JAMS

A Center of Excellence
AMTAS
Advanced Materials in
Transport Aircraft Structures

CECAM
center of excellence for
composites and advanced materials

Project:

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

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JAMS Meeting,
April 2011

UNIVERSITY OF
WASHINGTON

An Overview of the Project

covering

- Aeroelastic probabilistic reliability analysis of composite airframes
- Efficient aeroelastic simulation methods for composite airframes undergoing large deformation and possible damage
- Wind tunnel tests of scaled aeroelastic models of nonlinear and damaged composite airframes

Contributors

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  - **Sang Wu – PhD student**
- **Department of Mechanical Engineering**
  - **Francesca Paltera, PhD student**
  - **Dr. Mark Tuttle, co-PI, professor and chairman**
- **Boeing Commercial, Seattle**
  - **Dr. James Gordon, Associate Technical Fellow, Flutter Methods Development**
  - **Dr. Kumar Bhatia, Senior Technical Fellow, Aeroelasticity and Multidisciplinary Optimization**
- **FAA Technical Monitor**
  - **Lynn Pham, Advanced Materials & Structures, Aircraft and Airport Safety**
  - **Curtis Davies, Program Manager of JAMS, FAA/Materials & Structures**
- **Other FAA Personnel Involved**
  - **Dr. Larry Ilcewicz, Chief Scientific and Technical Advisor for Advanced Composite Materials**
  - **Carl Niedermeyer, FAA Airframe and Cabin Safety Branch (previously, Boeing flutter manager for the 787 and 747-8 programs)**

Motivation and Key Issues – a Review

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

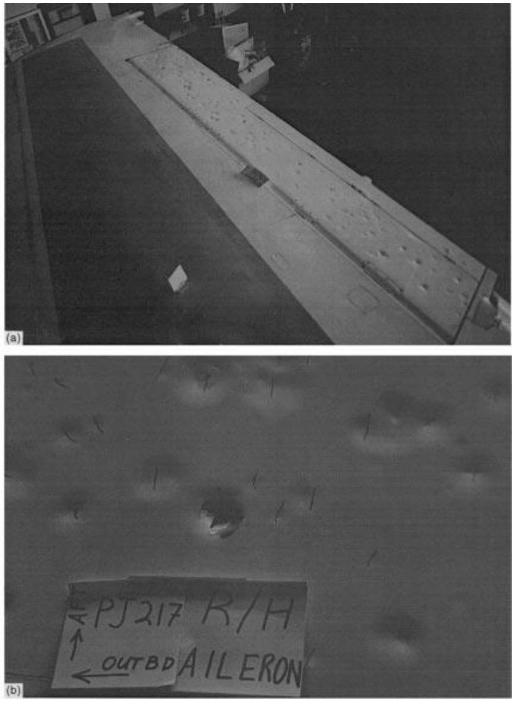
- Sources of uncertainty in composite structures:
  - Material property statistical spread
  - Damage
  - Delamination
  - Joint/attachment changes
  - Debonding
  - Environmental effects, etc.

- 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.

- Nonlinear structural behavior:
  - Highly flexible, optimized composite structures (undamaged or damaged) may exhibit geometrically nonlinear structural behavior, with aeroelastic consequences.

- Modification of control laws later in an airplane's service can affect dynamic loads and fatigue life.

