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

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A Center of Excellence
AMTAS
Advanced Materials in Transport Aircraft Structures

Spring Meeting,
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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

Motivation and Key Issues

- Variation (over time) of local structural characteristics might lead to a major impact on the global aeroservoelastic integrity of flight vehicles.

- Sources of uncertainty in composite structures:
  - Damage
  - Delamination
  - Joint/attachment changes
  - Debonding
  - Environmental effects, 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.

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.
- Integrate aeroelasticity work with work on damage mechanisms and material behavior in composite airframes.
- Develop aeroelastic simulation capabilities for structurally nonlinear systems, with nonlinearity due to damage development and large local or global deformation
- 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.
- Build a structural dynamic / aeroelastic testing capability and carry out experiments.

Approach

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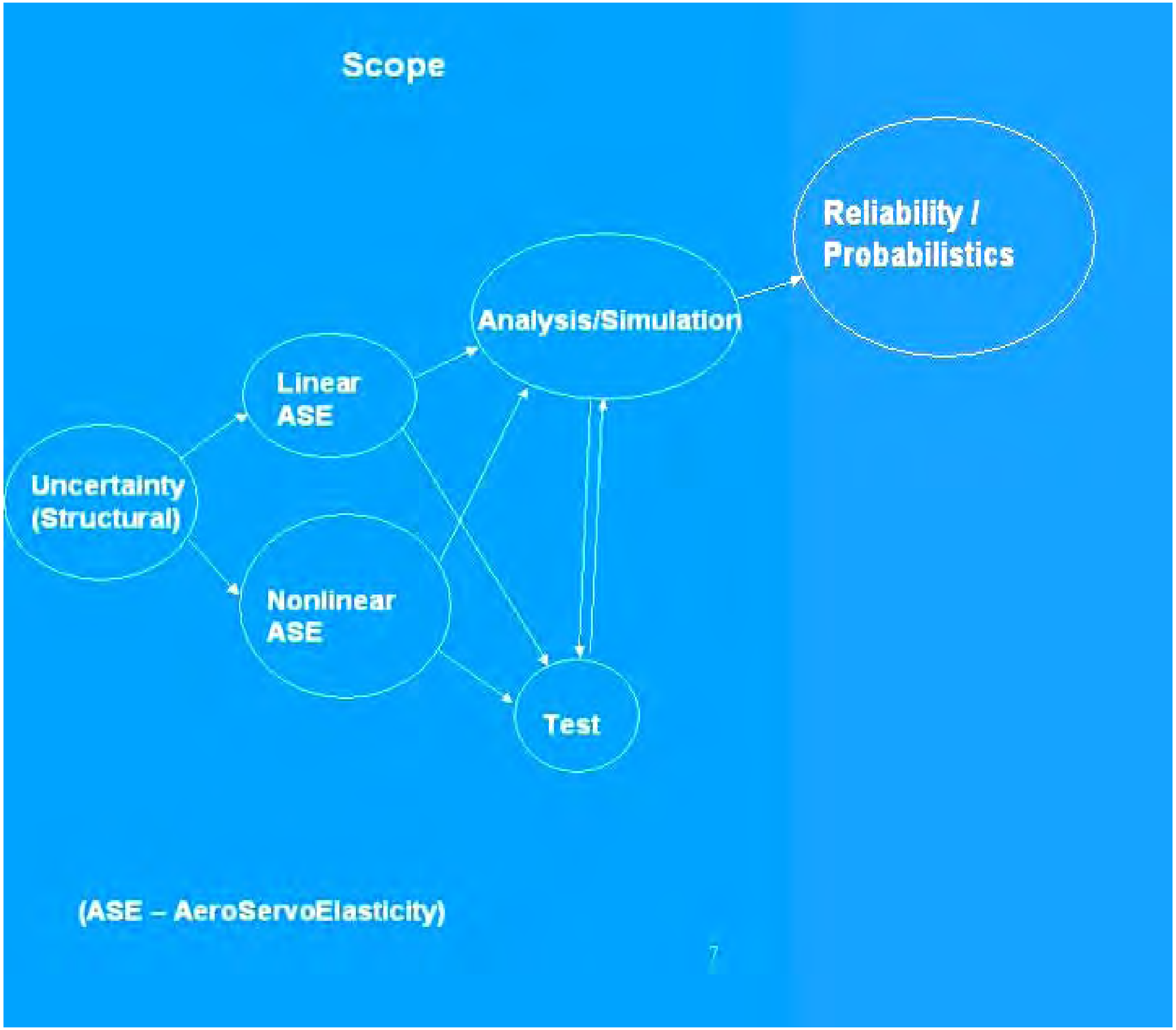


Approach

- **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 – Classical Flutter

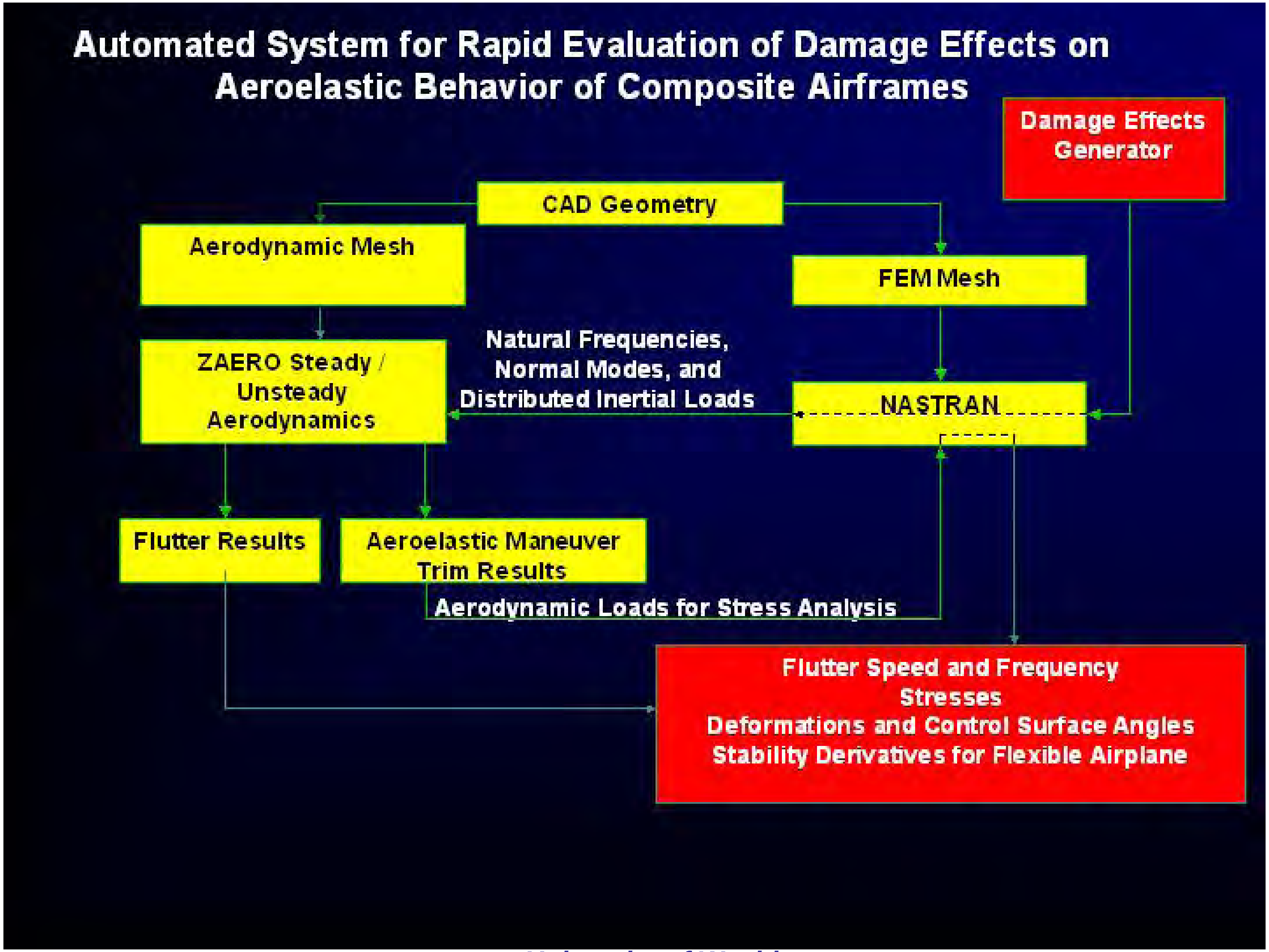
Automated simulations for carrying out fast repetitive analyses of large numbers of parameter variation cases

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)

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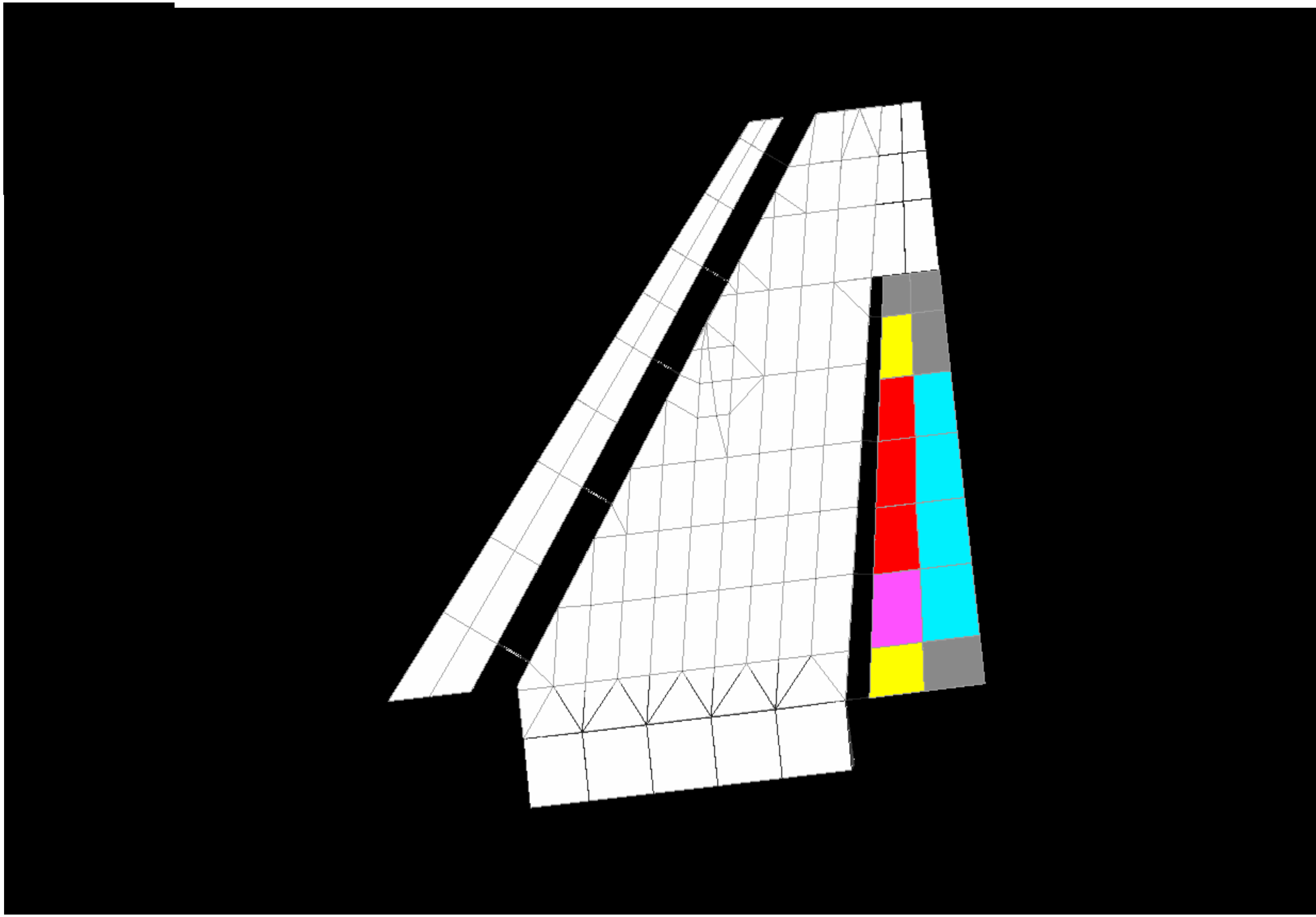
~10%

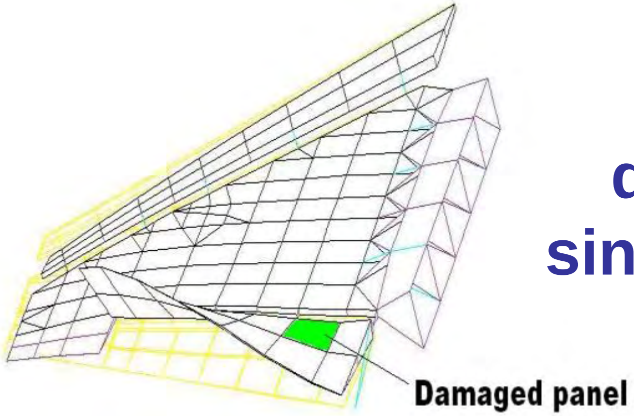
~8%

~4%

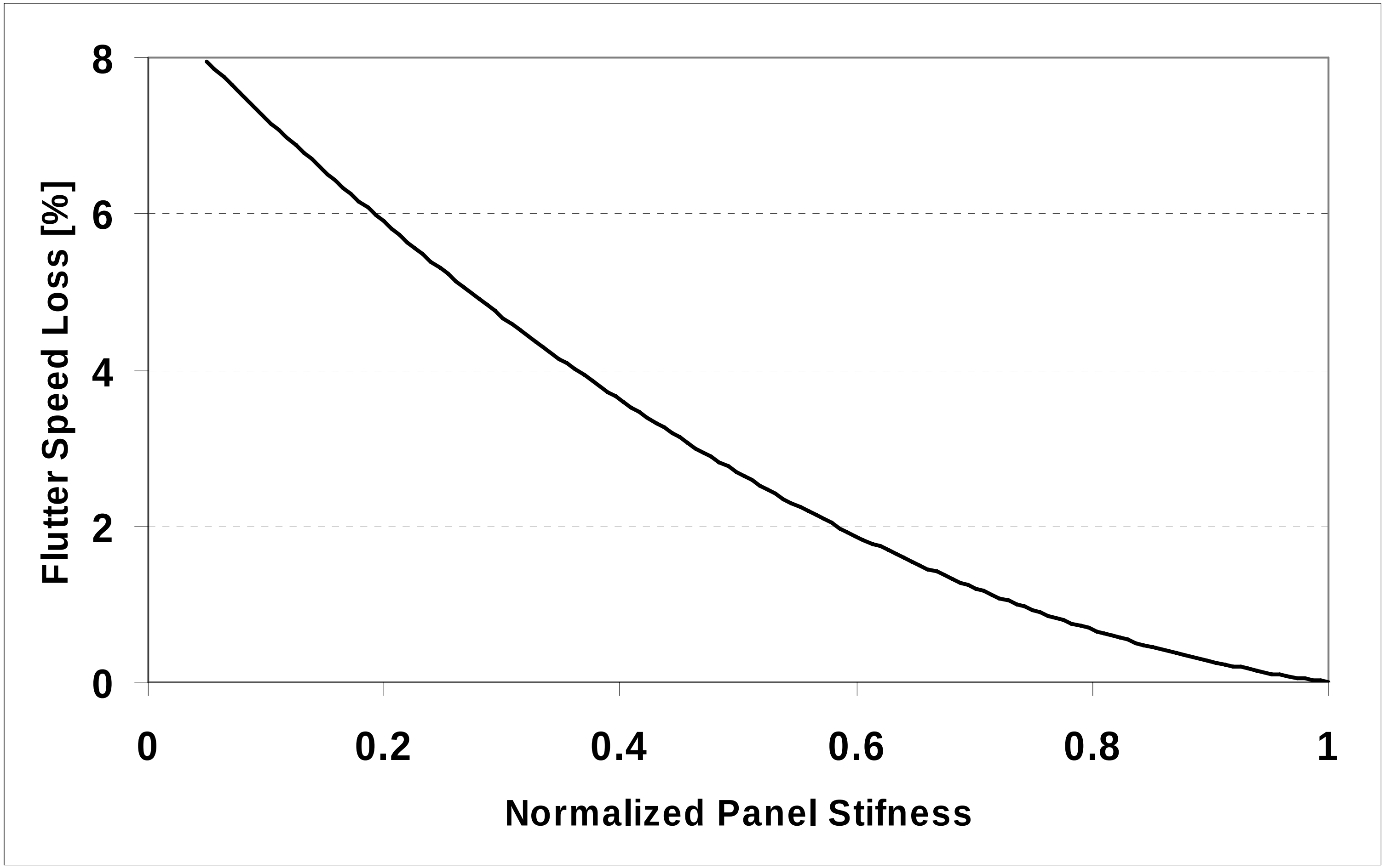
~1-2%

<1%



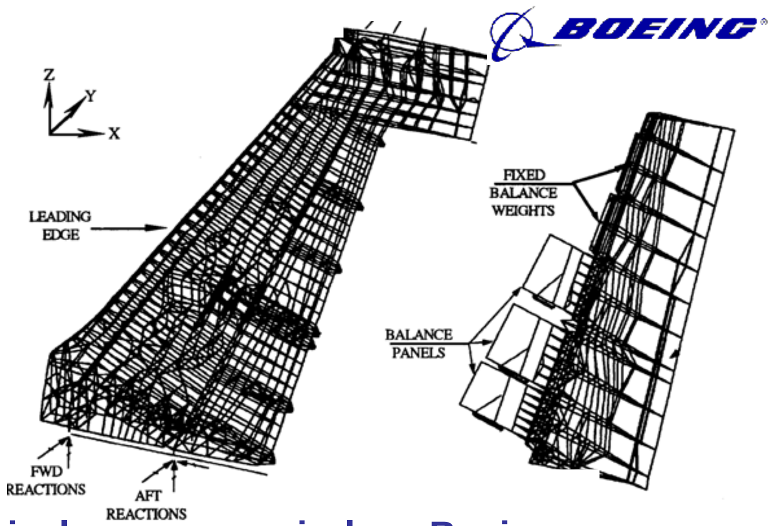


Flutter speed degradation due to loss of stiffness of a single upper skin panel on a TE flaperon



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

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Goals:

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

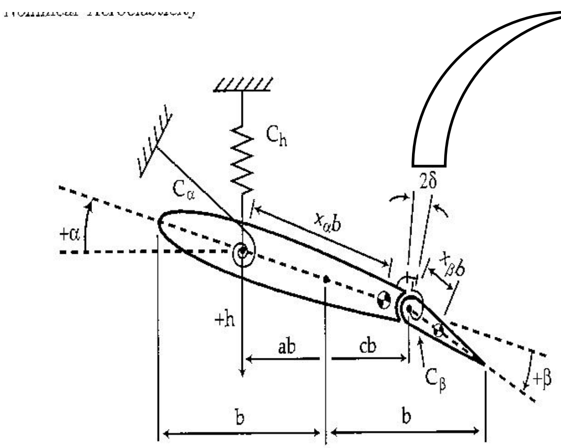
The Damaged airframe problem:

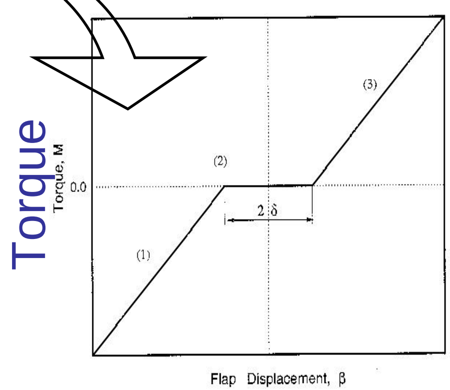
- Simulate nonlinear aeroelastic behavior due to nonlinear local structural effects due to local damage or degradation
- Use to identify possible damage mechanisms that can lead to such behavior
- Use in Monte Carlo simulations and reliability studies

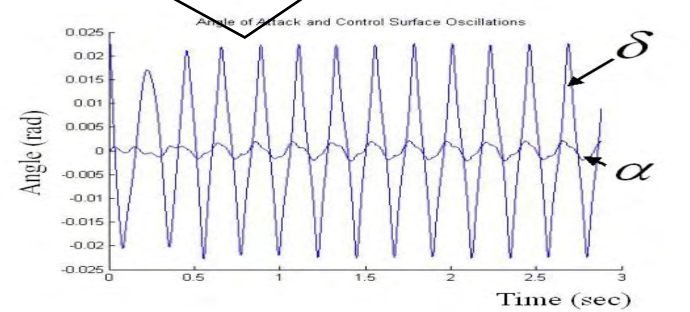
Limit Cycle Oscillations due to control surface freeplay

The Problem:

- **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.**



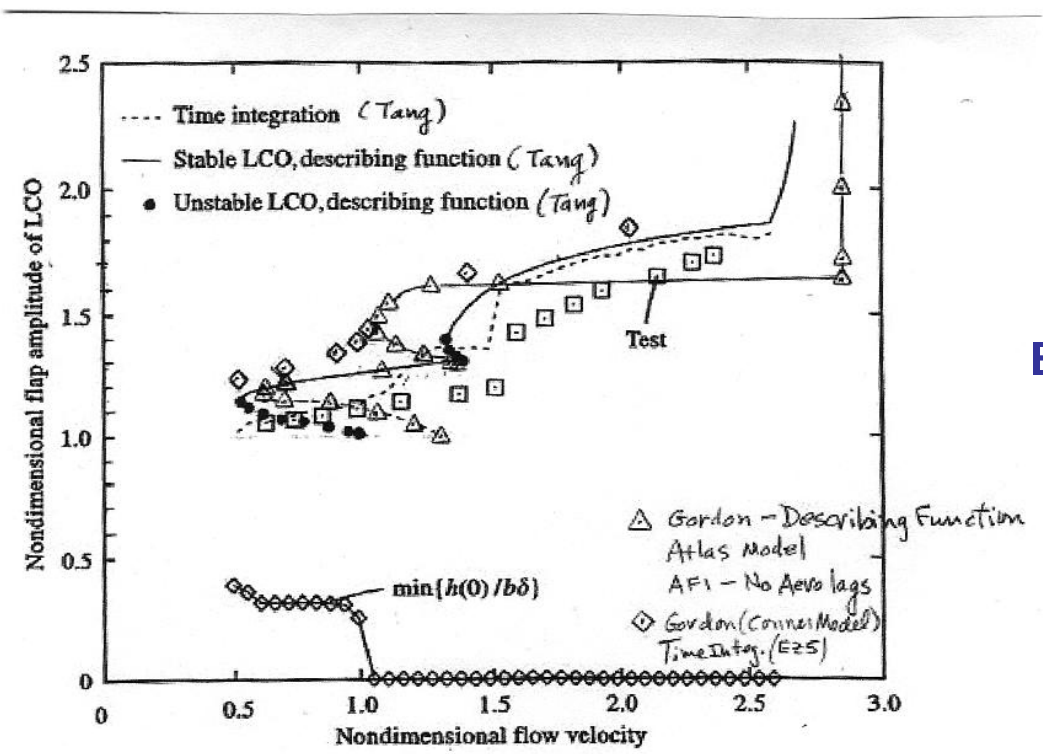




Flap Rotation

LCO simulation 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**



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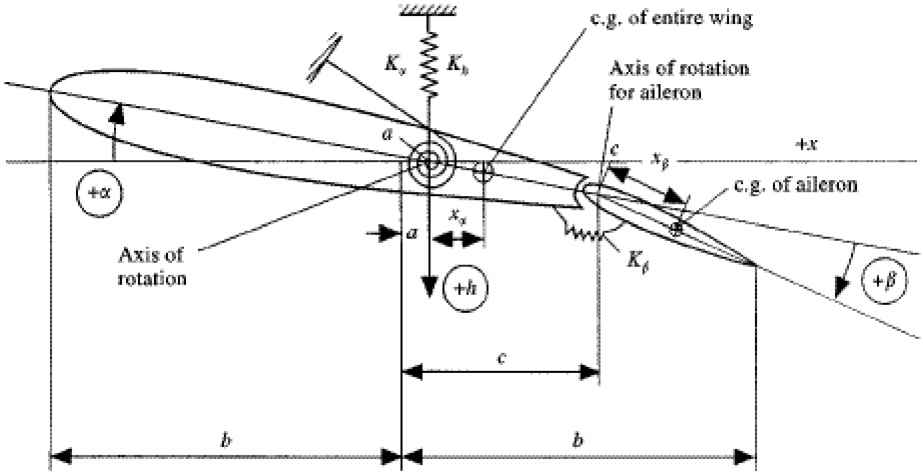
3DOF aeroelastic system

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**

3DOF Problem: Flutter Speed Sensitivity Study

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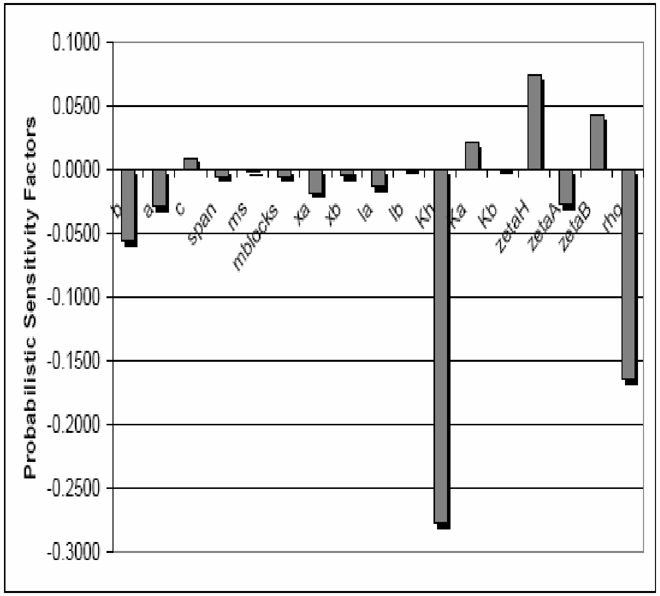
Variable	Description	PDF	mean	C_v
b	Semi-chord	Normal	0.127 m	0.2%
a_d	Elastic axis, m	Normal	-0.0635	1%
c_d	Hinge line, m	Normal	0.0635	1%
span	Span	Weibull	0.52 m	0.2%
x_a	c.g. of entire wing	Normal	0.0551 m	2%
x_b	c.g. of aileron	Normal	0.0025 m	2%
Ia	Moment of inertia of entire section	Normal	0.01347 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)



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

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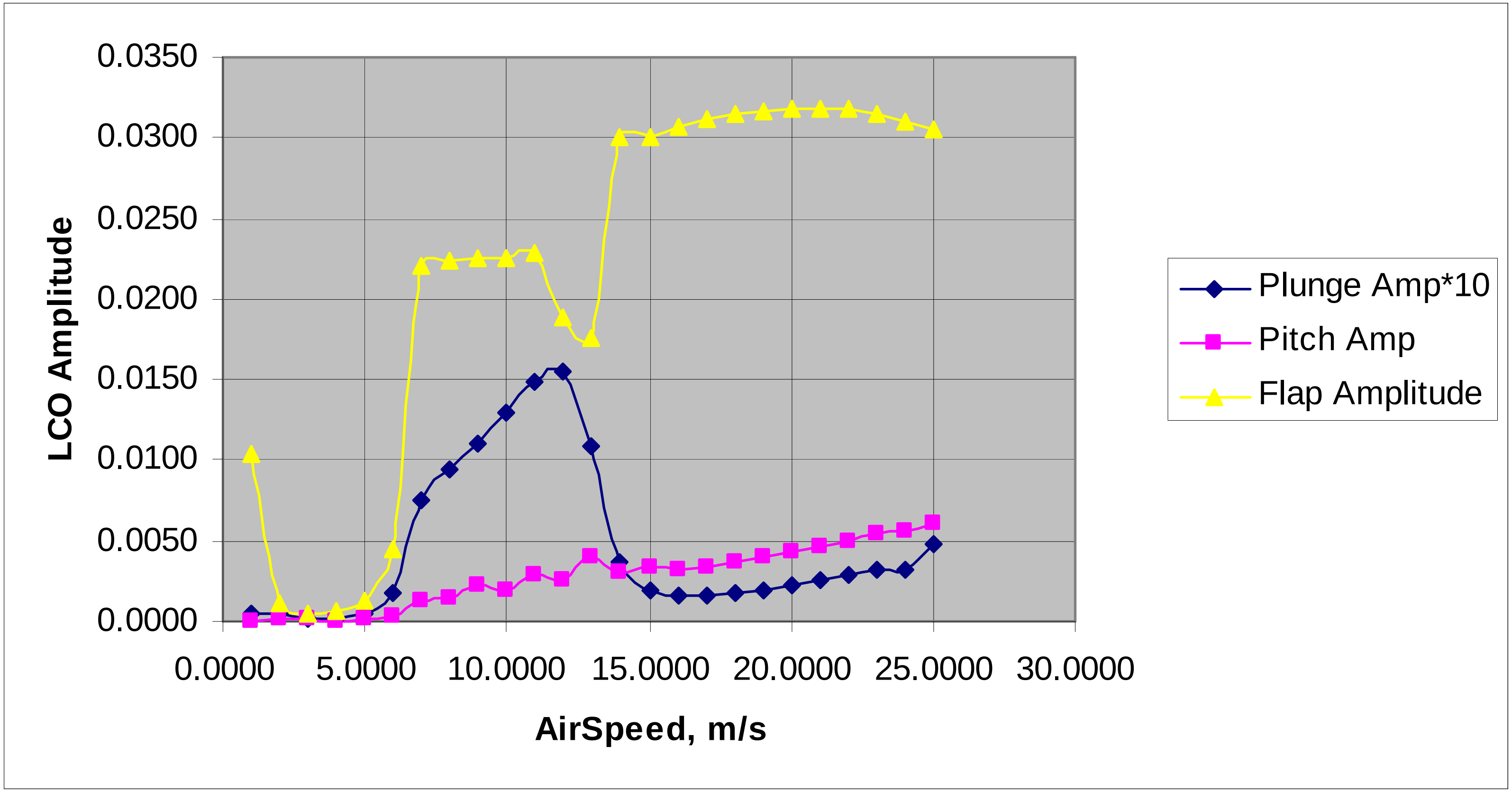
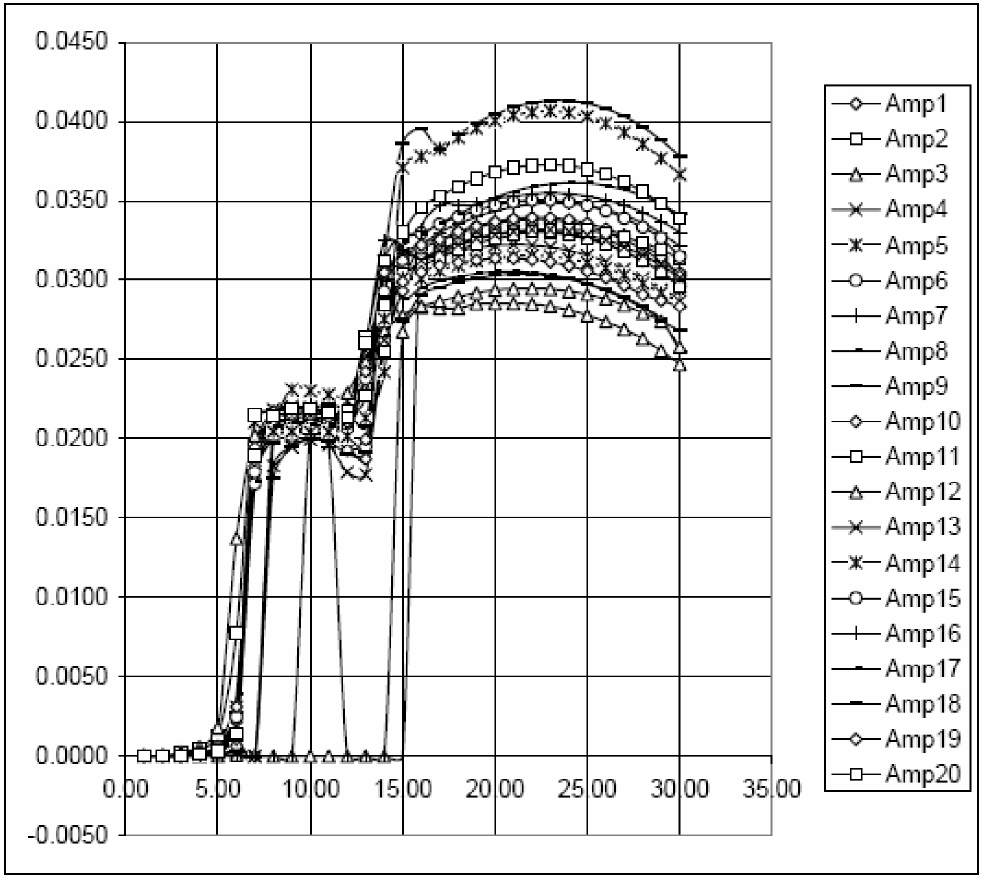


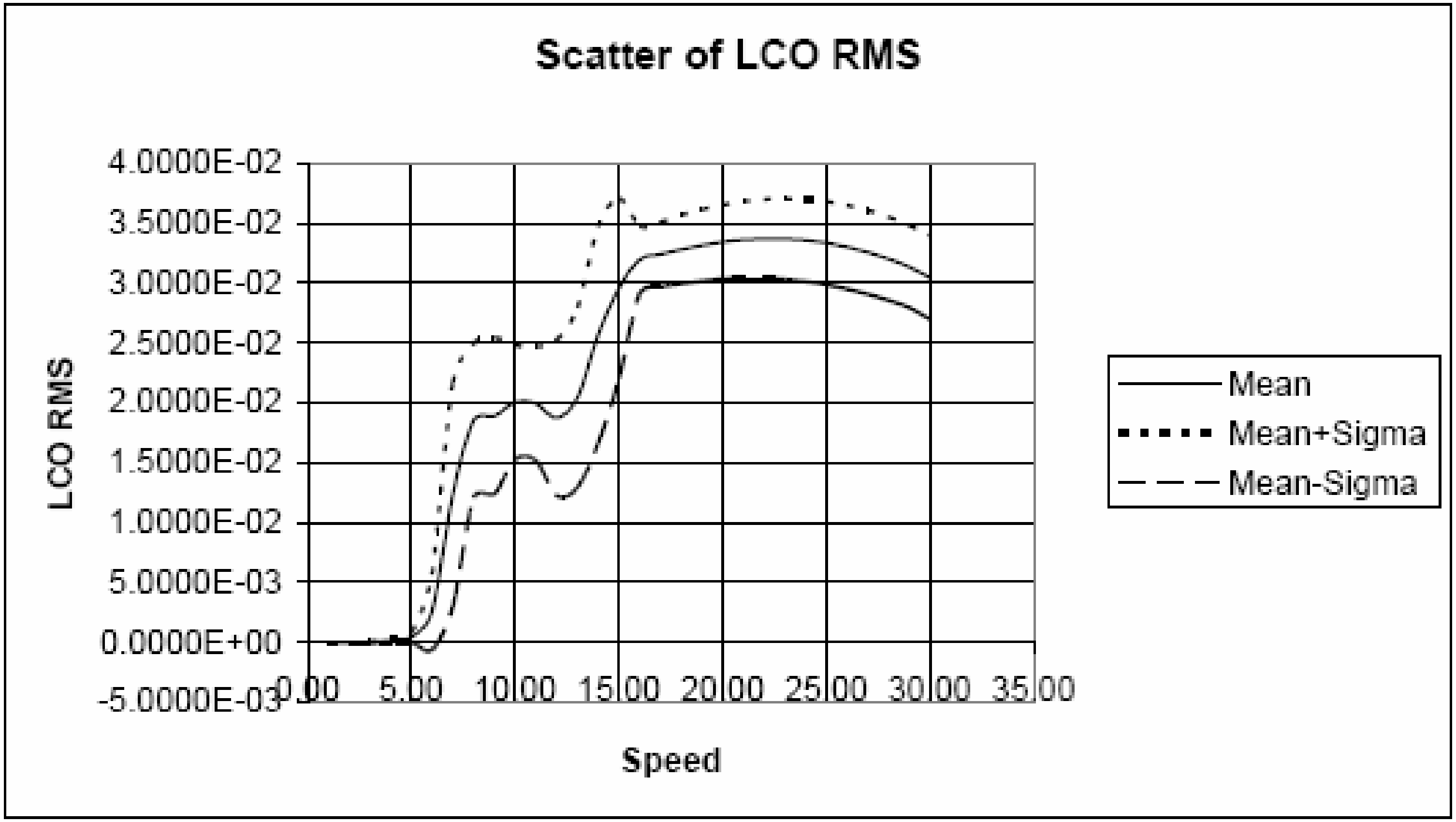
Variation of LCO amplitude in different degrees of freedom as function of flight (wind tunnel) speed (note the complex nonlinear nature of the LCO response

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



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

Motivation:

- **High flexibility and potential for large deformations of emerging composite airframes for passenger aircraft**
- **Local structural nonlinearity due to local damage mechanisms**

Approach:

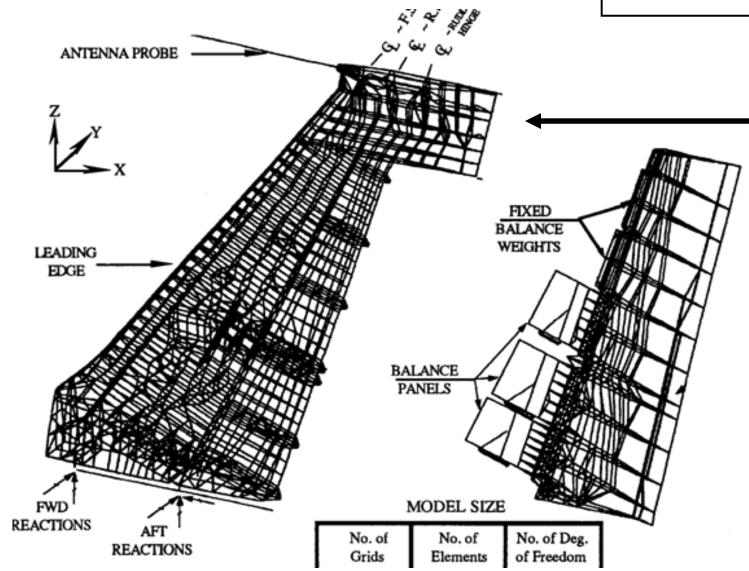
- **Develop efficient Finite Element (NASTRAN-like) modeling for geometrically nonlinear thin-walled composite airframes**
- **Couple with industry-standard linear unsteady aerodynamics (Doublet Lattice, ZAERO, etc.) and industry standard aeroelasticity / controls integration practices**

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

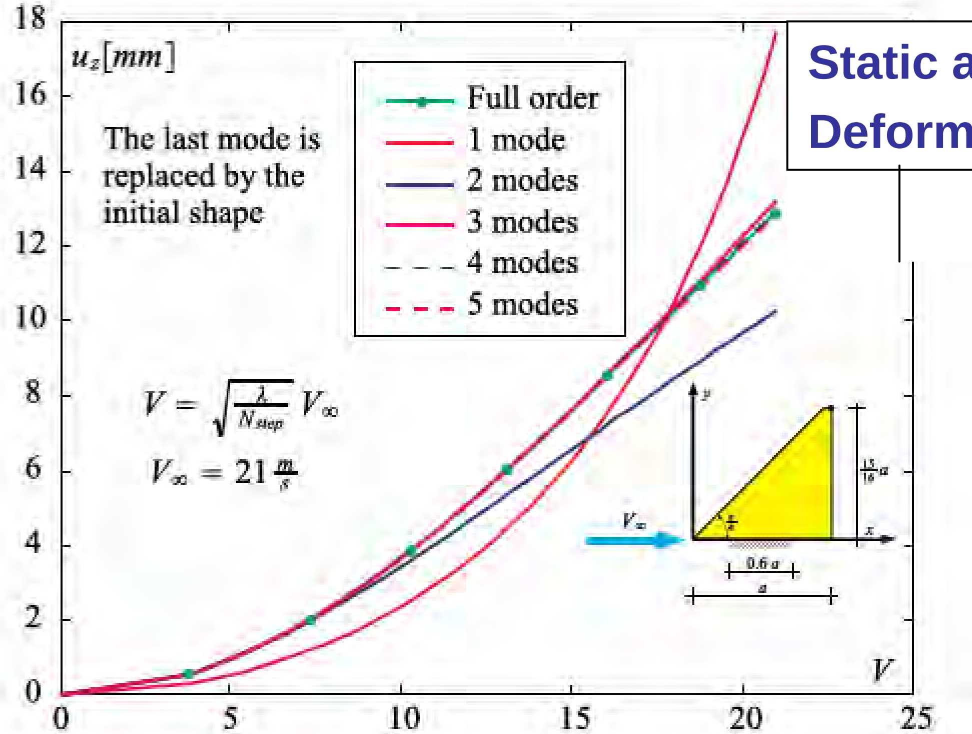
- **Status:**
  - Development complete
  - Major theoretical issues resolved (almost…)
  - Validation using experimental and computational results for a simple geometrically nonlinear test wing model – complete

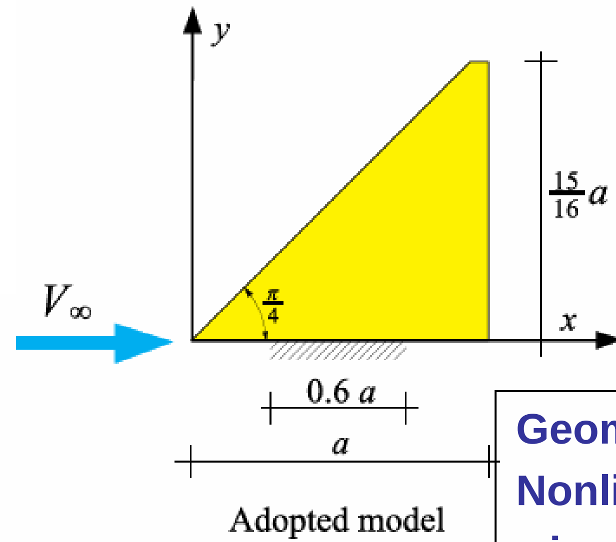
Possible large deformation

Possible nonlinear local behavior due to damage or degradation

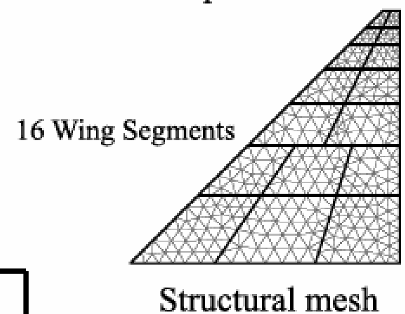


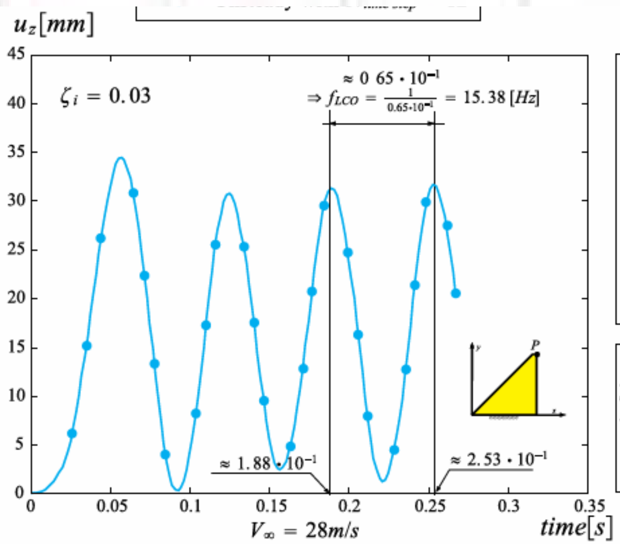
Static aeroelastic behavior
Deformation vs speed





Geometrically Nonlinear wing





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

Nonlinear flutter of the “bad” type

Rather than

- **Stiffening or gaining damping with increased amplitudes to limit the oscillation to some limit cycle steady state**

- **The structure “softens” at some point as the amplitude of oscillation grows (or due to large excitation) and destructive flutter occurs.**

- **Possible damage mechanisms in composites:**
  - **The shift to a post buckled state after delamination**
  - **Local slippage due to debonding or attachment degradation**

- **With large motions, mass balancing effects can change and affect the flutter of wing / control surface mechanisms**

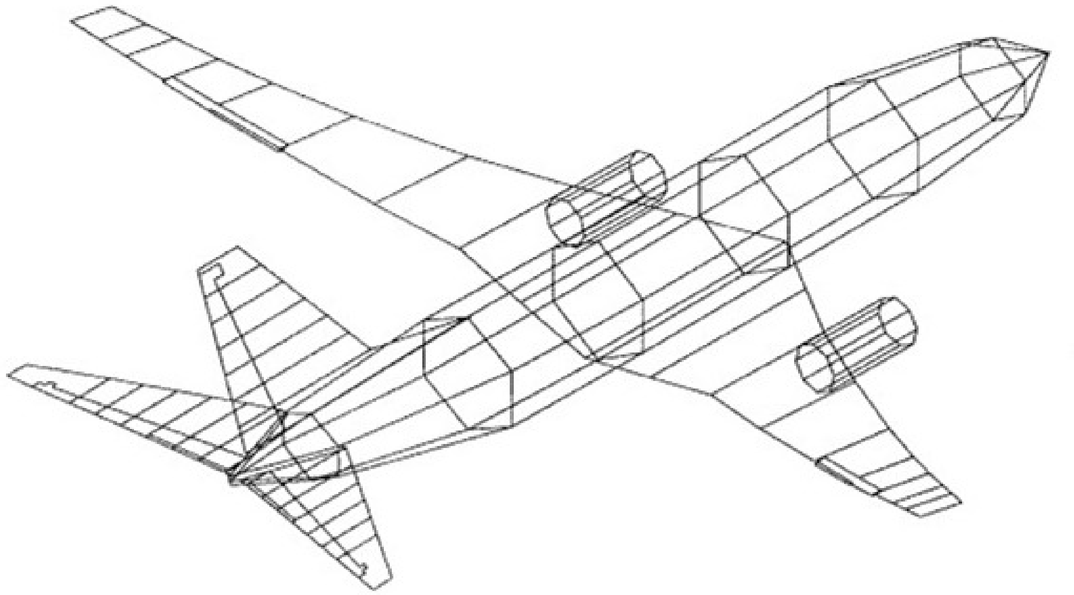
The Boeing LCO Test Case Study

- **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

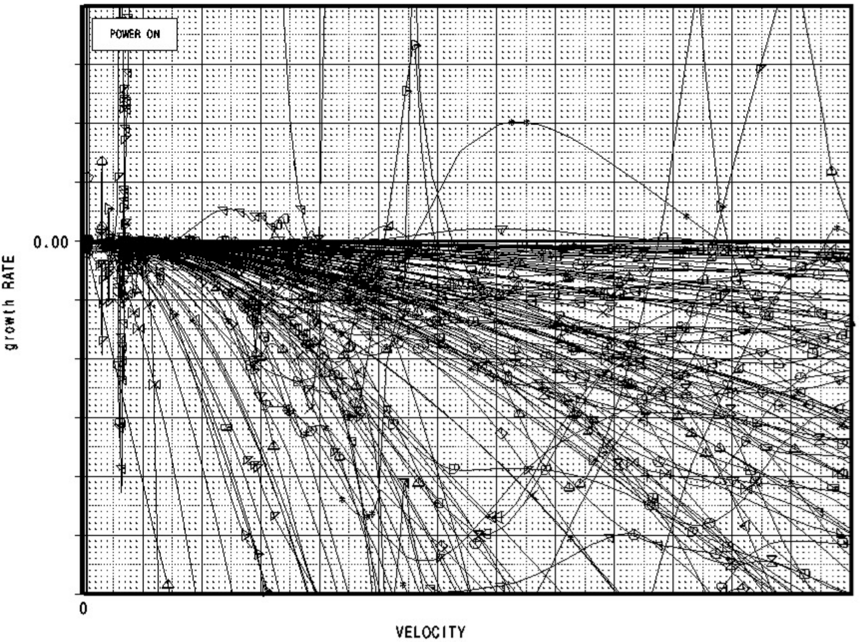
- Full size non-symmetric test-case passenger aircraft study
- 153 modes used
- Free-play allowed in one trim tab (only one side of the aircraft)
- Unsteady aerodynamics adjusted by wind tunnel data
- Algorithms and tools for automated determination of flutter speeds / frequencies in the case of large, 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

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

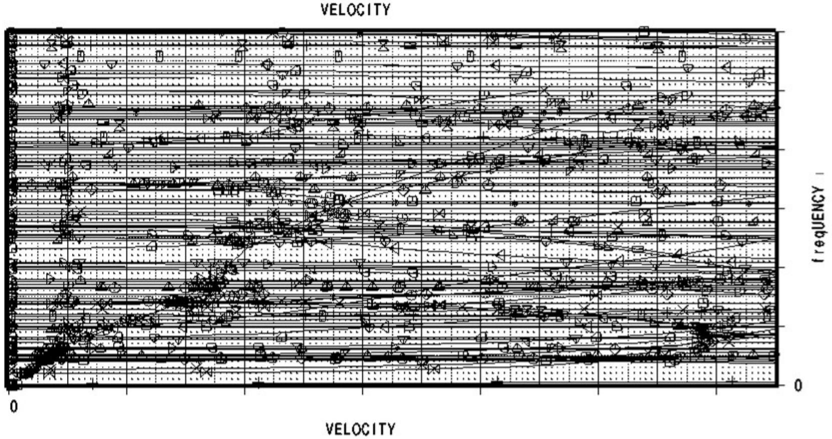
The challenging case of many degrees of freedom and closely-spaced Frequencies



Growth Rate
vs
Velocity

Effective tab rigid rotation stiffness = 0

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

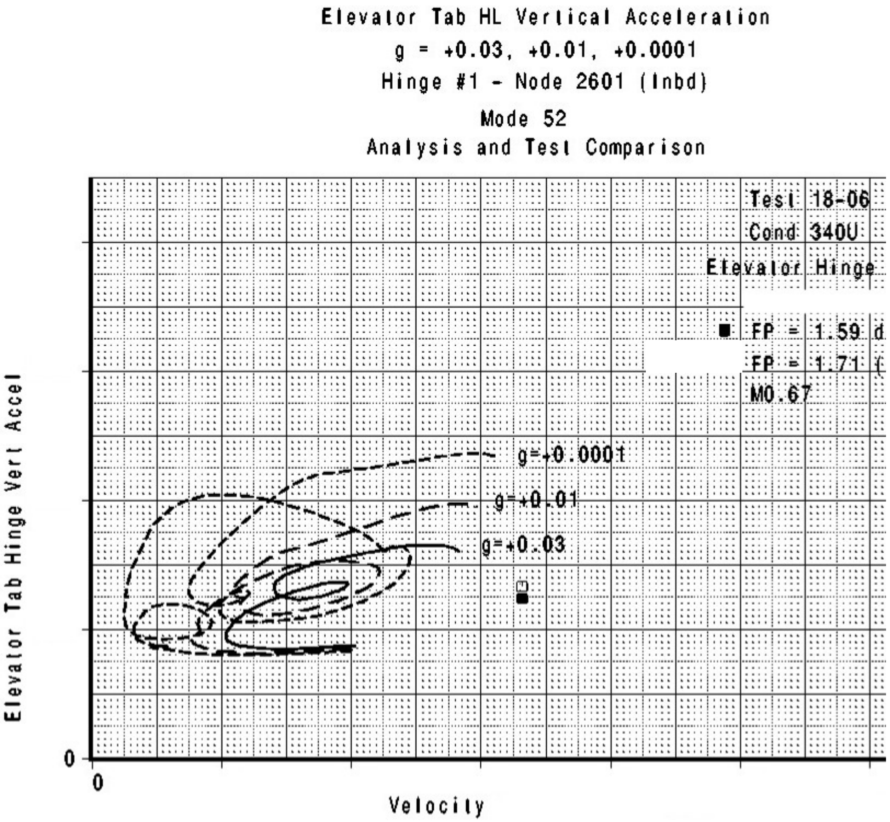


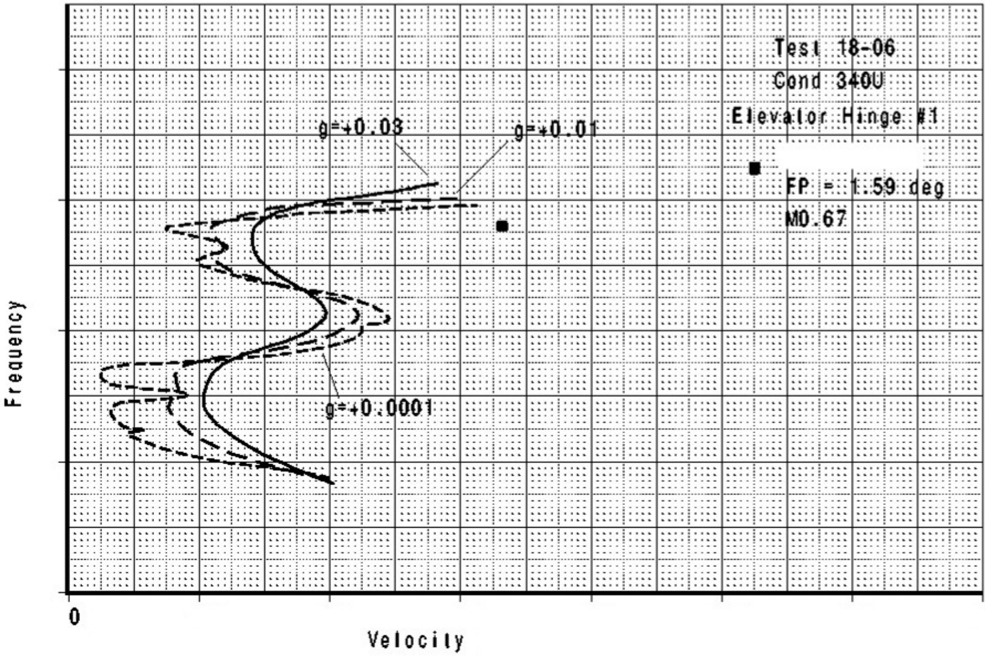
Frequency
vs
Velocity

Representative Describing Function Limit Cycle Predictions and Flight Test Results

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

$0 < g < +0.03$





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Representative Describing Function Limit Cycle Predictions and Flight Test Results

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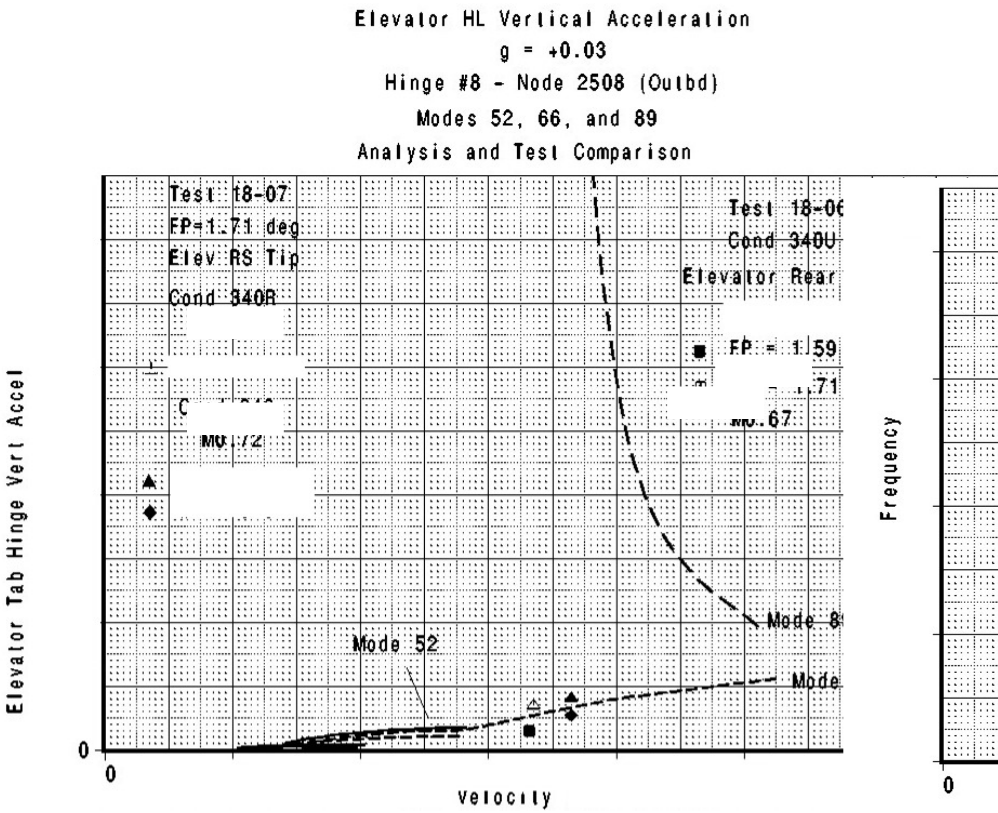
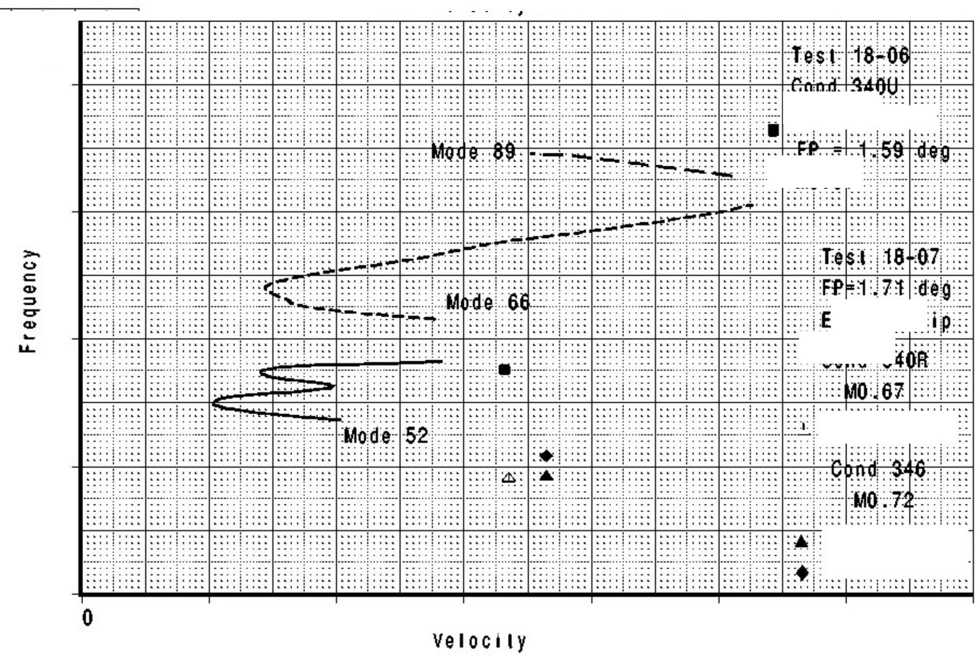
δ_{fp} = ±1.71 deg

g = +0.03





A Probabilistic Approach to Aeroservoelastic Reliability Estimation

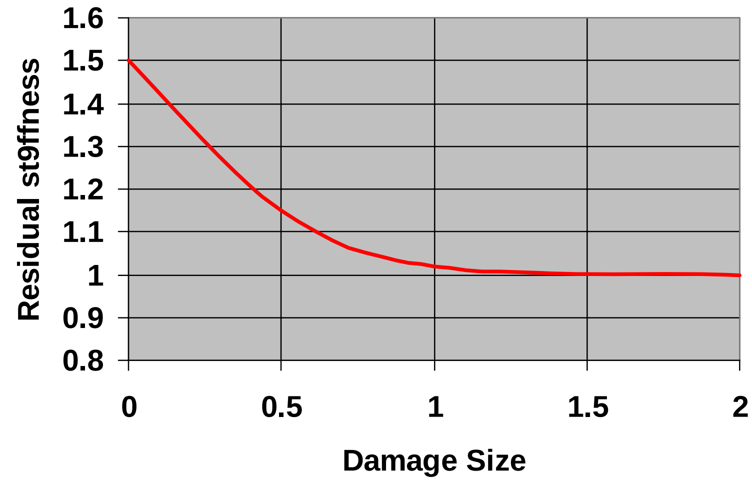
Deterministic Approach

- For normal conditions without failures, malfunctions, or adverse conditions: no aeroelastic instability for all combinations of altitudes and speeds encompassed by the VD/MD versus altitude envelope enlarged at all points by an increase of 15 percent in equivalent airspeed….

- In case of failures, malfunctions, and adverse conditions: no aeroelastic instability within an altitude-airspeed envelope defined by a 15 percent increase in equivalent airspeed above VC at constant altitude

- 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.

- Effects on flutter characteristics will be due to stiffness and mass variations



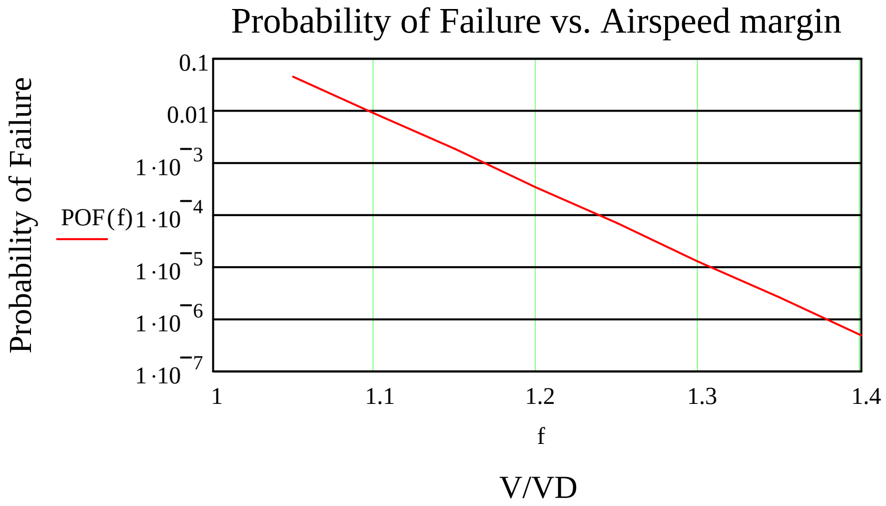
General probabilistic approach

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

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

F_{Va} is a CPF (cumulative probability function) of maximum random airspeed per life,

f_{vf} is PDF (probability distribution function) of random flutter speed



Failure types considered

- **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**

Probabilistic Data Mining

Data type	Availability in public domain/uncertainty	Demands	Conditions
Airspeed, Mach number, temperature	Typical data are available for airspeeds less than V_D	Reasonable extrapolation method	Some research efforts needed
Operational damage characterization	Extremely limited data on metal structures, windshields	Typical statistical data, prediction methods	Strict FAA requirements for data reporting
Damage detection capability	Limited data	Probabilistic characterization of certified inspection methods	Strict FAA requirements for method certification
Stiffness, mass, c.g. after repair	Almost unavailable	Probabilistic characterization of certified repair methods	Strict FAA requirements for method certification

Extreme Airspeeds

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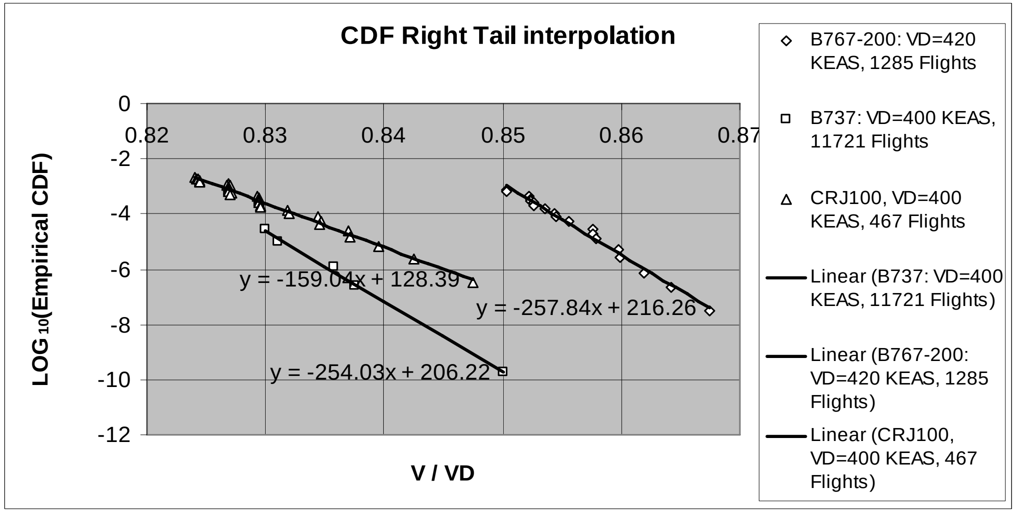
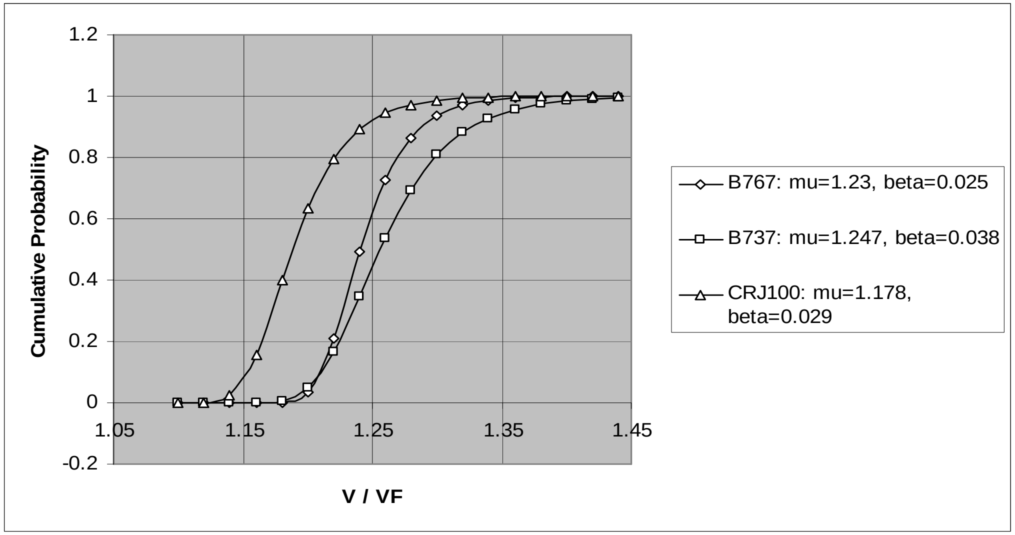




Extreme Value Type I (Gumbel) Distribution Function

$$G(V/V_D \mid \mu, \beta) = e^{-e^{-\frac{V/V_D-\mu}{\beta}}}$$

$$\beta = \frac{\sigma\sqrt{6}}{\pi};$$

$$\mu = \bar{x} - 0.5772\beta$$

Flaps-up configuration

$$F_{Va}(V/V_D) = F_{Va}(z) = \exp\left[-\exp\left(-\frac{z-1}{0.0063}\right)\right]$$

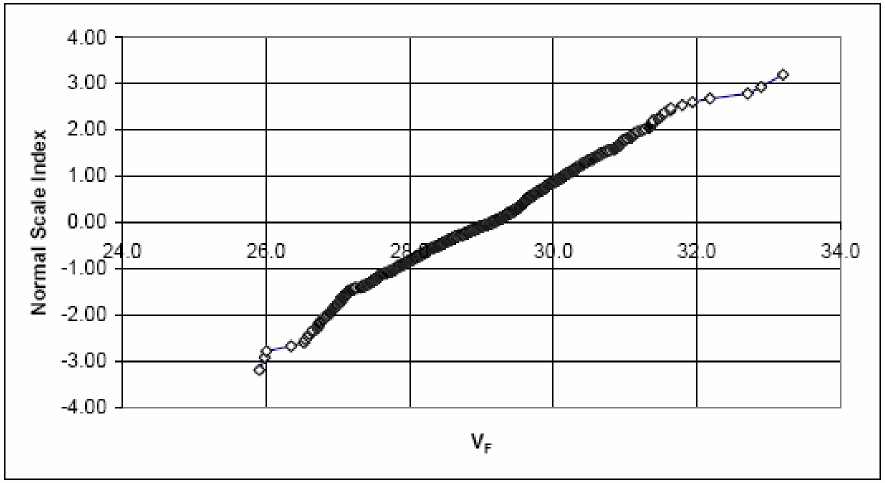
Flaps-down configuration

$$F_{Va}(V/V_{DF}) = F_{Va}(z) = \exp\left[-\exp\left(-\frac{z-1}{0.038}\right)\right]$$

Individual and Systemic Uncertainties of Flutter Speed

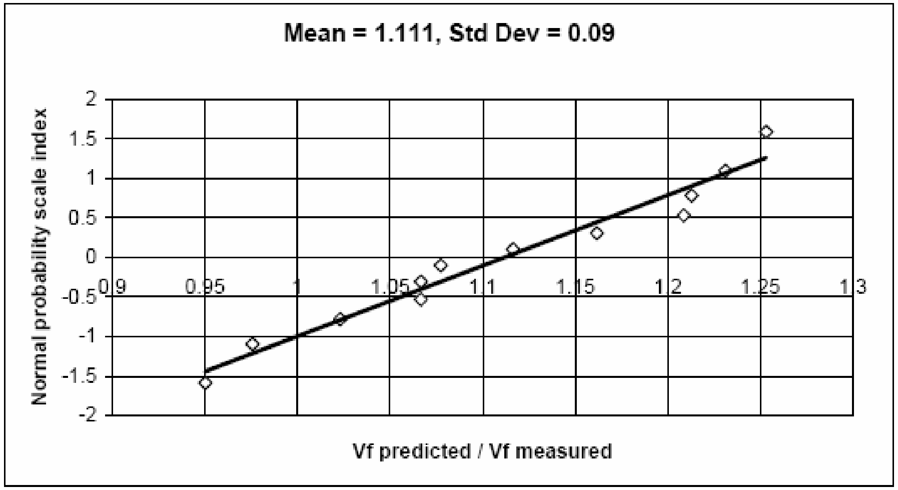
Individual Uncertainties:

Empirical CDF of Simulated Flutter Speed: Normal, C_V = 4%



Use of Sensitivities dV_f/dx_i

$$V_f(x_2, x_2, \ldots, x_n) = V_f(\overline{x}_2, \overline{x}_2, \ldots, \overline{x}_n) + \sum_{i=1}^{n} \frac{dV_f}{dx_i}(x_i - \overline{x}_i)$$



Systemic Uncertainties:

Empirical CDF for the Accuracy of Analytical Flutter Prediction

Normal; Mean = 1.11; σ = 0.09

Effect of flight tests – slide 1

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- Each fleet is described by V_f average value w.r.t. V_D; $\theta = E\{V_f\} / V_D$
- Scatter between various fleet's averages as described by prior CDF f_θ

$$f_\theta{}'(\theta) = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{(\theta - 1.11 \times 1.15 \times V_D)^2}{2\sigma^2}};$$

$$\sigma = 0.09 \times 1.15 \times V_D$$

Scatter of individual aircraft's V_f

$$f_Y(Y) = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{(Y-\theta)^2}{2\sigma^2}};$$

$$\sigma = 0.04 \times \theta$$

Population CDF(V_f/V_D) without tests (Prior CDF):

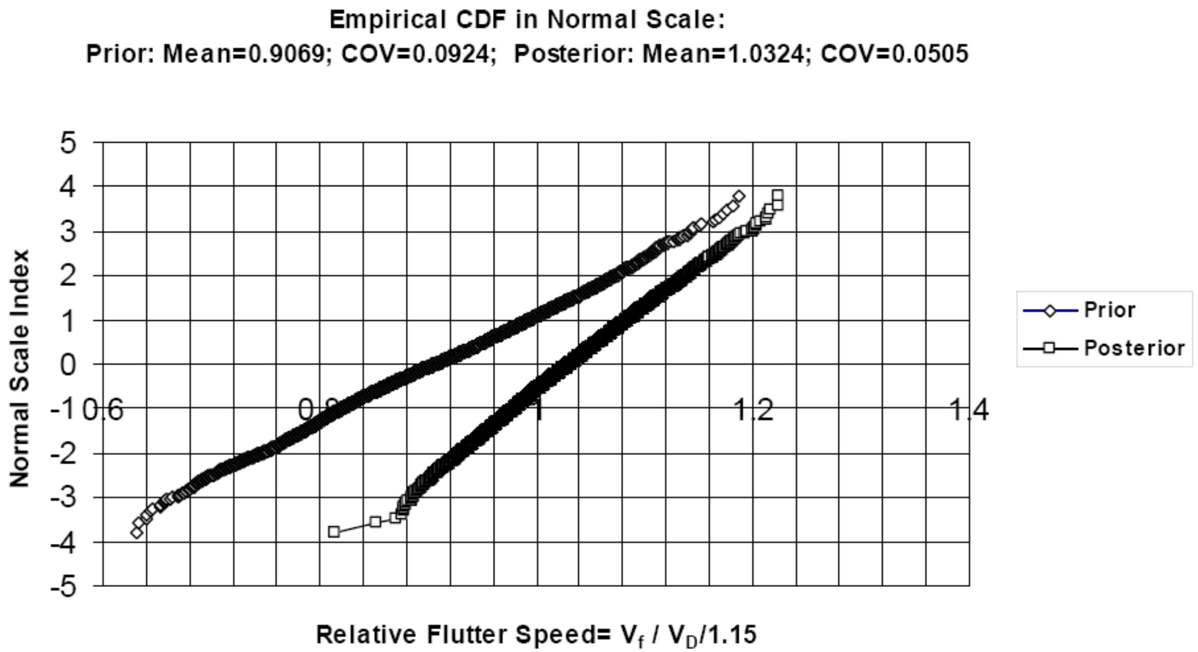
$$f_V(V) = \int_0^\infty \frac{1}{\theta} f_\theta(\theta)\, f_Y\left(\frac{V}{\theta}\right) d\theta$$

Effect of flight tests- slide 2

CDF of Flutter Speed without and With Flight Tests; Unconservative Design.

Bayes formula for posterior PDF:

$$f_\theta''(\theta) = \frac{f_z(z\,|\,\theta)\, f_\theta'(\theta)}{\int f_z(z\,|\,\theta)\, f_\theta'(\theta) d\theta}$$



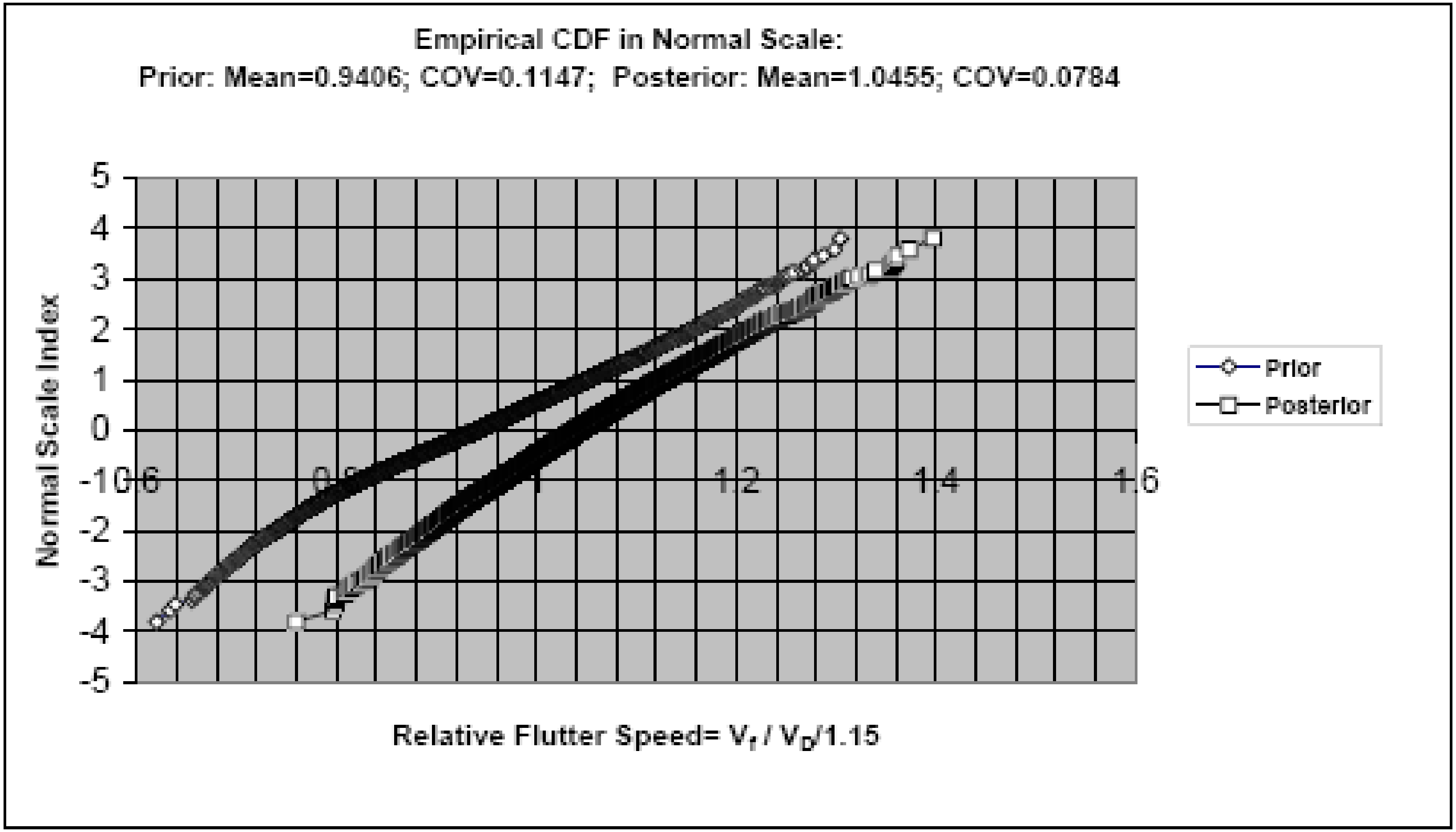
Effect of flight tests –slide 3

Spring Meeting
April 12, 2007

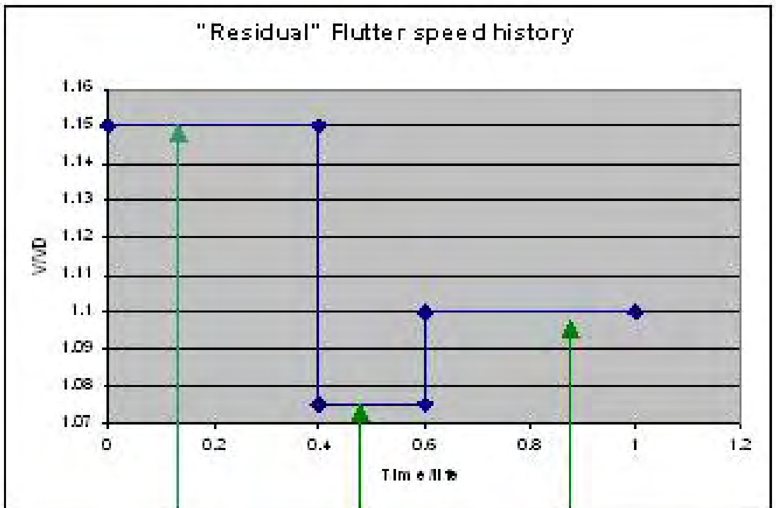
Metal structure: model mean COV = 9%, Fleet articles COV = 4%, Test extrapolation C_V = 1%								
	Analysis only				Analysis Supported by Flight Tests			
	Mean	C_V,%	POF, flaps retracted	POF, flaps extended	Mean	C_V,%	POF, flaps retracted	POF, flaps extended
Unconservative Design	0.9	9.8	0.35	0.45	1.032	5.05	0.00045	0.025
Conservative Design	1.11	9.8.	0.0088	0.031	1.127	8.7	8.5E-5	0.007
Composite structure: model mean COV = 9%, Fleet articles C_V = 6%, Test extrapolation C_V = 1%								
	Analysis only				Analysis Supported by Flight Tests			
	Mean	C_V,%	POF, flaps retracted	POF, flaps extended	Mean	C_V,%	POF, flaps retracted	POF, flaps extended
Unconservative Design	0.89	10	0.44	0.45	1.042	8.1	0.017	0.05
A-allowable for stiffness	1.15	12	0.01	0.03	1.16	10	0.0026	0.013
Design for 25% stability margin	0.9	11	0.18	0.22	1.05	8	4.9E-4	0.0078

Effect of flight tests – slide 4

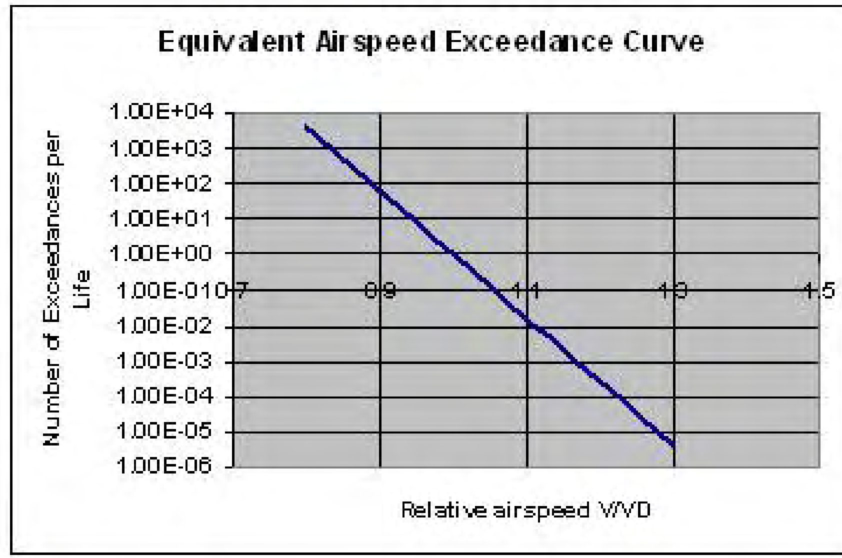
CDF of Flutter Speed without and With Flight Tests; Unconservative Design; Composite structure; Stability Margin = 25%



Probability of Failure Formulation 1



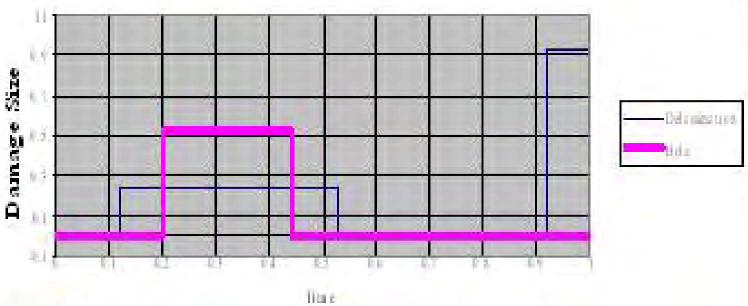
Before Damage | With Damage | After Repair
Flutter speed



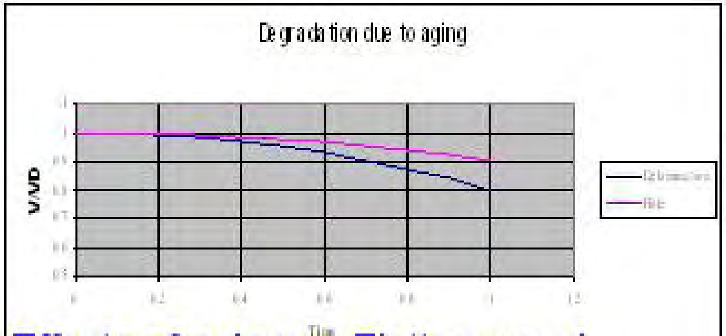
$$P_f = 1 - \prod_{i=1}^{N=3} [1 - P_f(V_i, t_i)]$$

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

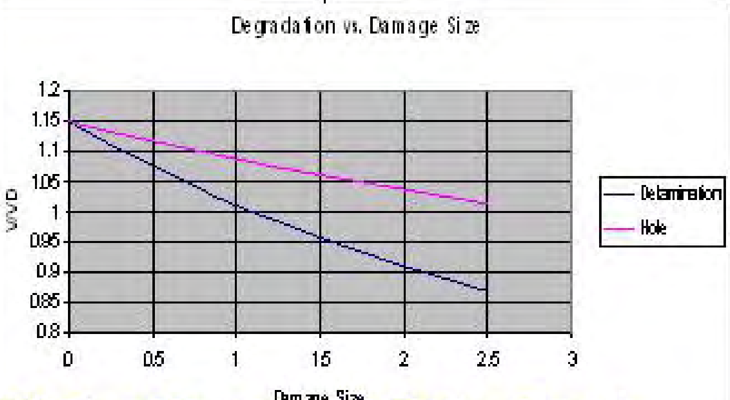
Probability of Failure Formulation 2



Multiple damages / times / repairs



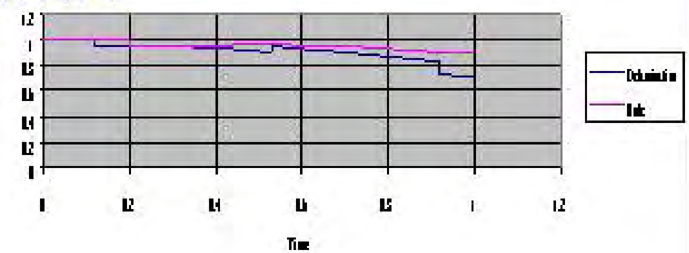
Effects of aging on Flutter speed



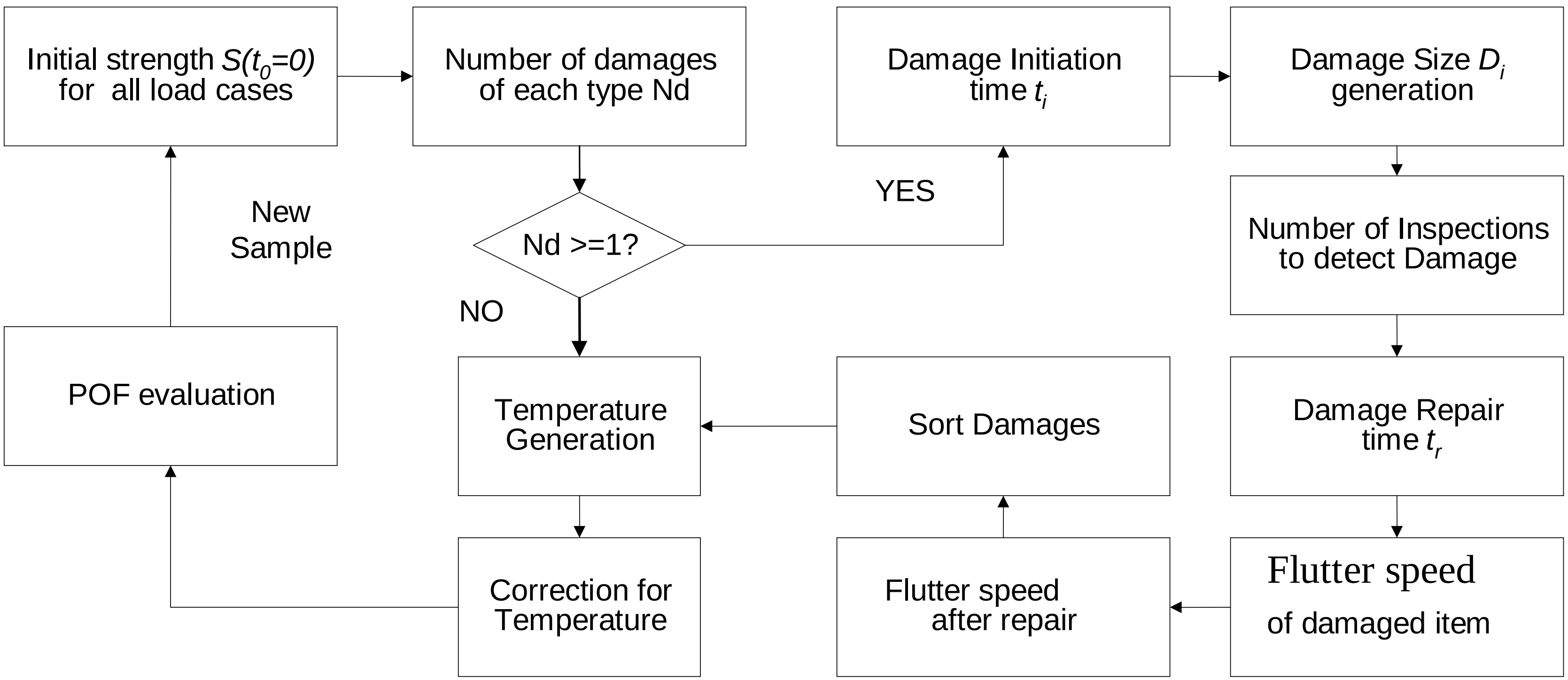
Effects of Damage on Flutter Speed

Total degradation for both damages

VF/VF0



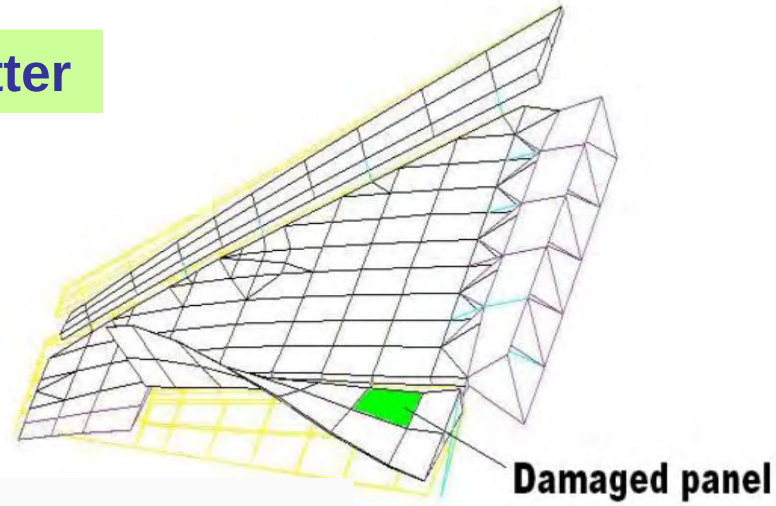
Simulation flowchart

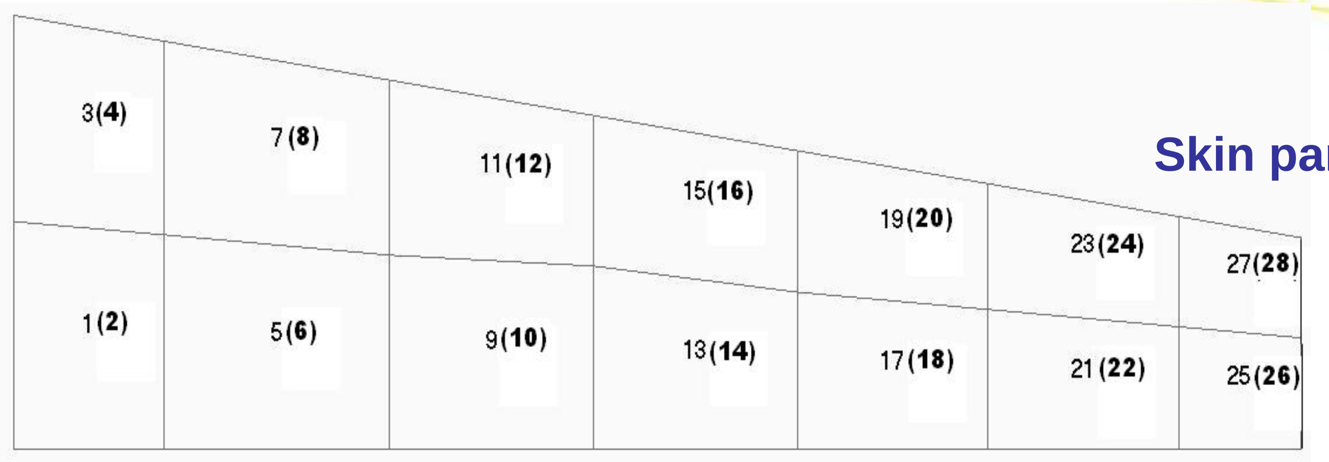


3D Airframe example problem –slide 1

Spring Meeting
April 12, 2007

Realistic wing-flaperon system flutter



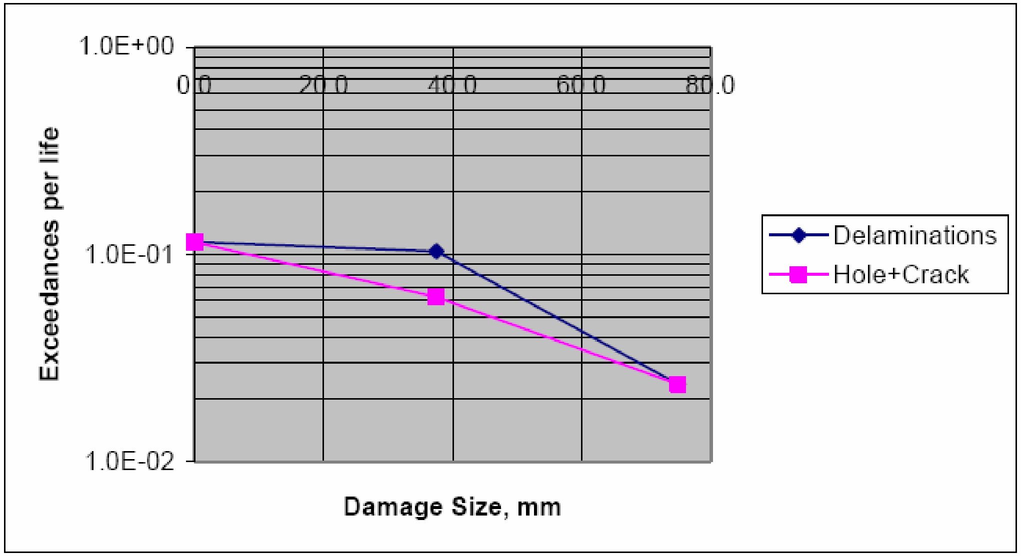


Skin panel IDs top (bottom)

