The Effects of Damage and Uncertainty on the Aeroelastic / Aeroservoelastic Behavior and Safety of Composite Aircraft

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  - Gerry Lakin (now retired), FAA Transport Airplane Directorate, Standardization Branch

Scope

- **Motivation & Key Issues**
- **Linear flutter of damaged and uncertain composite airframes**
- **Nonlinear flutter of damaged and uncertain composite airframes:**
  - **LCOs and explosive flutter cases**
- **Probabilistic approach to the aeroelastic reliability of damaged composite aircraft**
- **Automated simulation capabilities: linear and nonlinear**
- **Sensitivity analyses and worst-case scenario identification tools**
- **Monte Carlo simulations**
- **Experimental capabilities development**

The Problem

Damage / Change – Magnitude, location, statistics

↓

Changes in stiffness and mass characteristics

↓

Aeroelastic consequences:

Linear: flutter, dynamic loads

Nonlinear: buckling / flutter interactions, limit cycle oscillations, vibrations

↓ ↓

Worst case scenarios | Reliability

↓ ↓

Design and maintenance practices

Some sources of uncertainty in composite structures

Damage

Delamination

Joint/attachment changes

Debonding

Environmental effects, etc.

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.

Linear Behavior – Classical Flutter

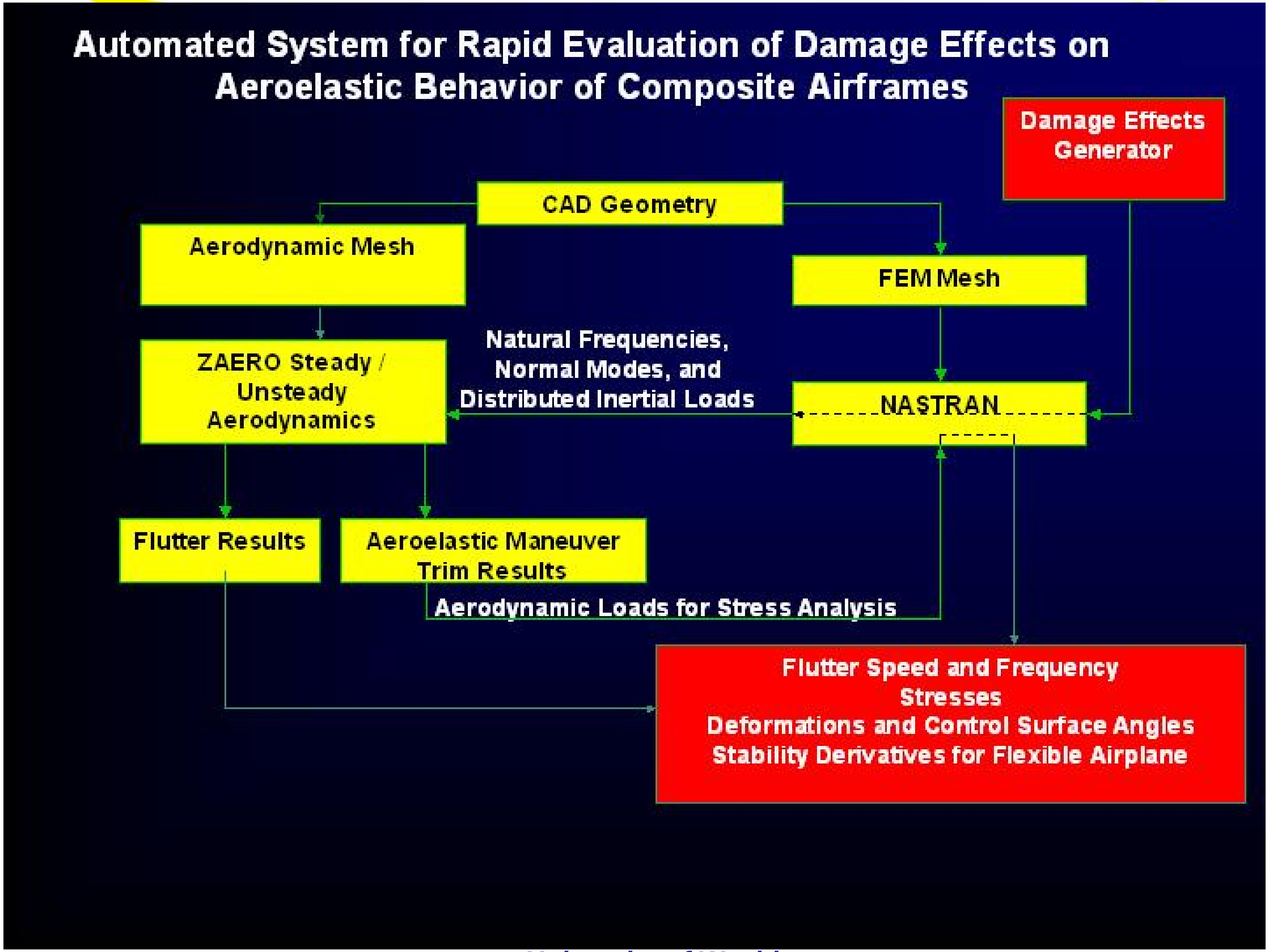
Automated simulations for carrying out fast repetitive analyses of large numbers of parameter variation cases

Goals:

Identify worst case damage and structural variation scenarios and critical areas

Provide flutter information for Monte Carlo (or other) statistical simulations

Automated System for Calculating Flutter Speeds of Large Numbers of Airframe Structural Variations



Reduction in flutter speed on a TE flaperon due to loss of local panel stiffness due to damage (top covers)

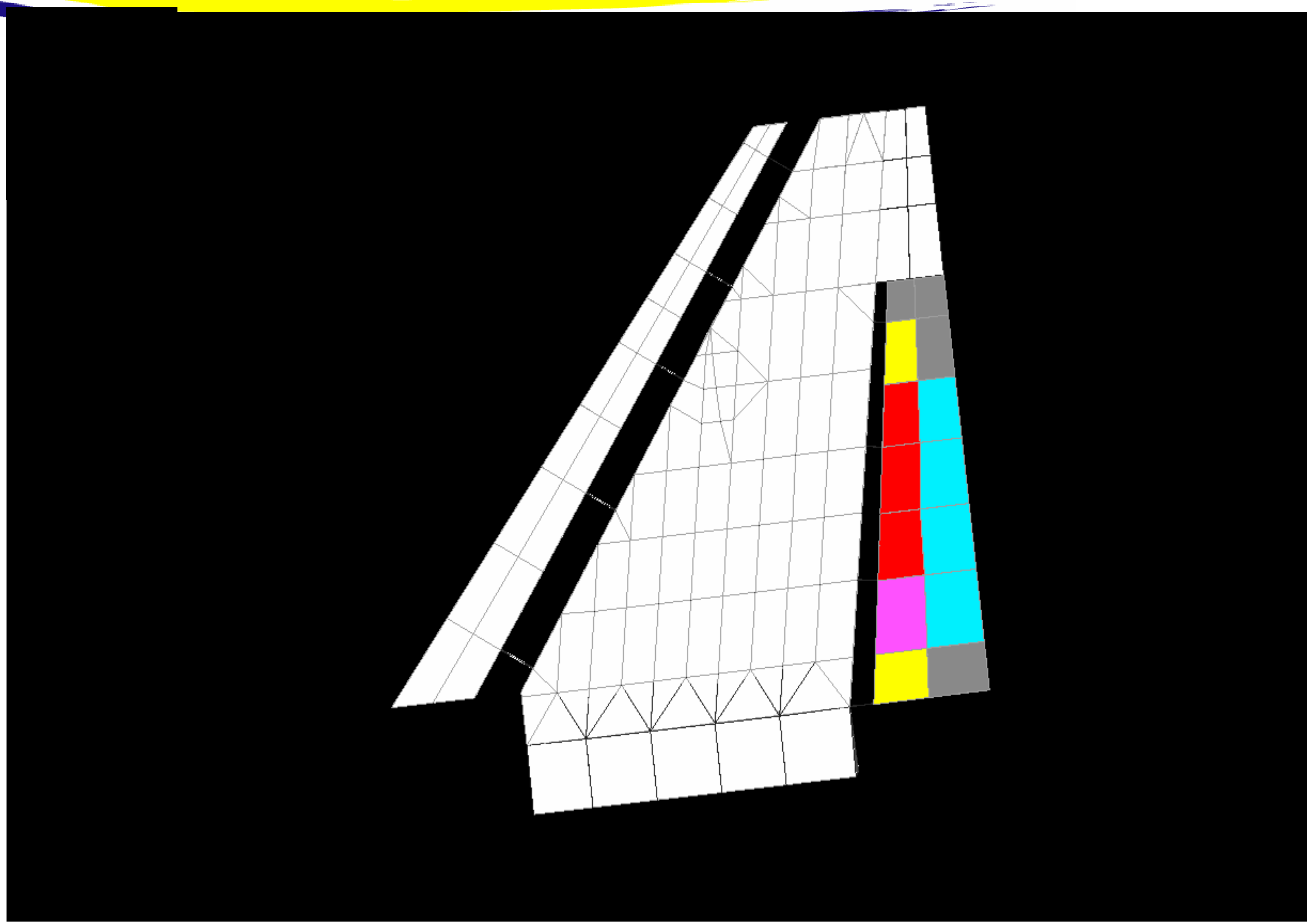
~10%

~8%

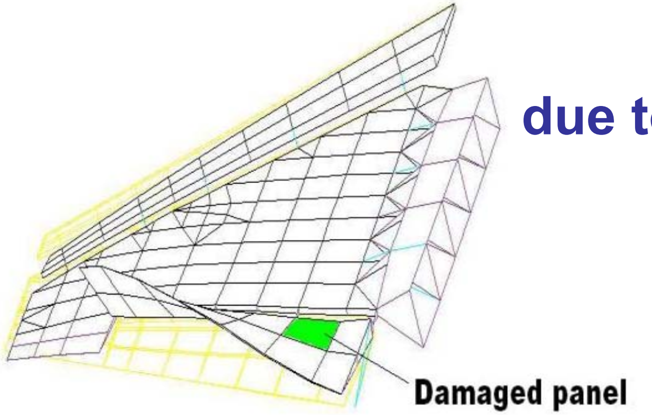
~4%

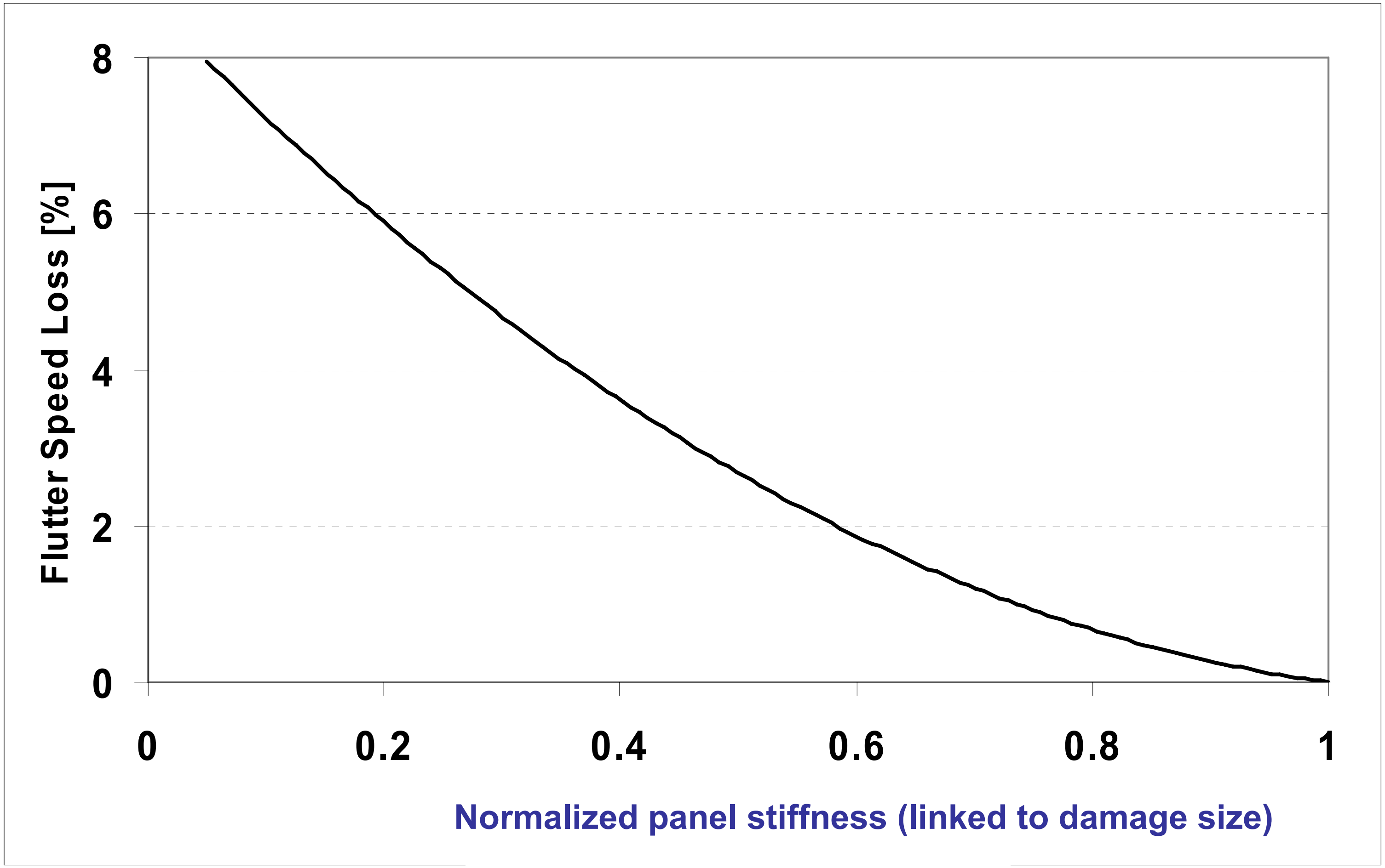
~1-2%

<1%



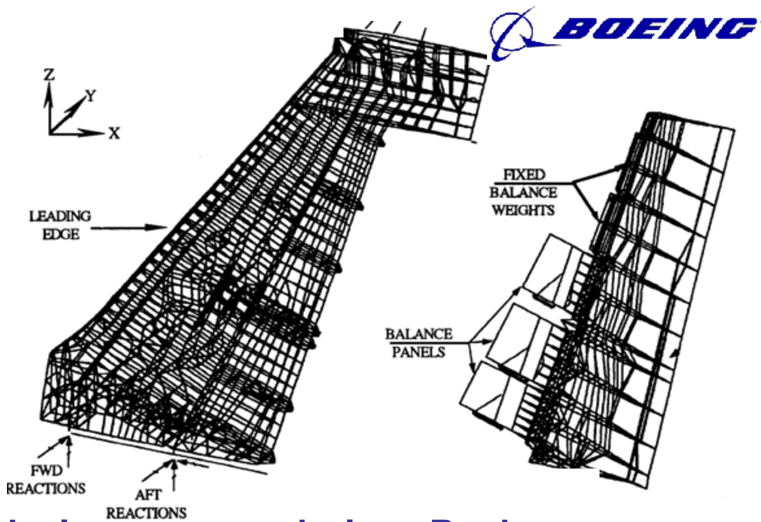
Flutter speed degradation due to loss of stiffness of a single upper skin panel on a TE flaperon





Linear flutter of damaged and uncertain composite airframes

- Computational array of industry standard tools – ready and tested
- Used for flutter damage-sensitivity studies of fighter wing / flaperon system
- Used for flutter-failure reliability studies of fighter wing / flaperon system
- Ready for Boeing generic composite vertical tail / rudder system NASTRAN model
- Boeing NASTRAN model will be provided soon (in a way clear of proprietary and ITAR limitations), and used in flutter sensitivity-to-damage and reliability studies.



A typical passenger airplane Boeing vertical tail / rudder NASTRAN model

Automated nonlinear aeroelastic behavior simulations

The control surface free-play problem:

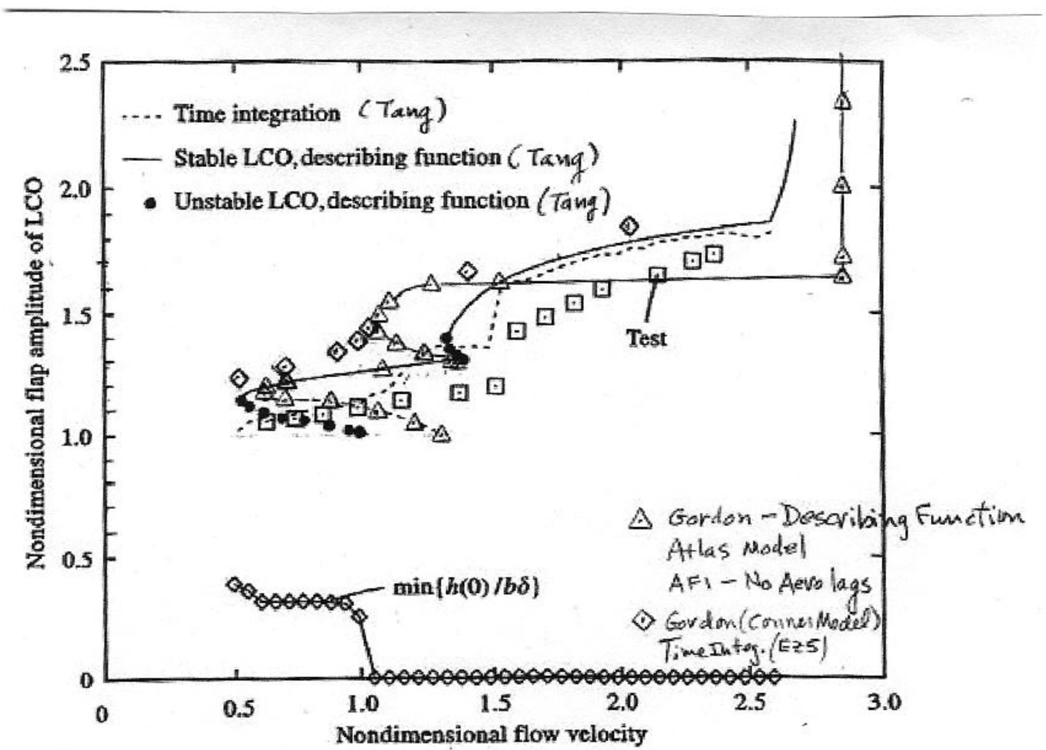
- Simulate wing / control surface systems with control system free-play over a range of parameter variations to capture LCO (limit cycle oscillations) behavior automatically
- Use in Monte Carlo simulations to obtain behavior statistics and reliability estimates
- Contribute to the aeroelastic design of currently emerging composite airframe passenger aircraft

The Damaged airframe problem:

- Simulate nonlinear aeroelastic behavior due to nonlinear local structural effects due to local damage or degradation
- Use to identify possible damage mechanisms that can lead to such behavior
- Use in Monte Carlo simulations and reliability studies

LCO simulation capabilities status

- **Automated LCO simulation capabilities for 2D prototype airfoil / control surface systems –**
  - completed
  - validated against experimental results
  - Used in Monte Carlo simulations to obtain response statistics due to a large number of system's parameter uncertainties



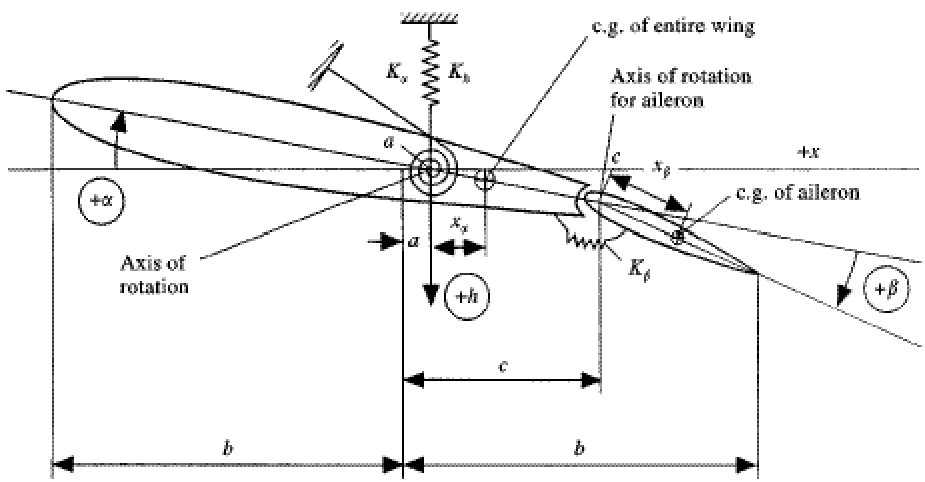
Boeing - UW

n

3DOF aeroelastic system

Damage may result in:

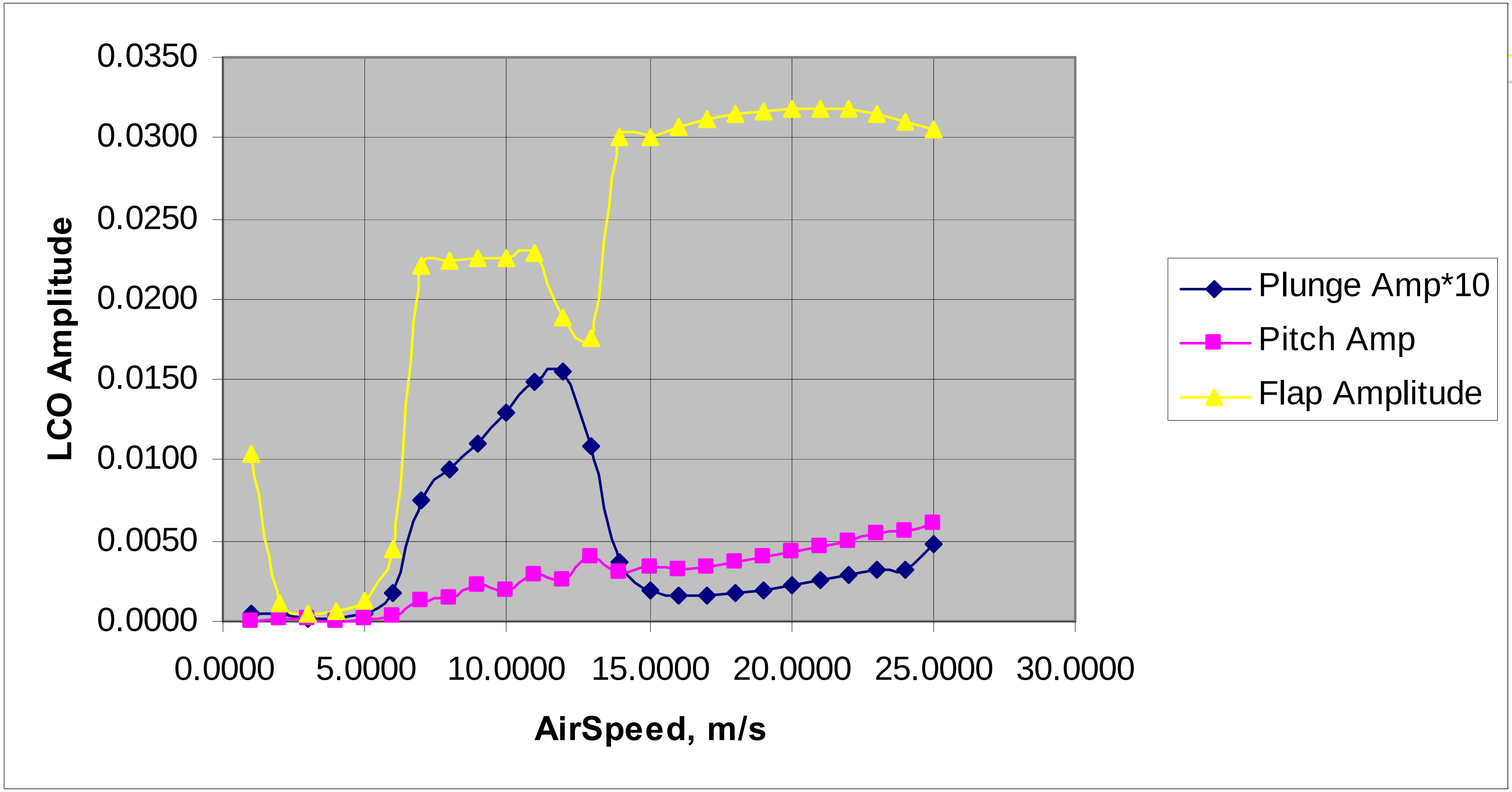
- **reduction of stiffness**
- **moisture absorption and possible changes in properties**
- **changes in stiffness and inertia properties after damage repair**
- **irreversible properties degradation due to aging**



Random Simulation

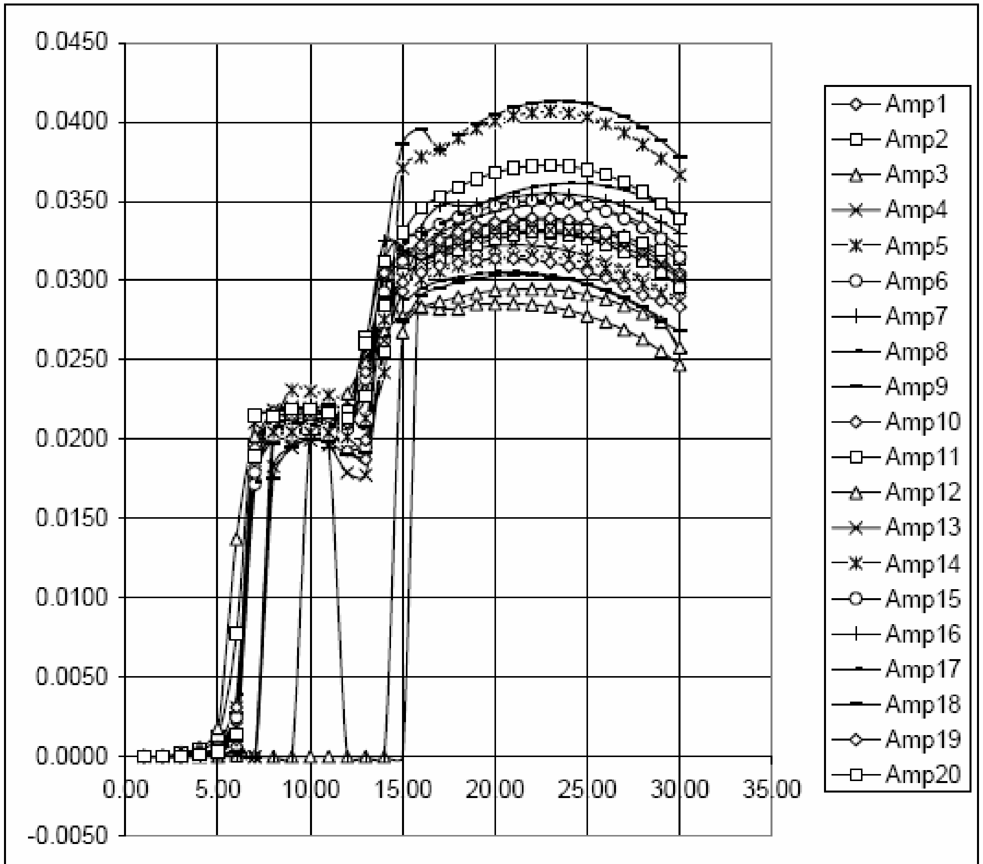
- **5 geometrical parameters**
- **6 inertia parameters**
- **4 stiffness parameters**
- **3 structural damping parameters**
- **2 free-play parameters**
- **air density, airspeed, discrete gust velocity**

LCO Study of wing / control surface 3dof system: nominal parameters



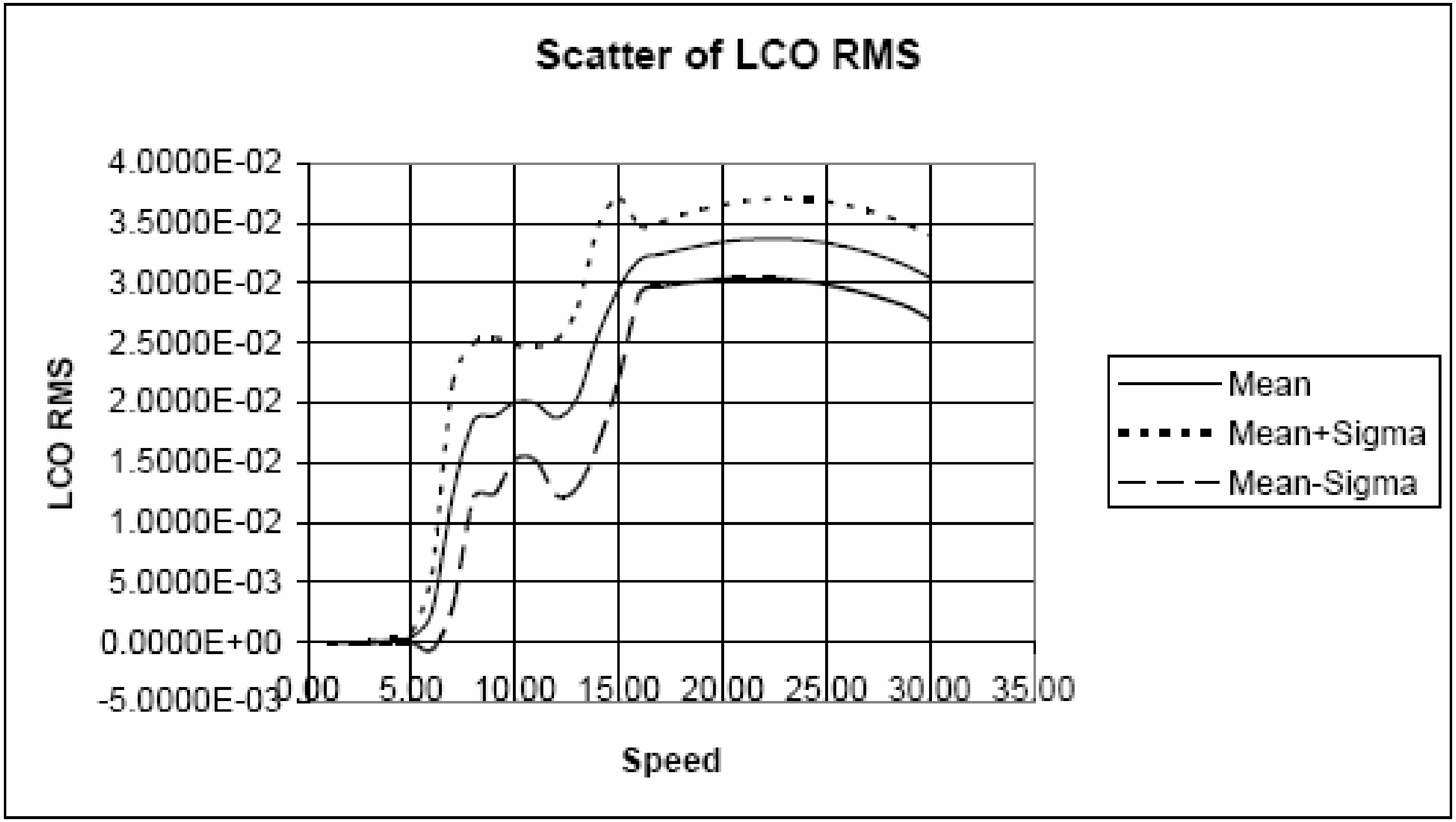
Variation of LCO amplitude in different degrees of freedom as function of flight (wind tunnel) speed (note the complex nonlinear nature of the LCO response

LCO study: Monte-Carlo results wing / control surface system



Distribution of LCO aileron amplitudes in a sample of time response simulations (as a function of speed).

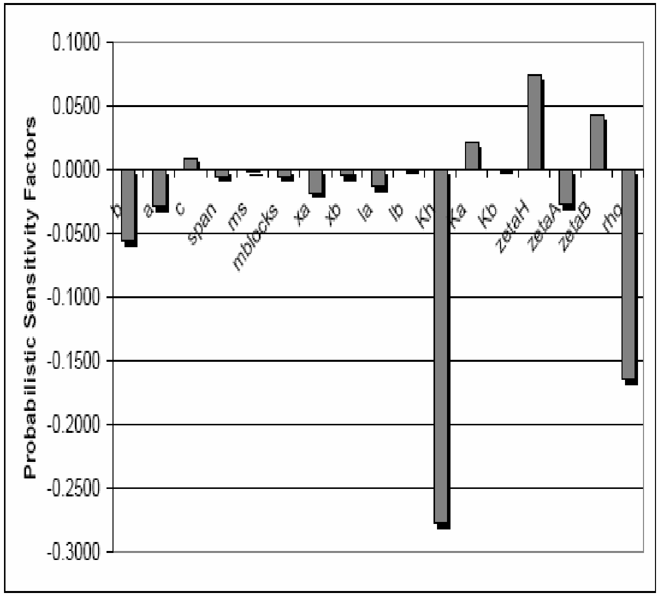
LCO study of wing / control surface system: scatter band