Effects of Uncertainty and Damage on Aeroelastic Behavior and Safety



Objectives – a Review of the Multi-Year Program

- **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.**

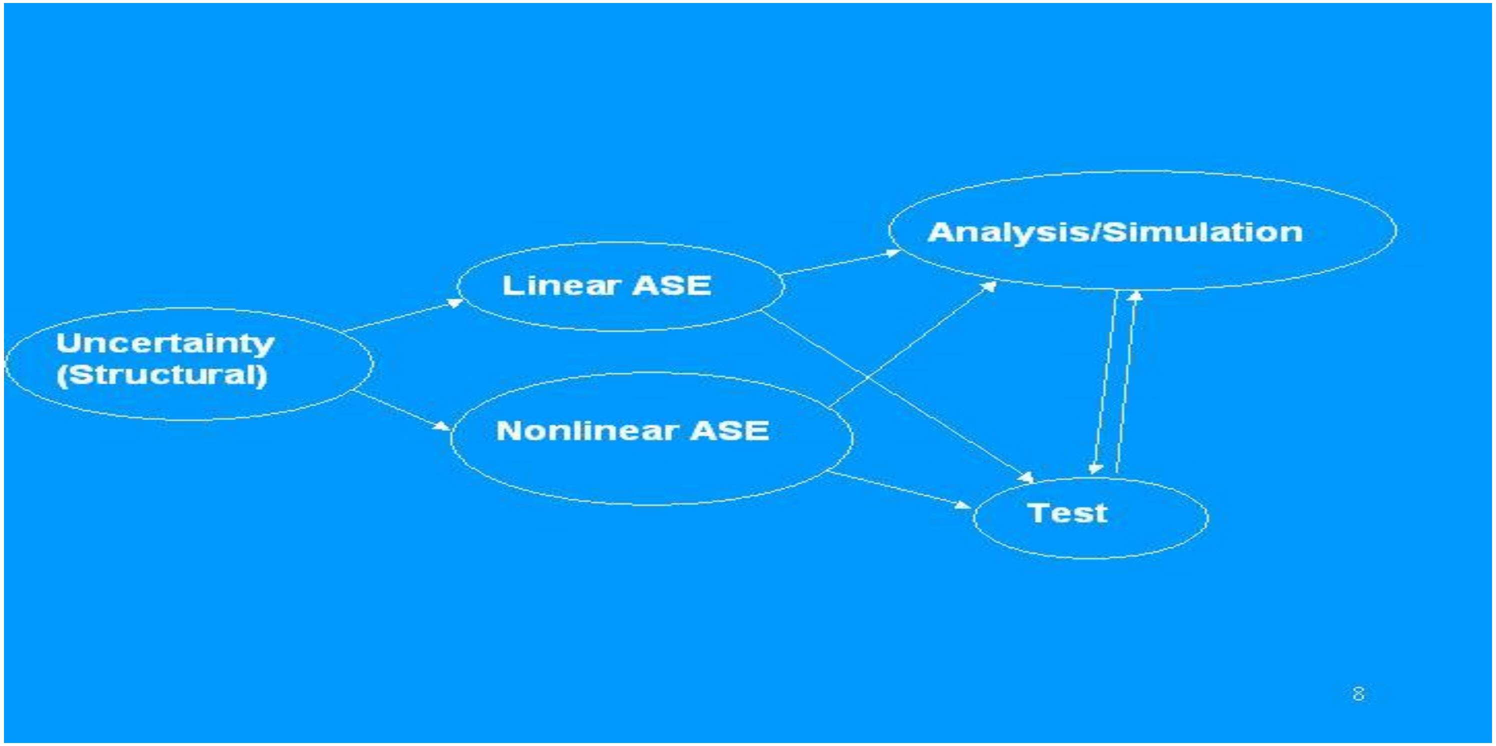
- **Link with design optimization tools to affect design and repair considerations.**

- **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.**

Program Approach

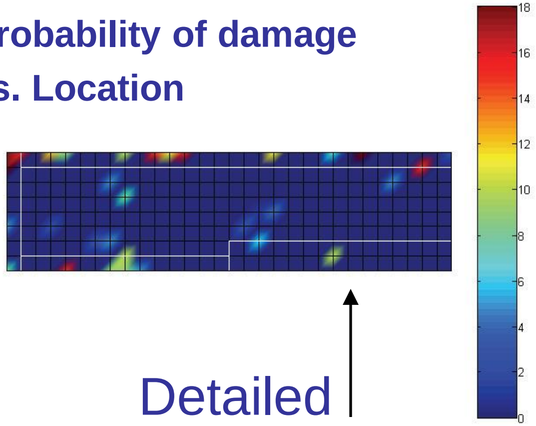
- Efficient simulation (linear & nonlinear).
- Probabilistic reliability assessment.
- Aeroelastic tests of aeroelastically scaled models.



Life Cycle Probabilistic Structural / Aeroelastic Modeling for Reliability Evaluation of Damage Tolerant Composite Structures

Damage statistics: Type, Size, Location, