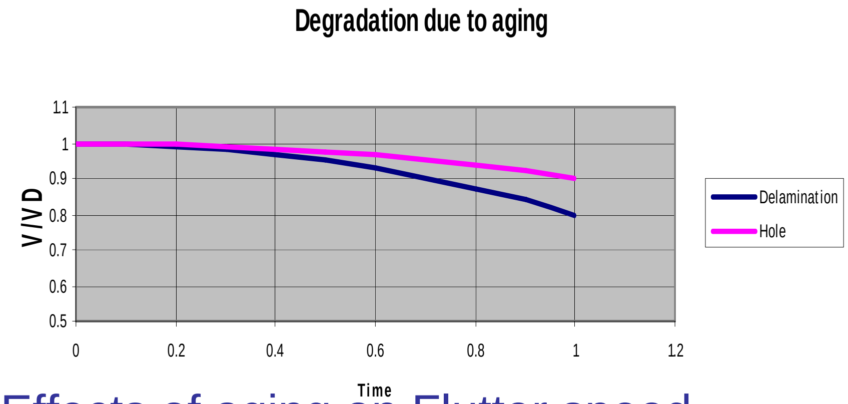
Interval #	Probability of Failure
1 (new structure)	8.0E-04
2 (damaged structure)	8.9E-03
3 (repaired structure)	6.33E-03
Total POF =	1.60E-02

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

Probability of Failure Formulation 2

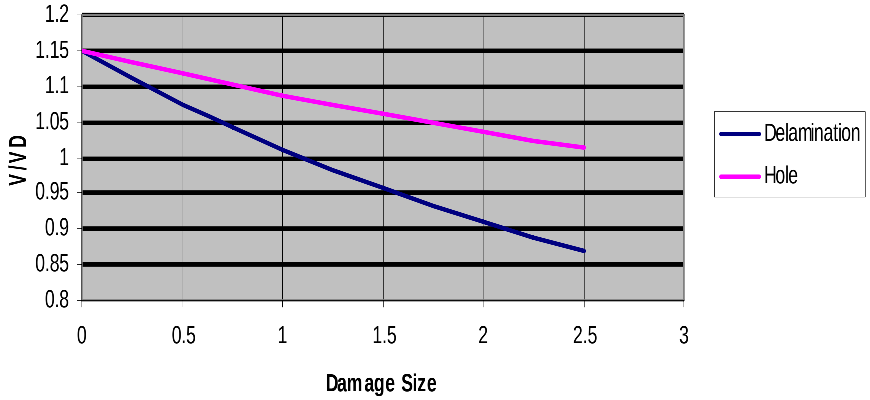


Multiple damages / times / repairs

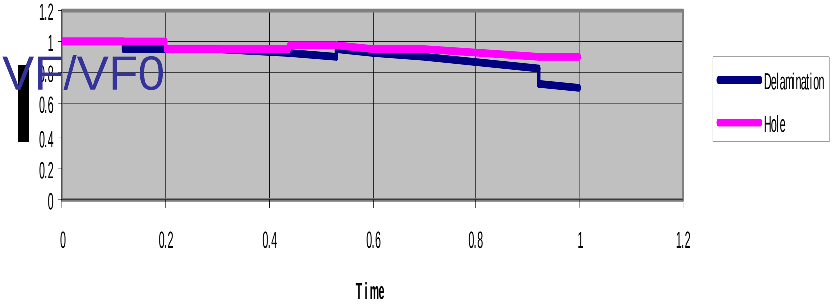


Effects of aging on Flutter speed

Effects of Damage on Flutter Speed



Total degradation for both damages



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.

Conclusion

- 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: Lab is running. Focus: training.
  - 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.