3DOF Problem: Flutter Speed Sensitivity Study

Variable	Description	PDF	mean	C_v
b	Semi-chord	Normal	0.127 m	0.2%
a_d	Elastic axis, m	Normal	-0.0635	1%
c_d	Hinge line, m	Normal	0.0635	1%
span	Span	Weibull	0.52 m	0.2%
x_a	c.g. of entire wing	Normal	0.0551 m	2%
x_b	c.g. of aileron	Normal	0.0025 m	2%
Ia	Moment of inertia of entire section	Normal	0.01347 kg m^2	4%
Ib	Moment of inertia of aileron-tab	Weibull	0.0003264 kg m^2	4%
ms	Mass of section	Normal	1.558 kg	0.2%
m_{blocks}	Mass of support blocks	Normal	0.9497 kg	0.2%
Kh	Stiffness in deflection (per span)	Normal	2818.8 kg/m/s^2	3%
Ka	Torsion stiffness (per span)	Normal	37.3 kg m/s^2	4%
Kb	Torsion stiffness (per span)	Normal	3.9 kg m /s^2	4%
zetaH	Plunge Damping	Normal	5.6500E-04	5%
zetaA	Rotation Damping	Normal	8.1300E-04	5%
zetaB	Aileron Damping	Normal	5.7500E-04	5%
Rho	air density	Normal	1.225 kg/m^3	1.5%

Probabilistic Sensitivity Factors for 3DOF 2D System (Normalized Regression Coefficients)

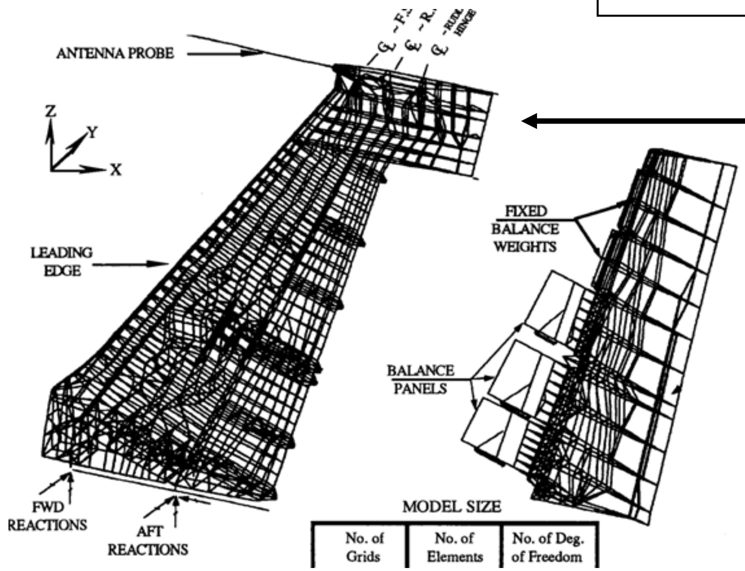


Simulation of structurally nonlinear aeroelastic behavior due to distributed large deformations and damage in composite airframes

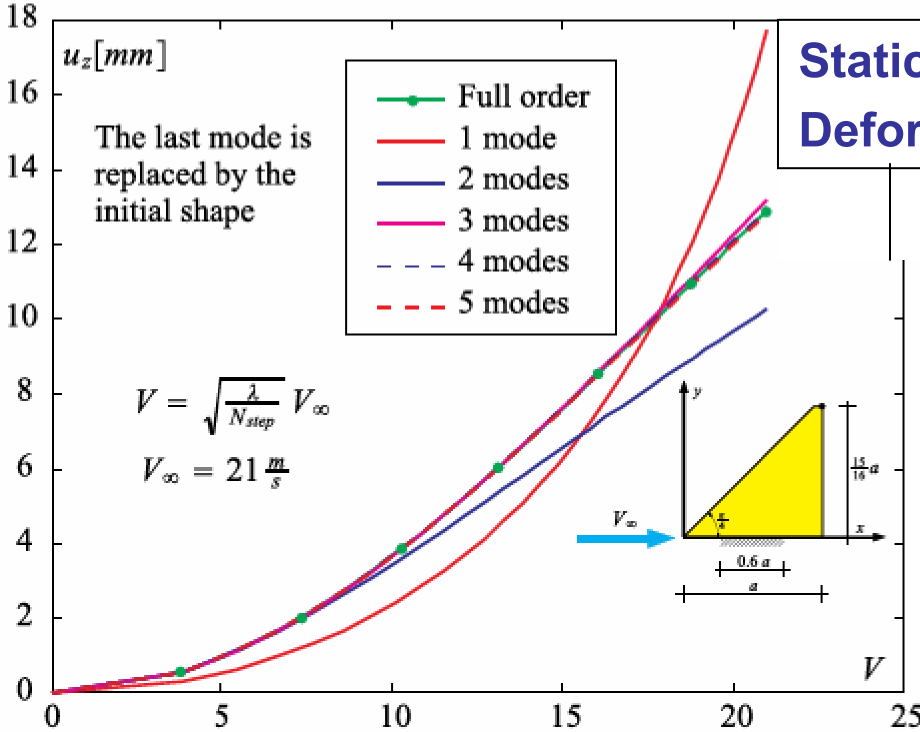
- **Status:**
  - Development complete
  - Major theoretical issues resolved
  - Validation using experimental and computational results for a simple geometrically nonlinear test wing model – complete

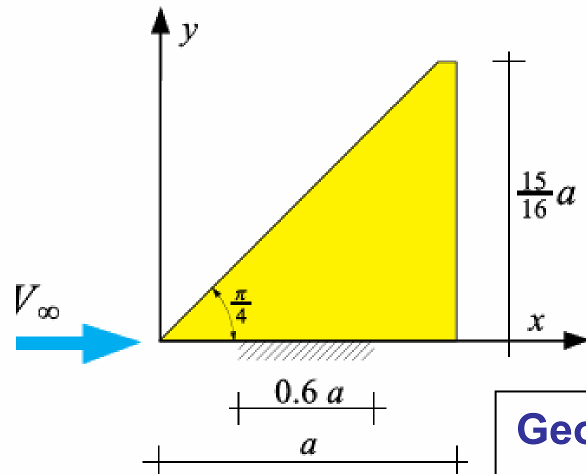
Possible large deformation

Possible nonlinear local behavior due to damage or degradation



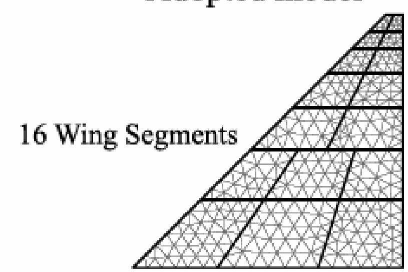
Static aeroelastic behavior
Deformation vs speed



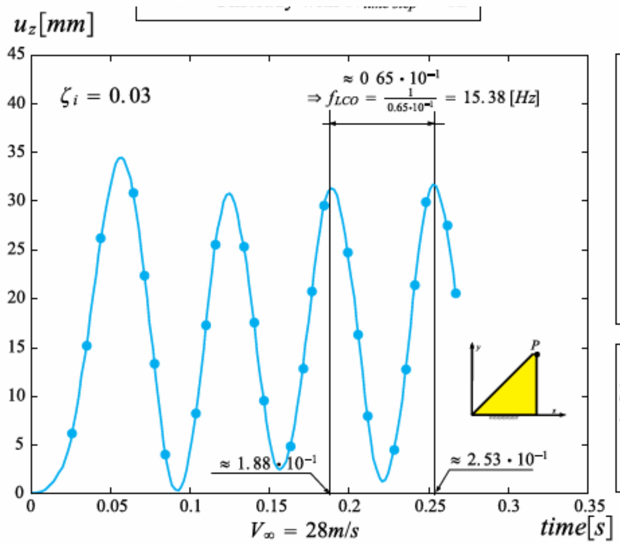


Adopted model

Geometrically Nonlinear wing



Structural mesh



Aerodynamic generalized matrices approximated using 20 modes.
Six lag terms have been used

Reference damping matrix defined using 20 modes

Method 1 has been used and the last mode adopted for the aerodynamics has been replaced with the shape corresponding to $\alpha = 1°$

$V_F^{linear} = 23.7\,[m/s]$	$f_F^{linear} = 14.0\,[Hz]$
$V_F^{consistent} = 24.5\,[m/s]$	$f_F^{consistent} = 14.5\,[Hz]$
$V_F^{ADW} = 24.5\,[m/s]$	$f_F^{ADW} = 14.5\,[Hz]$

ADW = Attar, Dowell, White (experimental result)

Figure 20. The delta wing. Post-flutter LCO (tip displacement). $V_\infty = 28m/s$.

Dynamic aeroelastic behavior
Amplitude of oscillation
At a speed beyond the linear flutter speed

Numerical simulation capabilities for structurally nonlinear aeroelstic problems using detailed industry-standard modeling techniques – recent papers

- Demasi, L., and Livne, E., “Dynamic Aeroelasticity of Structurally Nonlinear Joined Wing Configurations Using Linear Modally Reduced Aerodynamic Generalized Forces”, AIAA Paper 2007-2105, 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Honolulu, Hawaii, Apr. 23-26, 2007

- Demasi, L., and Livne, E., “Performance of Order Reduction Techniques in the Case of Structurally Nonlinear Joined-Wing Configurations”, AIAA Paper 2007-2052, 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Honolulu, Hawaii, Apr. 23-26, 2007

- Note: the joined-wing configuration (with structural composites) has structural nonlinearities of both local and global nature. It was used to validate the new codes, but the methodology is general and applies to any nonlinear composite structure

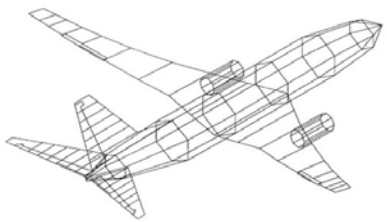
Numerical simulation capabilities for structurally nonlinear aeroelstic problems using detailed industry-standard modeling techniques – localized nonlinearities

- Local structural nonlinearity due to local damage mechanisms
- Develop efficient Finite Element (NASTRAN-like) modeling for geometrically nonlinear thin-walled composite airframes
- Couple with industry-standard linear unsteady aerodynamics (Doublet Lattice, ZAERO, etc.) and industry standard aeroelasticity / controls integration practices
- Major parts completed. In progress.

The Boeing LCO Test Case Study

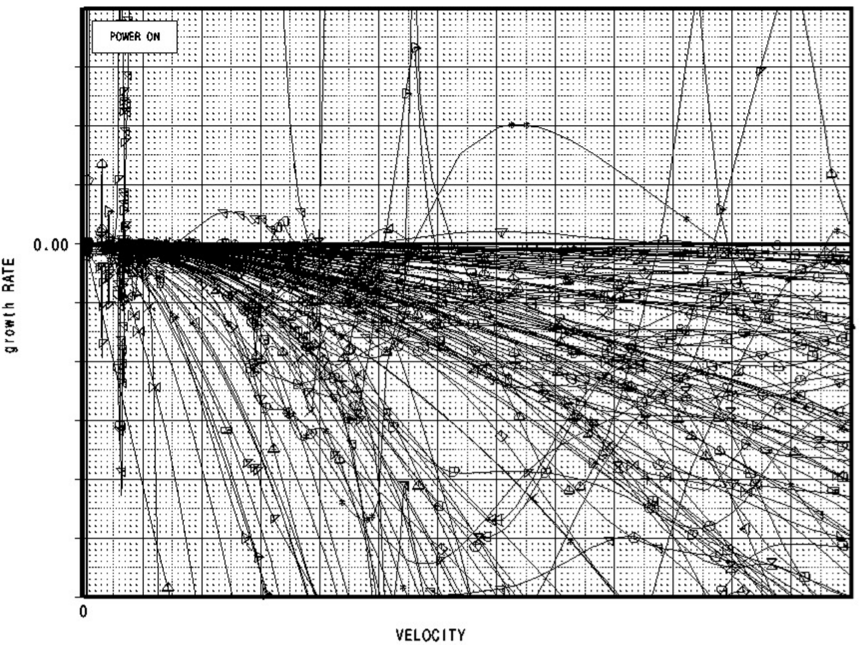
- Test case uses representative airplane model with associated real-world complexity
- Test case does not reflect any service configuration / flight conditions
- Test case used freeplay values far in excess of any maximum in-service limits

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

The challenging case of many degrees of freedom and closely-spaced Frequencies



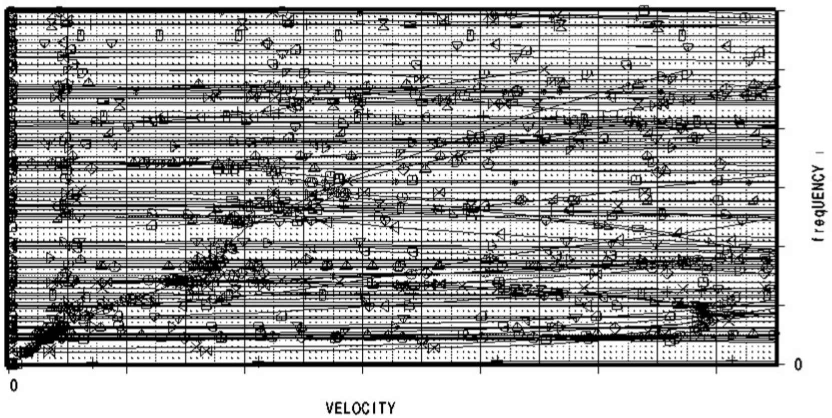
Growth Rate

vs

Velocity

Effective tab rigid rotation stiffness = 0

Note the many closely-spaced modes, and the difficulty in tracking them



Frequency

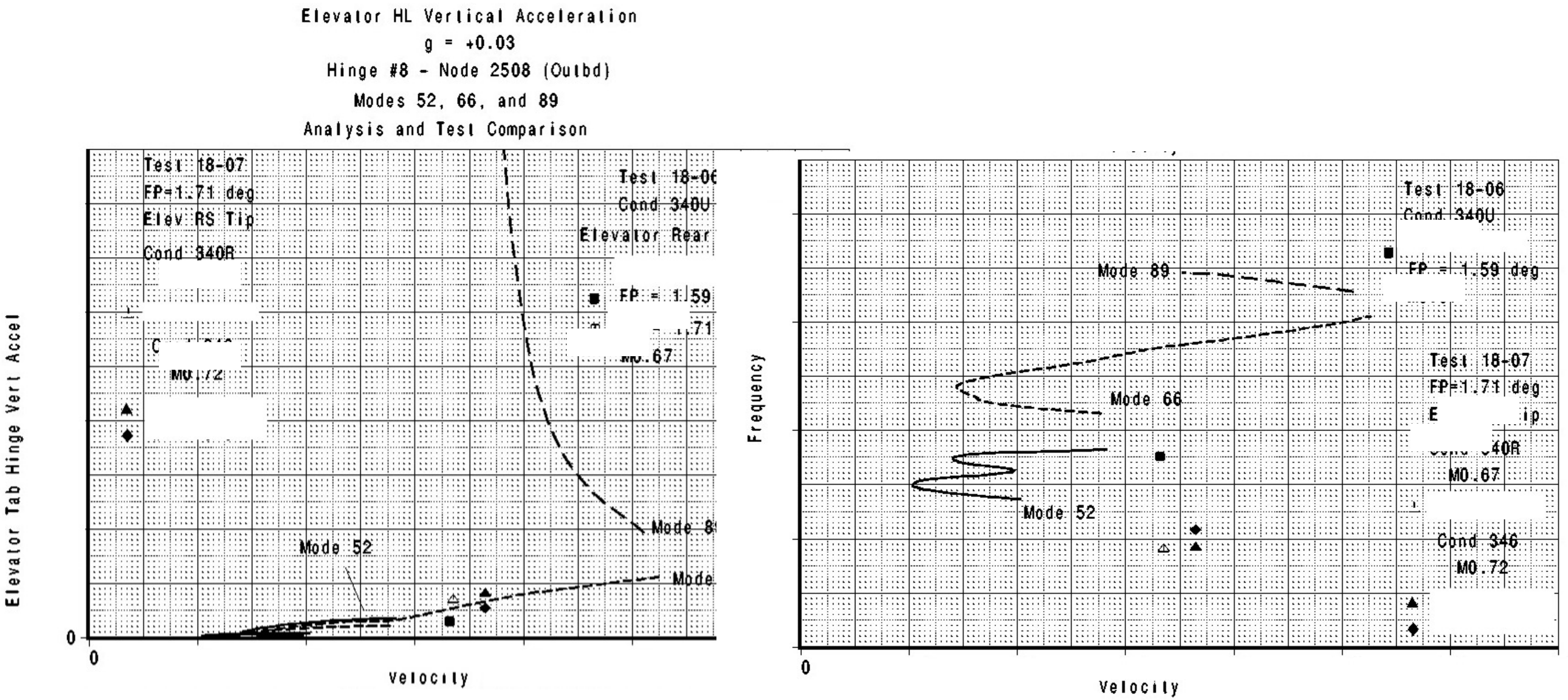
vs

Velocity

Representative Describing Function Limit Cycle Predictions and Flight Test Results

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

g = +0.03



A Probabilistic Approach to Aeroservoelastic Reliability Estimation

Details:

Styuart, A., Mor, M., Livne, E., and Lin, K.,

“Risk Assessment of Aeroelastic Failure Phenomena in Damage Tolerant Composite Structures”,

AIAA Paper 2007-1981, 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics,

and Materials Conference, Honolulu, Hawaii, Apr. 23-26, 2007

Considerations

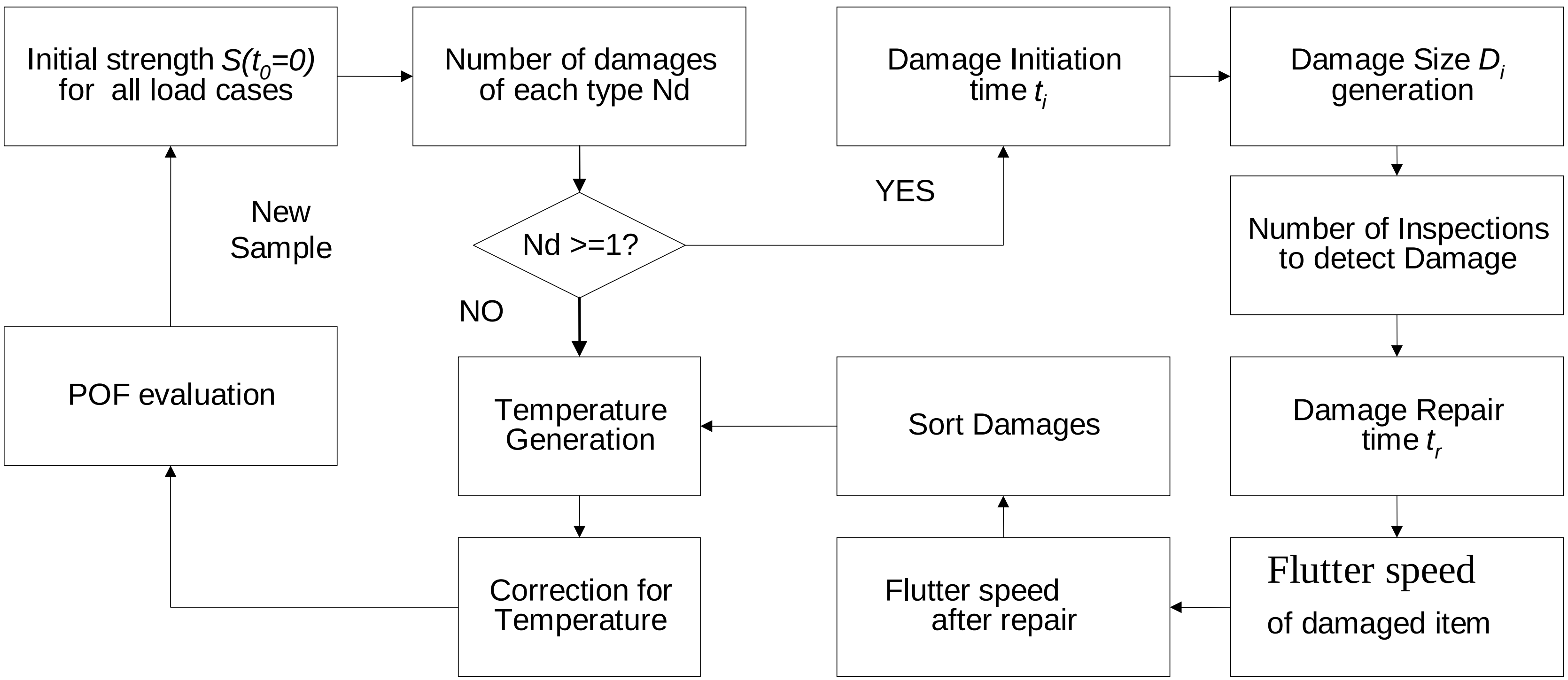
- **Failure types:**

- **Flutter: airspeed exceeds the flutter speed of damaged structure**
- **Post-static-failure flutter failure: airspeed exceeds flutter speed of buckled / failed structure**
- **High amplitude limit cycle oscillations: the acceptable level of vibrations is exceeded**

- **Uncertainties:**

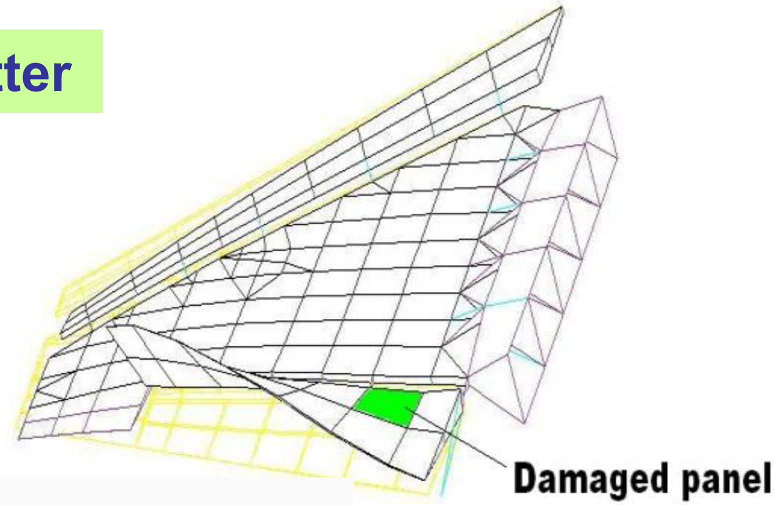
- **Flutter speed prediction: systemic (accuracy of simulation technology)**
- **Flutter speed prediction: individual (variation of properties)**
- **Fleet variability**
- **Flight tests of one specimen (and possible modifications, if required)**
- **Add damage statistics (size, location, type)**

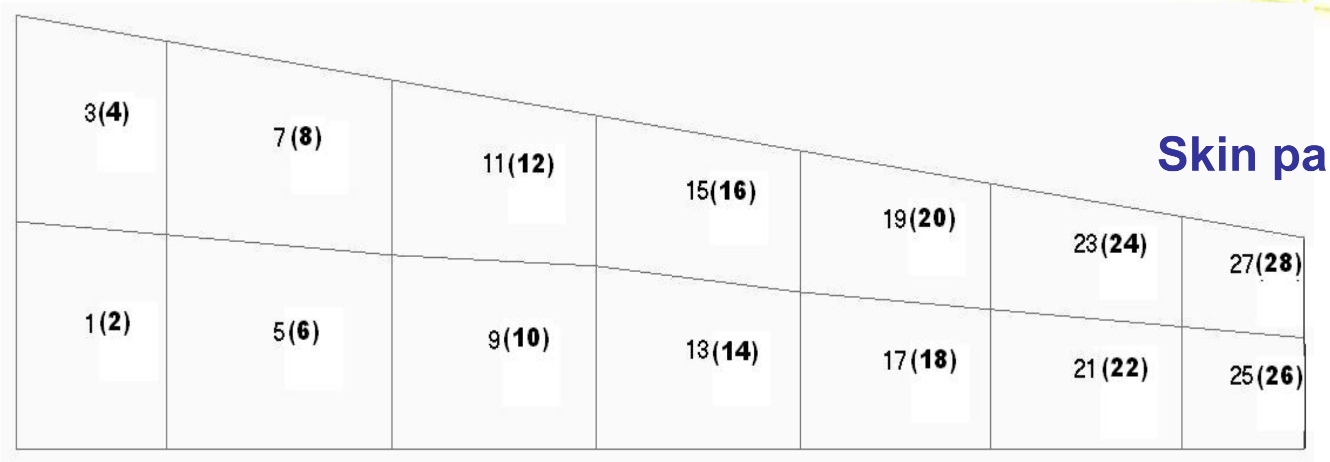
Simulation flowchart



3D Airframe example problem –slide 1

Realistic wing-flaperon system flutter



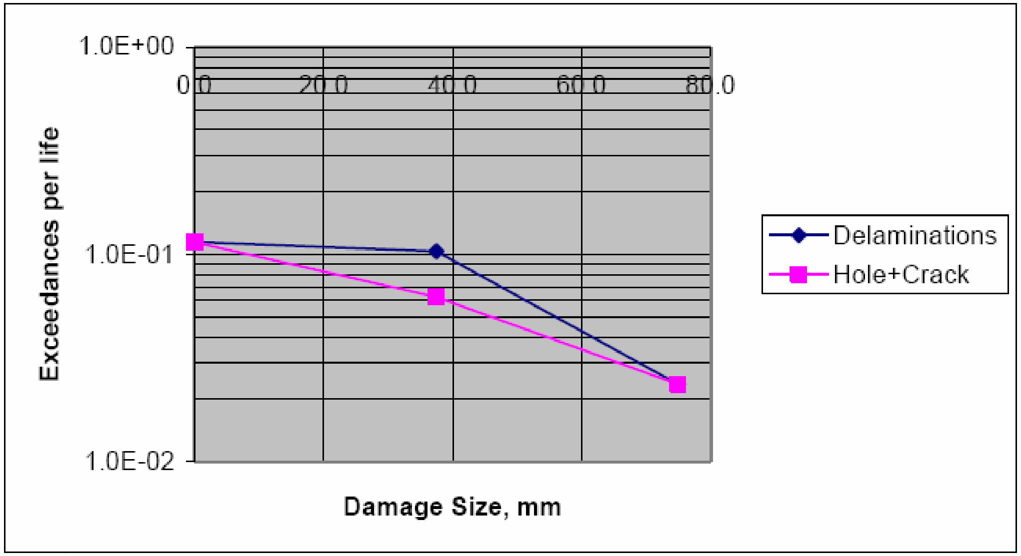


Skin panel IDs top (bottom)

3D example problem – slide 2

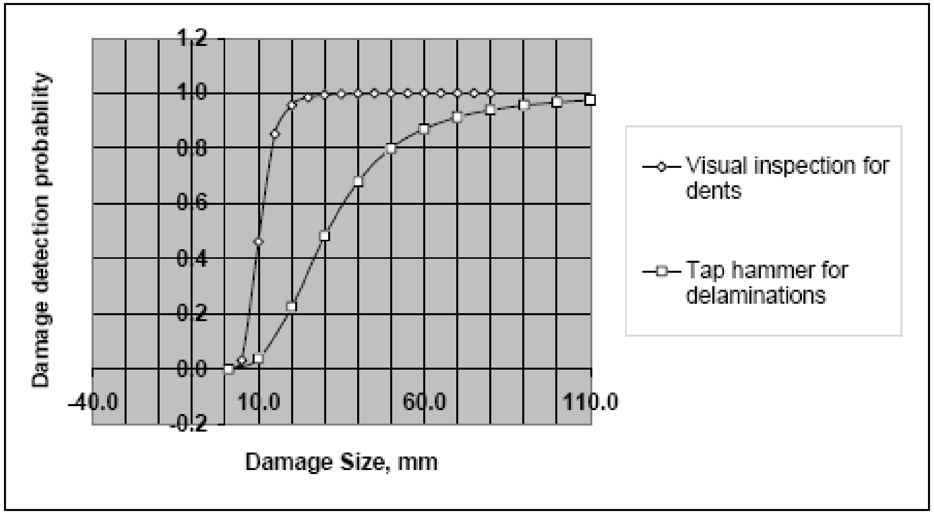
<u>Damage Exceedance Data:</u>

Delaminations; Holes and Cracks



<u>Probability of Damage Detection per inspection:</u>

Visual inspection; tap hammer inspection



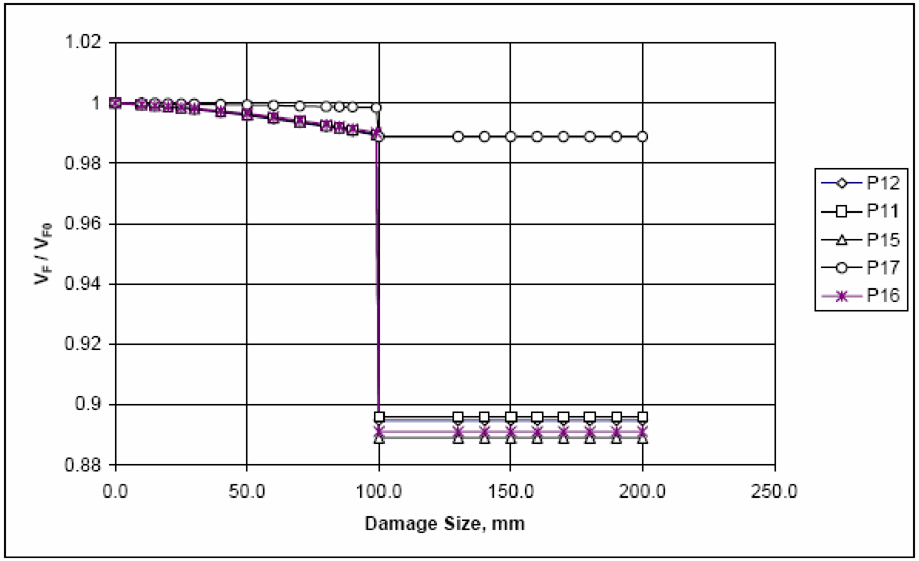
3D example problem – slide 3

Residual Flutter Speed vs. Damage Size for Most Stiffness-Critical Panels.

Residual stiffness based on rule-of-mixtures

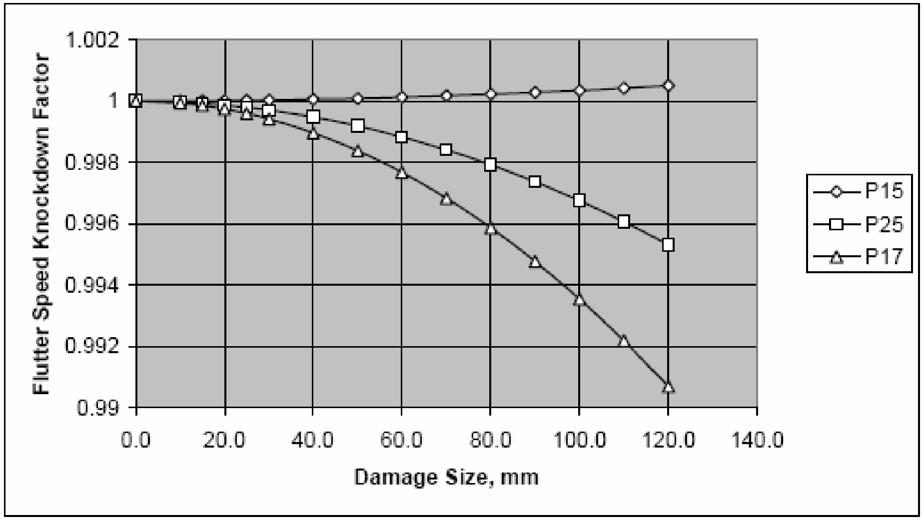
$$\kappa_T = \left(\frac{W - W_D}{W}\right)\kappa_{T(U)} + \left(\frac{W_D}{W}\right)\kappa_{T(D)};$$

$$\kappa_C = \left(\frac{W - W_D}{W}\right)\kappa_{C(U)} + \left(\frac{W_D}{W}\right)\kappa_{C(D)}$$