3D example problem – slide 2

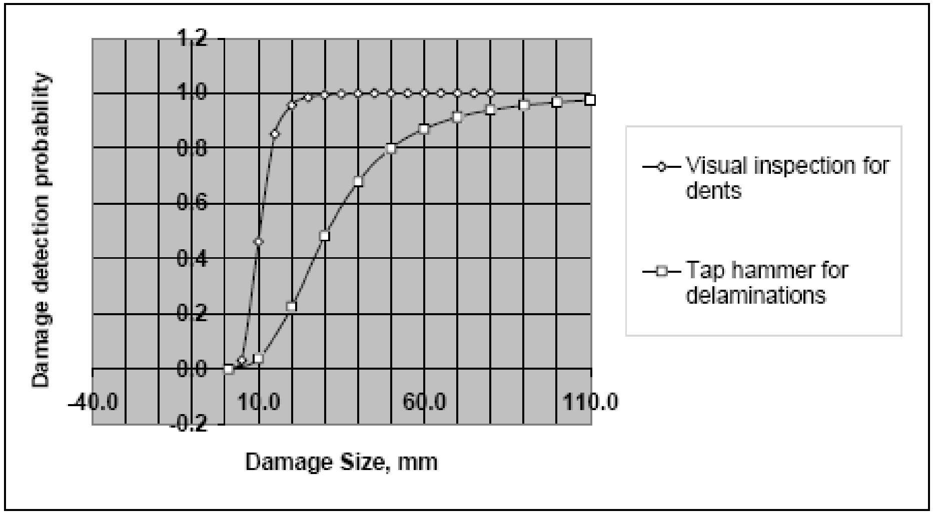
Damage Exceedance Data:

Delaminations; Holes and Cracks



Probability of Damage Detection per inspection:

Visual inspection; tap hammer inspection



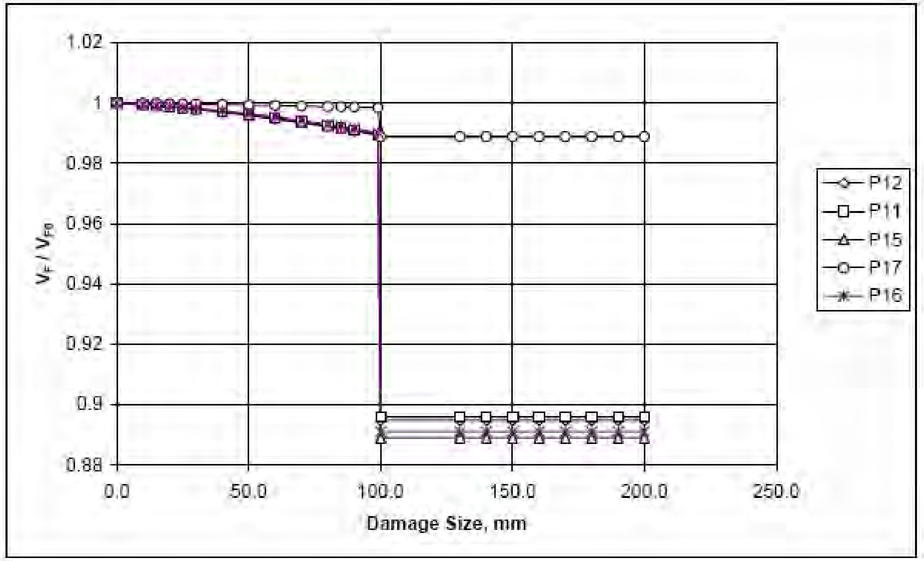
3D example problem – slide 3

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

Residual stiffness based on rule-of-mixtures

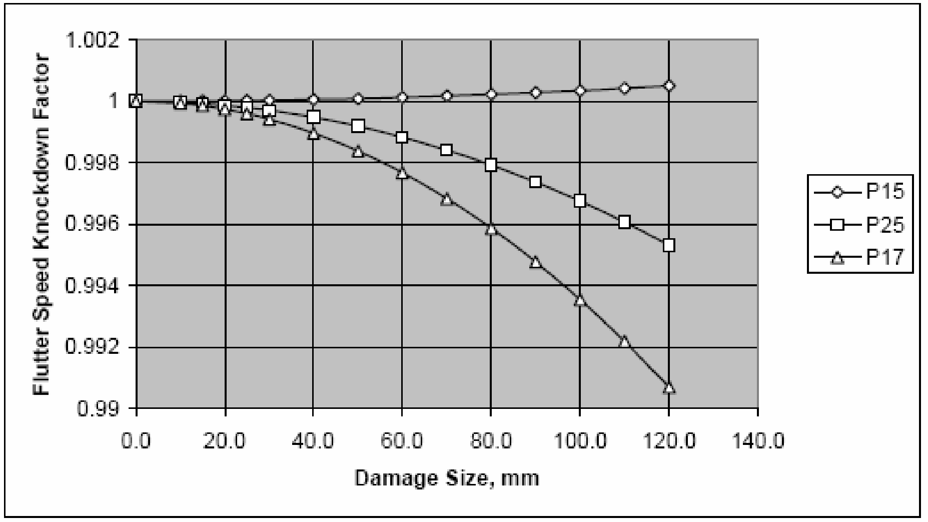
$$\kappa_T = \left(\frac{W - W_D}{W}\right)\kappa_{T(U)} + \left(\frac{W_D}{W}\right)\kappa_{T(D)};$$

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



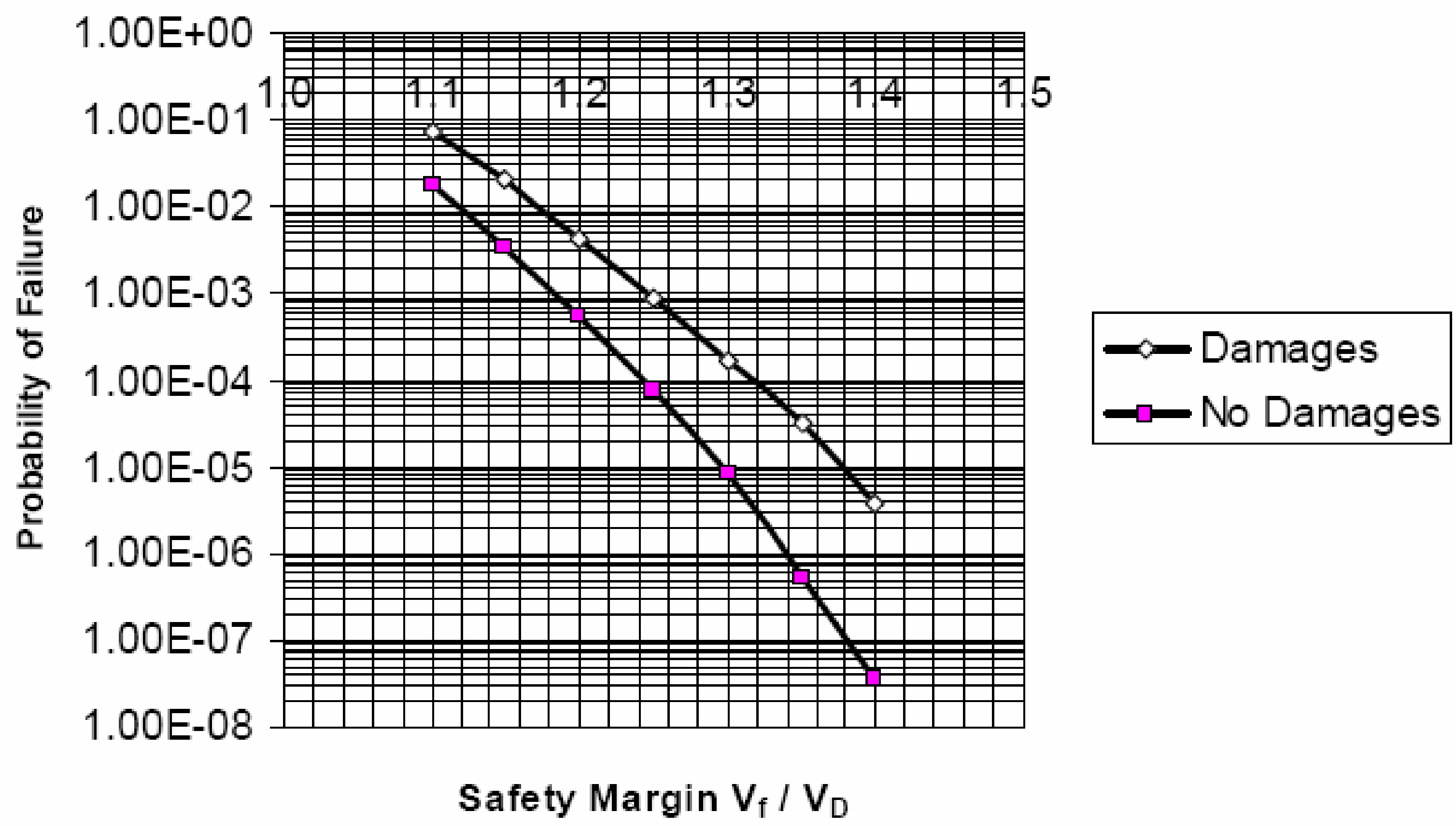
Flutter Speed Repair Recovery

Knockdown factor for different panels



3D example problem – slide 4

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



Problems to solve

- LCO of real vertical stabilizer-rudder system
  - The present method allows engineers to design damage tolerant composite structures for a predetermined level of reliability, as required by FAR 25.
  - The present study makes it possible to determine the relationship among the reliability level, inspection interval, inspection method, and repair quality to minimize the maintenance cost and risk of aeroelastic instability.

- Future needs
  - Residual stiffness for damaged local elements by detailed nonlinear FE simulations
  - A standardized methodology for establishing an optimal inspection schedule for aircraft manufacturers and operators.
  - Enhanced damage data reporting requirements regulated by the FAA.

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**

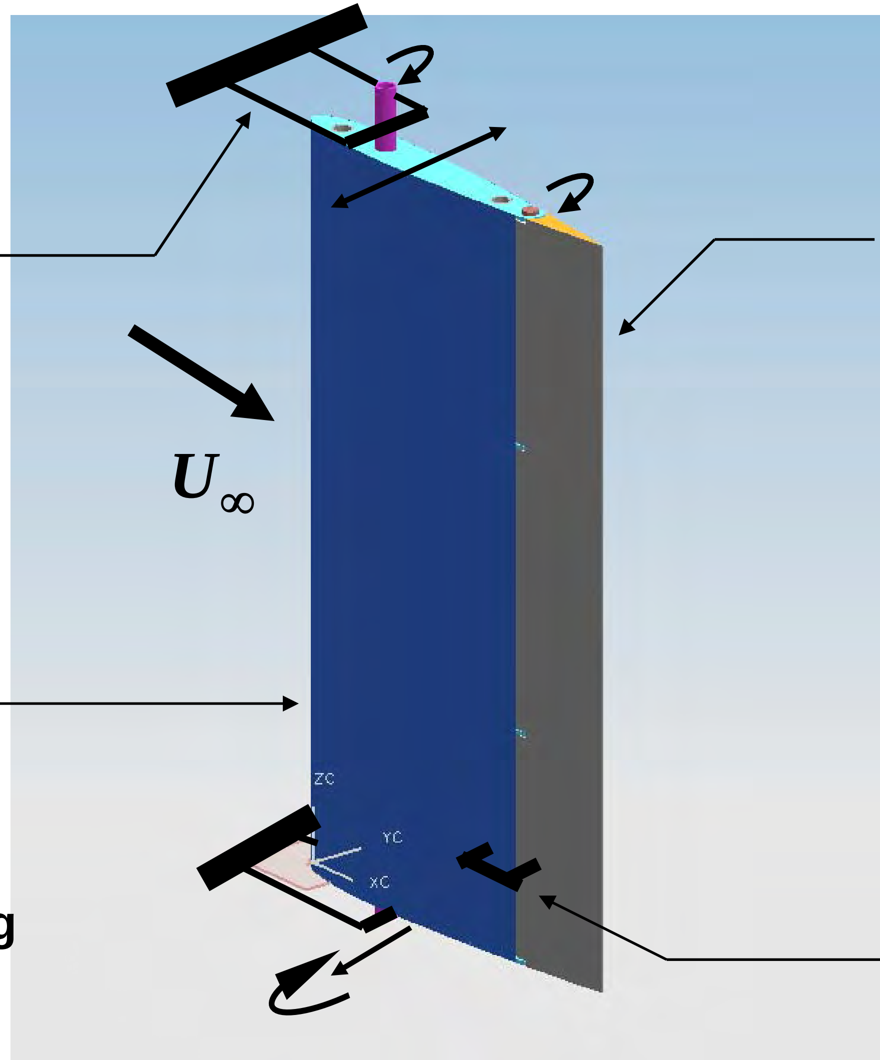
Experiments and experimental capabilities development

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

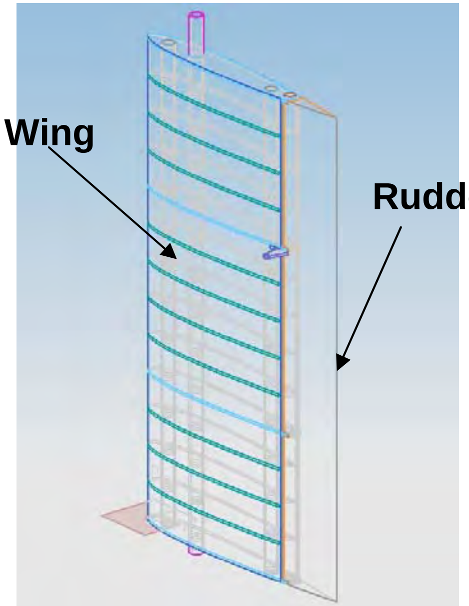
Wing - wind tunnel mount
Providing linear Plunge
And torsional pitch stiffnesses

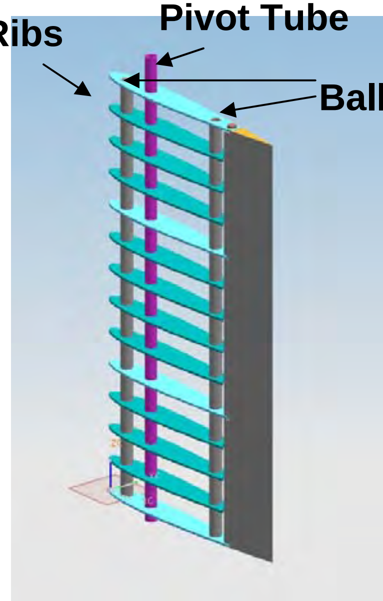


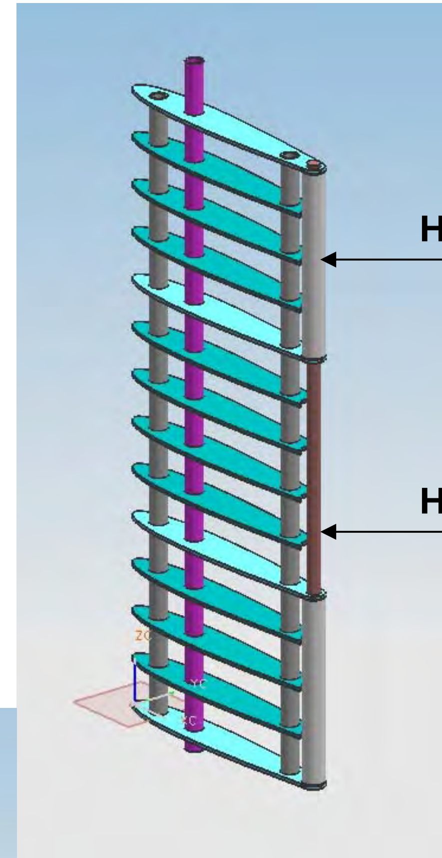
Rudder – composite construction allowing for simulations of damage and hinge failure

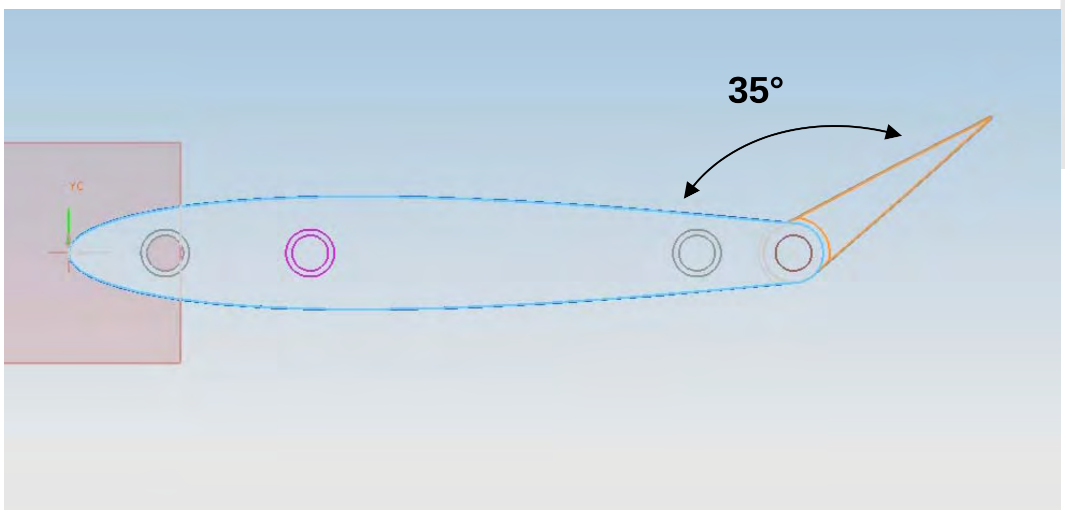
Aluminum wing allowing for variable inertia / cg properties

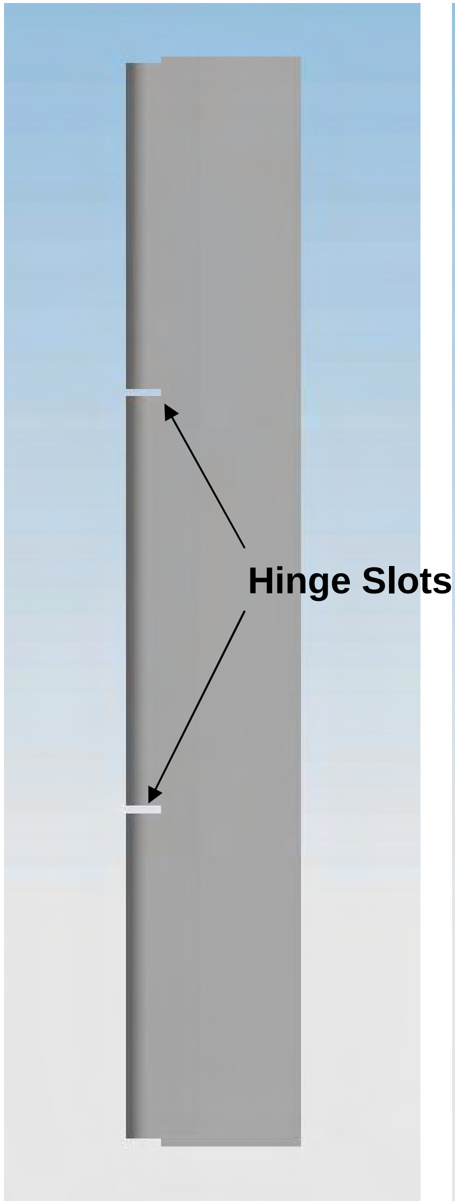
Simulated actuator attachment allowing for different nonlinearities

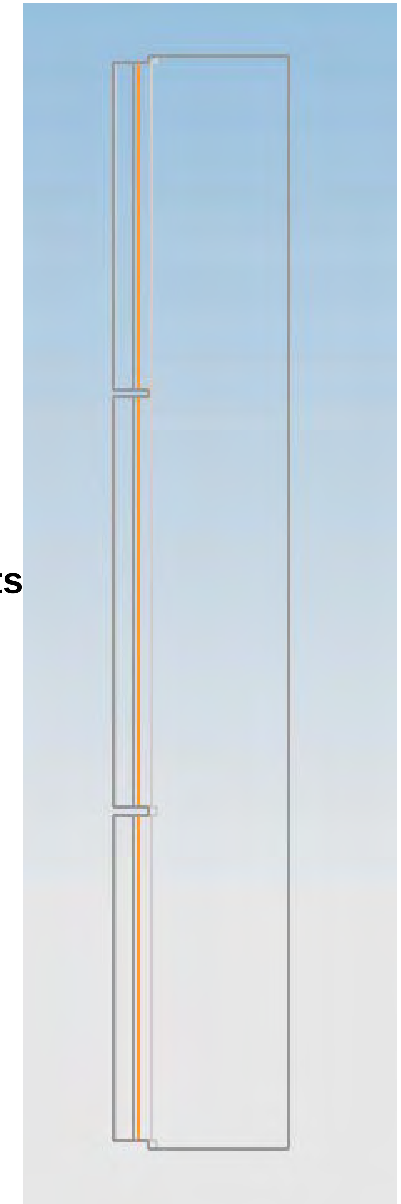

Wing
Rudder

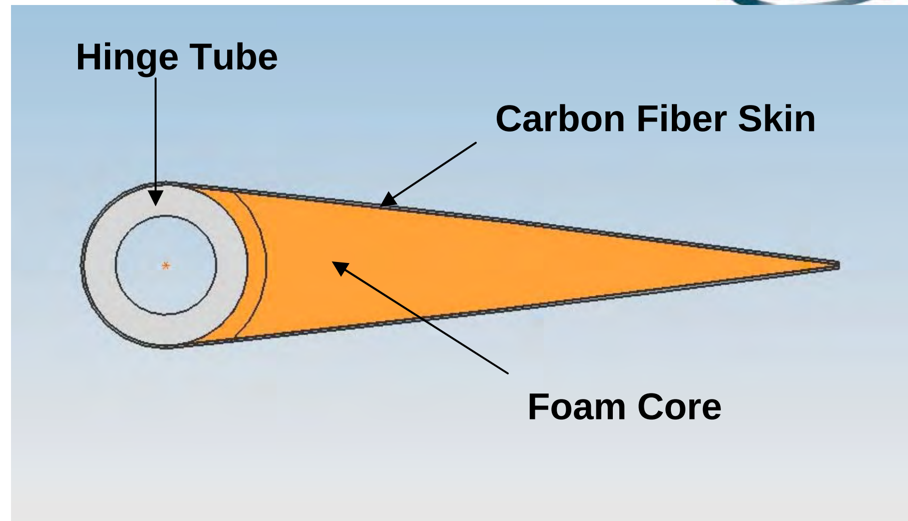

Ribs
Pivot Tube
Ballast Tube


Hinge Tube
Hinge Shaft

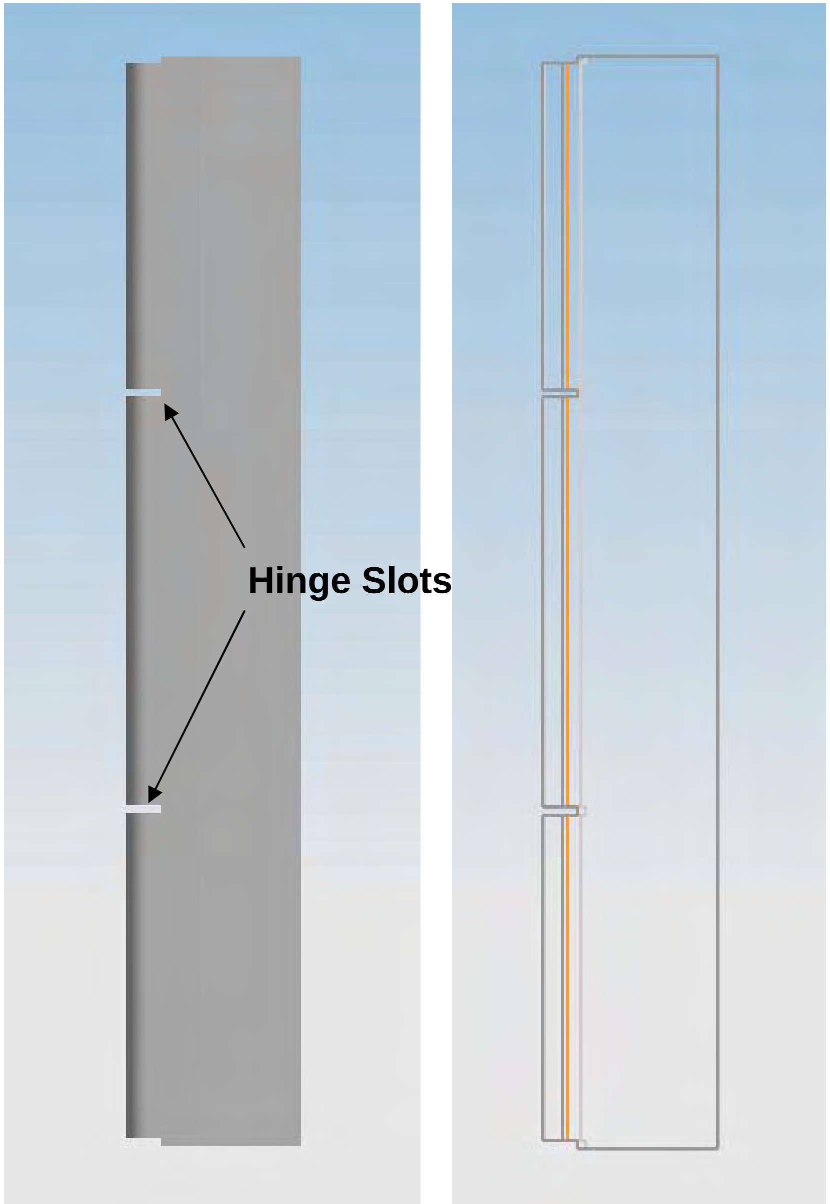

35°

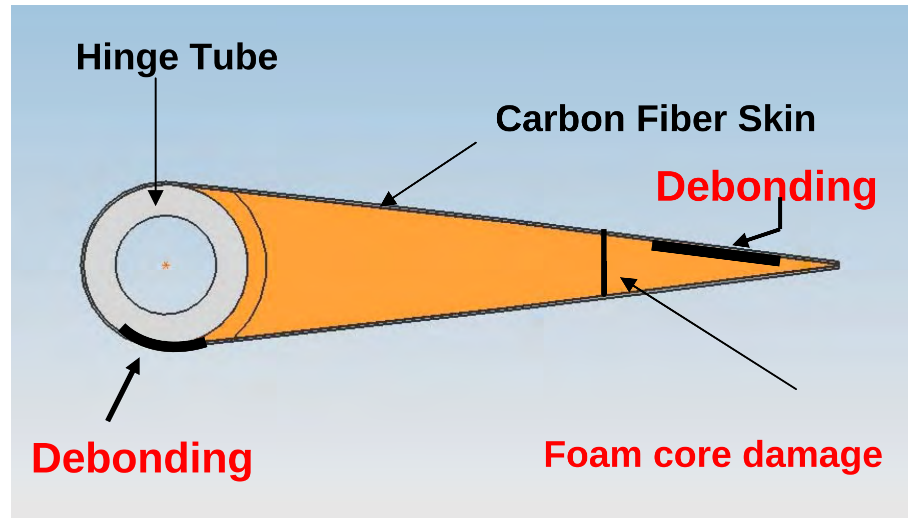






- **Rudder Assembly**
  - **Foam core is CNC machined.**
  - **The aluminum hinge tube is epoxy bonded to the foam core.**
  - **Carbon fiber is layed up around the aluminum/foam assembly and cured.**
  - **Slots are machined to accommodate the hinge ribs.**

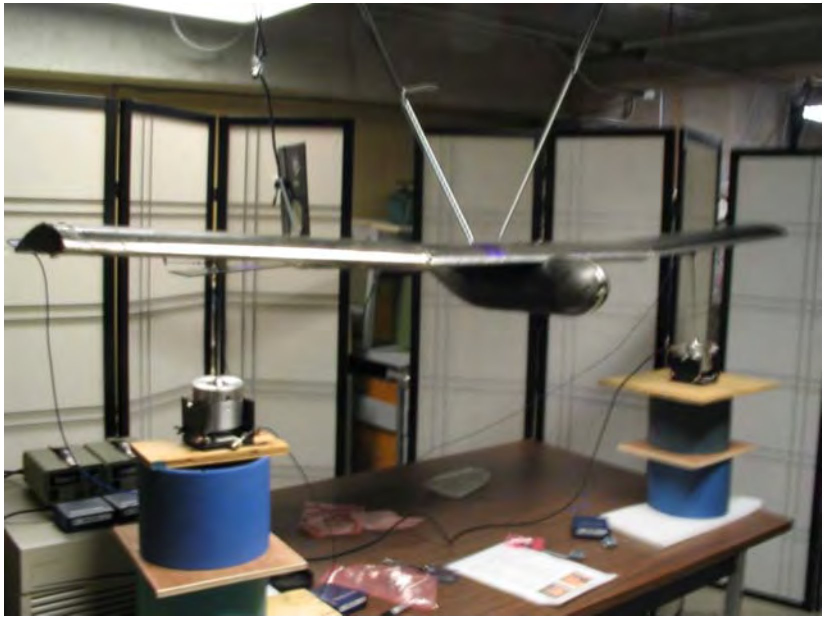




- Damage modes
  - Debonding.
  - Delamination
  - Core cracking
  - Hinge failure

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.

Plans

- **Linear Flutter**
  - Continue development of the UW in-house nonlinear aeroelastic simulation capability to include delamination, post-buckling, and other nonlinear damage mechanisms in composites.
  - Continue development of the integrated NASTRAN / ZAERO simulation environment:
    - Test using models with complexity representative of real passenger aircraft (a Boeing vertical tail / rudder system)
    - Improve automation of analysis and computational speed to allow efficient execution of the large number of simulations needed for probabilistic studies
    - Use sensitivity analysis / optimization to identify worst case damage scenarios
  - Use the Boeing vertical tail / rudder model to study damage effects on aeroelastic behavior
  - Add flight controls models for complete aeroservoelstic simulation

Plans

- **Nonlinear Aeroelasticity: LCO and explosive nonlinear flutter**
  - **Extend the UW time-domain LCO simulation capability to complete airplanes and their finite element models.**
  - **Integrate with probabilistic / reliability analysis.**
  - **Continue development of LCO and general nonlinear structure / aeroelasticity simulation tools for large-scale aeroelastically complex flight vehicles.**
  - **Develop a probabilistic approach to nonlinear aeroelastic problems.**

Plans

- **Probabilistics & Reliability**
  - **Develop models for generating local stiffness / mass information as function of damage type / size in key composite airframe components.**
  - **Study the aeroelastic reliability of comoposite airframes with time-dependent damage evolution.**
  - **Develop statistical models linking damage and repair statistics to stiffness / mass statistics.**
  - **Develop a comprehensive reliability methodology for composite airframes (with design and maintenance consequences) covering aeroelastic / aeroservoelastic failure modes.**

Plans

- **Experimental work**
  - **Build and test the wing / control surface model in the UW 3 x 3 wind tunnel. Validate the new testing capability by correlation with reference results: experimental (Duke) and by UW numerical simulation capabilities.**
  - **Use the wing / control surface model to test effects of damage and actuator nonlinearity on flutter characteristics.**
  - **Design nonlinear small scale models (with different sources of service life and damage-related nonlinearity) for the 3 x 3 tunnel.**
  - **Carry out numerical simulations, correlate with structural dynamic tests, and follow up with aeroelastic wind tunnel tests.**
  - **Expand aeroelastic test capabilities at the UW (aditional test equipment and planning for tests with large aeroelastic models at the Kirsten wind tunnel**