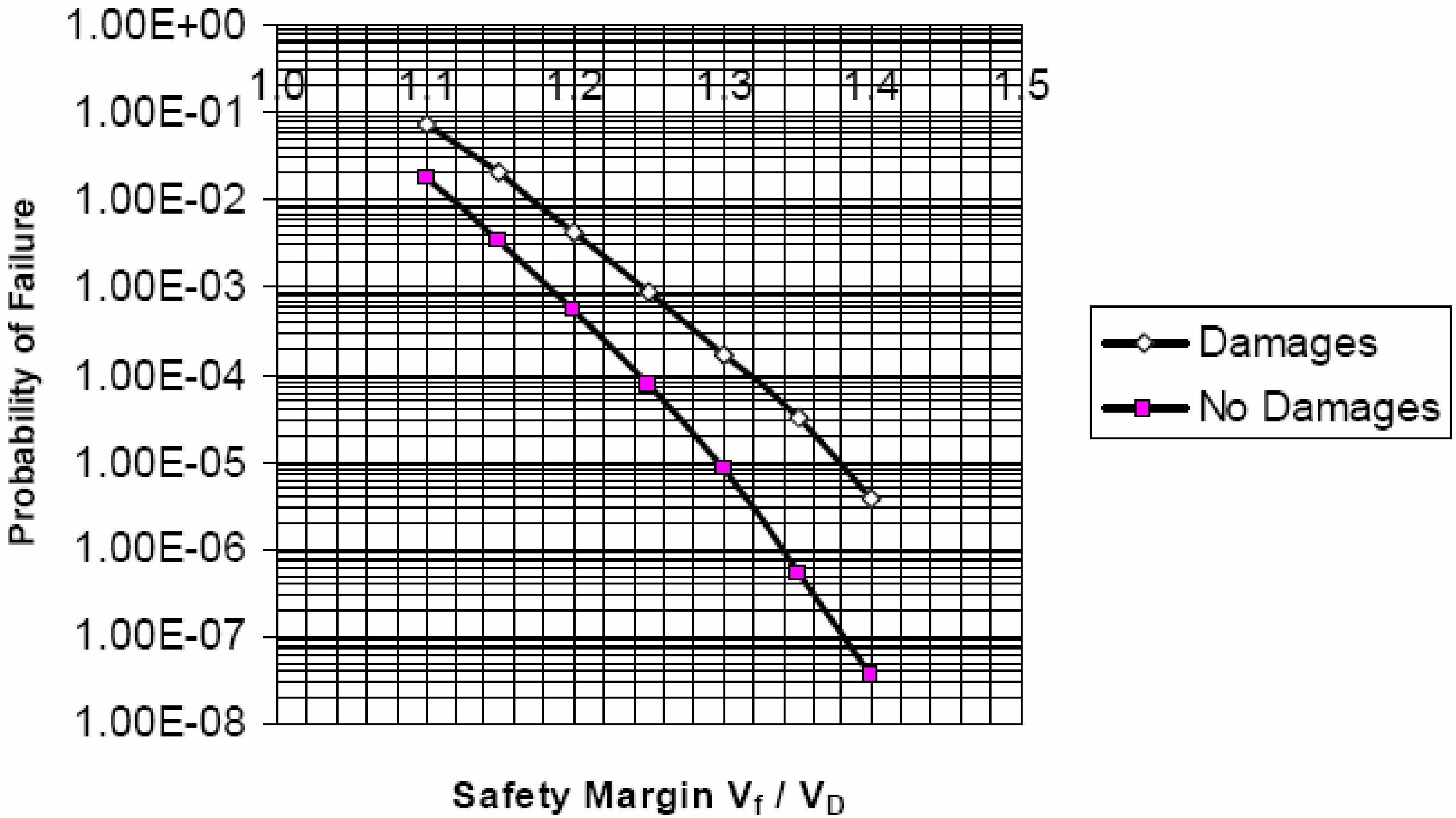
Flutter Speed Repair Recovery

Knockdown factor for different panels



3D example problem – slide 4

Probability of Failure due to Panel 15 vs. Safety Margin with Damage Accounting



Experiments and experimental capabilities development

Goals:

- Develop a low-cost rapid aeroelastic testing capability at the UW for studies of aeroelastic problems of interest, with special emphasis on
  - Composites
  - damaged airframes

  and
  - nonlinear aeroelastic behavior

- Use tests to validate and calibrate numerical models

- Use tests to support FAA / NTSB work

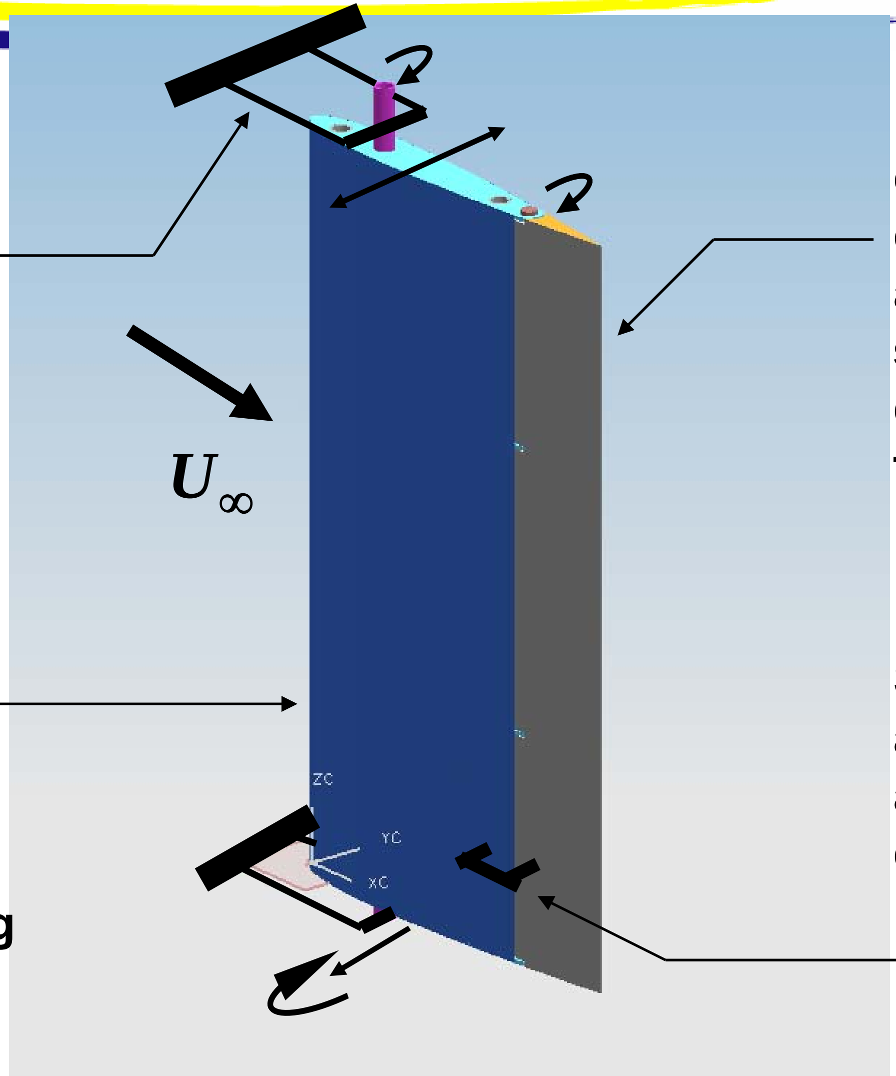
Experiments and experimental capabilities development

Approach:

- Start with simple models for which experimental and theoretical results already exist – the Duke U wing / control surface LCO model
- Expand and generalize by adding
  - Composite construction components
  - Nonlinearity types for the actuator and support system
  - Simulation of damage in different mechanisms: debonding, attachment failure, delamination, hinge failure
- Develop the model design & construction and test conduction as ell as data processing hardware and software tools
- Use as a foundation upon which to build aeroelastic experimental capabilities using more complex models
  - first an empennage with multiple interacting nonlinearities for the 3 x 3 tunnel
  - Later, large aeroelastic models and associated tests at the Kirsten wind tunnel

UW Flutter Test Wing / Control Surface Design mounted vertically in the UW A&A 3 x 3 wind tunnel

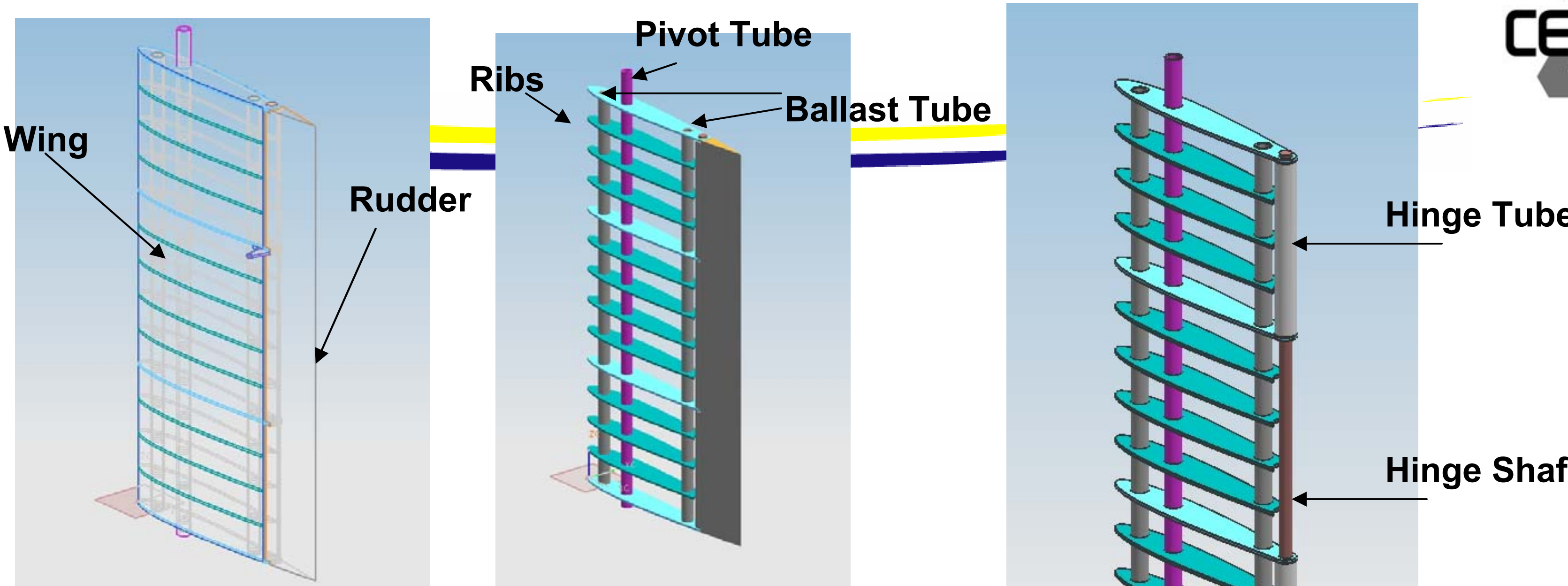
Wing - wind tunnel mount
Providing linear Plunge
And torsional pitch stiffnesses

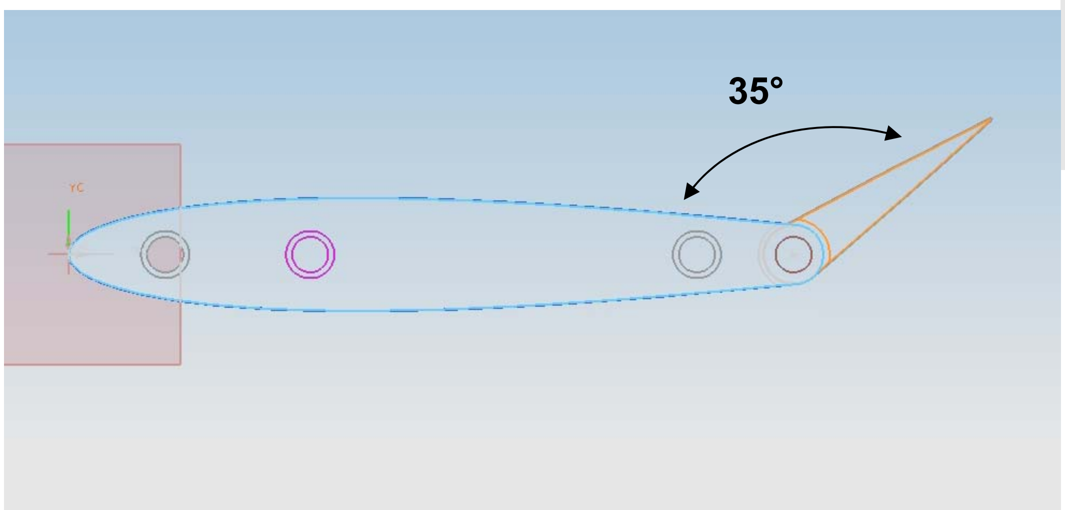


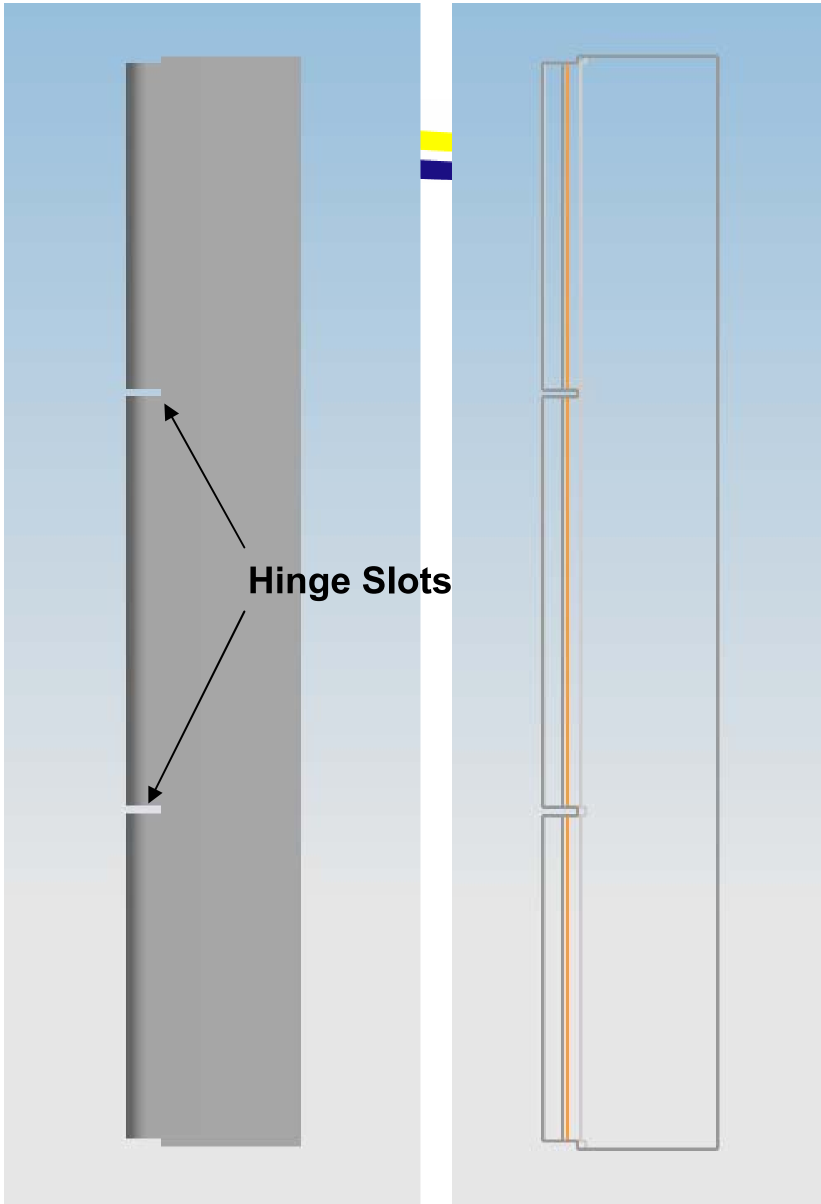
Rudder – composite construction allowing for simulations of damage and hinge failure

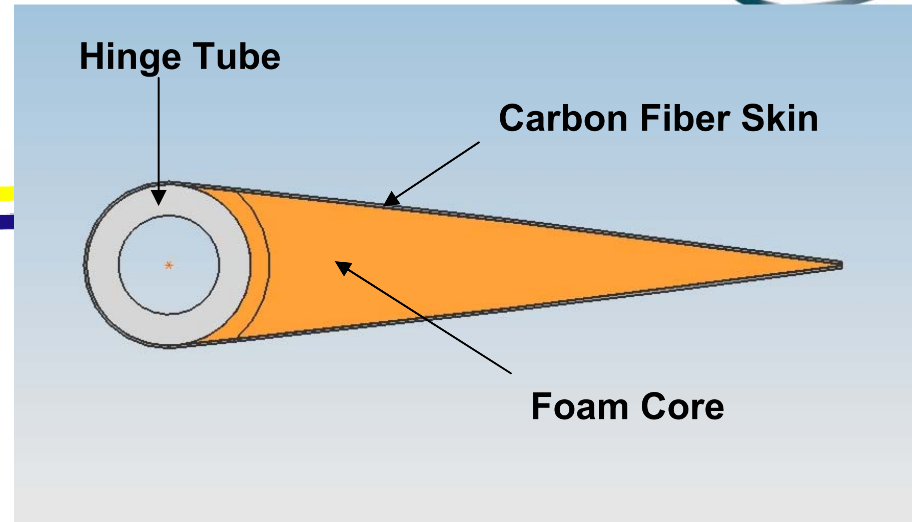
Aluminum wing allowing for variable inertia / cg properties

Simulated actuator attachment allowing for different nonlinearities

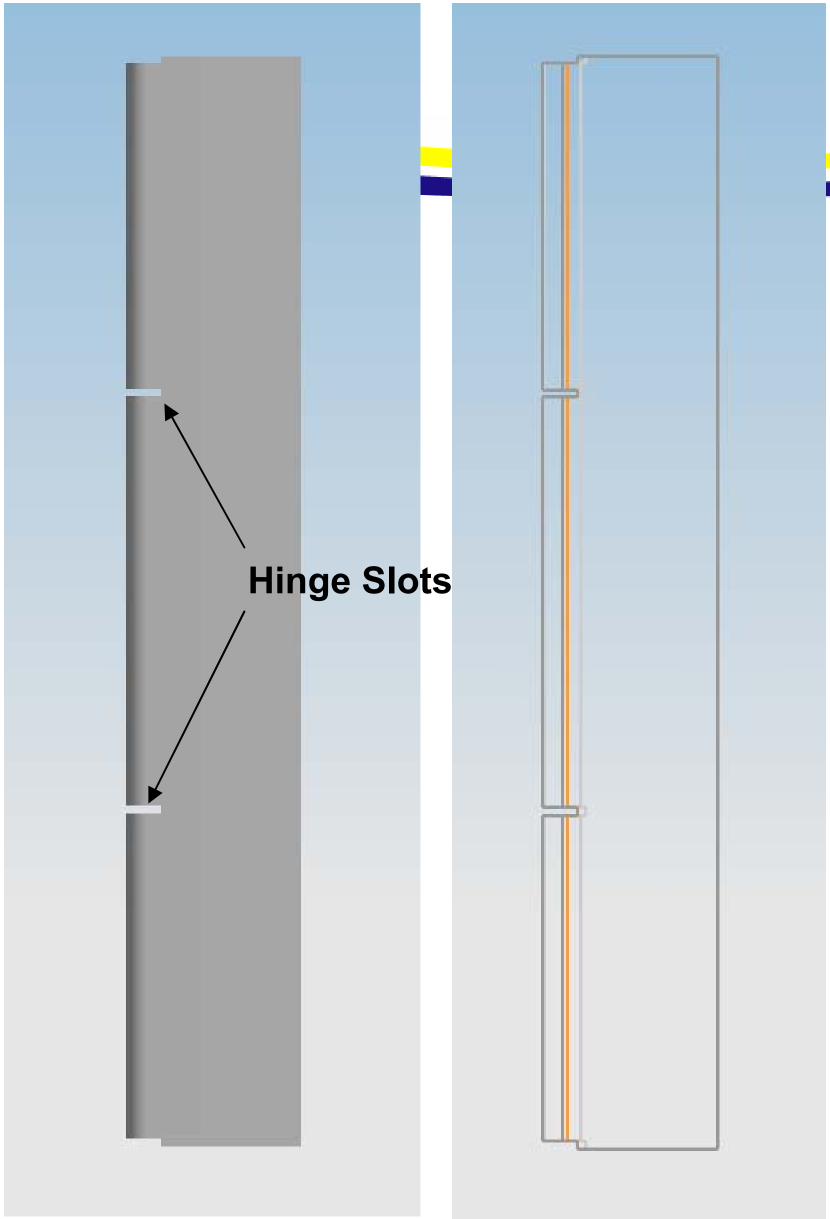

Wing
Rudder
Ribs
Pivot Tube
Ballast Tube
Hinge Tube
Hinge Shaft

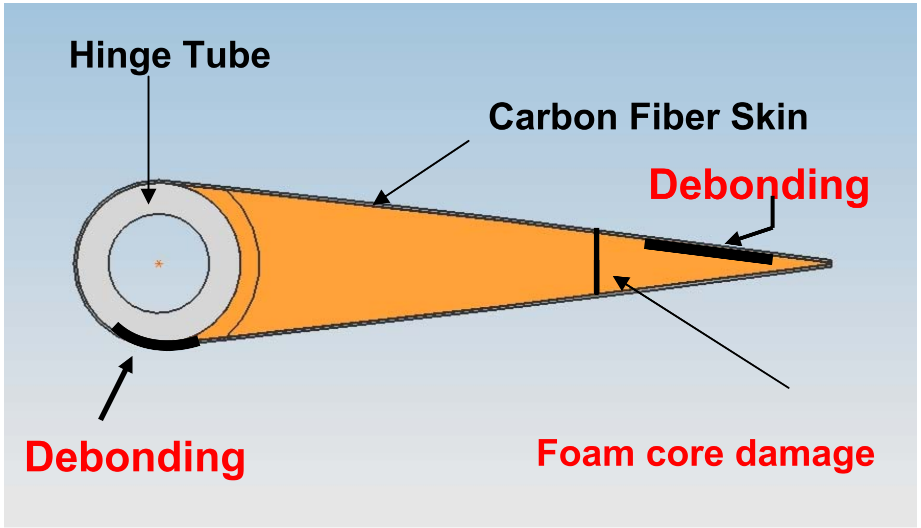

35°





- **Rudder Assembly**
  - **Foam core is CNC machined.**
  - **The aluminum hinge tube is epoxy bonded to the foam core.**
  - **Carbon fiber is layed up around the aluminum/foam assembly and cured.**
  - **Slots are machined to accommodate the hinge ribs.**





- Damage modes
  - Debonding.
  - Delamination
  - Core cracking
  - Hinge failure

Development of Experimental Capabilities - Status

- **New Modal testing system: arrived and installed.**
- **Experience building in modal testing: underway**
- **Wing / control surface aeroelastic model: in design.**
- **Numerical simulation capabilities to support tests: ready.**

Conclusion

- Progress in all major areas of this R&D effort:
  - Efficient simulation tools for uncertain airframes covering flutter and LCO constraints, including linear and nonlinear structural models
  - 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
  - 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.

Benefits to Aviation

- 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, covering:
  - Different damage types in composite airframes and their statistics;
  - Aeroelastic stability due to linear and nonlinear mechanisms;
  - Aeroelastic response levels (vibration levels and fatigue due to gust response and response to other dynamic excitations);
  - Theoretical, computational, and experimental work with aeroelastic systems ranging from basic to complex full-size airplanes, to serve as benchmark for industry methods development and for understanding basic physics as well as design & maintenance tradeoffs.

Plans

- Apply linear simulation tools to a representative (generic) Boeing-supplied vertical tail / rudder model.
- Extend the UW time-domain LCO simulation capability to complete airplanes and their finite element models.
- Integrate with probabilistic / reliability analysis.
- Apply nonlinear simulation tools to a representative (generic) Boeing-supplied vertical tail / rudder model.
- Develop a comprehensive reliability methodology for composite airframes (with design and maintenance consequences) covering aeroelastic / aeroservoelastic failure modes.
- Continue development of the UW Aeroelastic experimental capability, and use to generate useful data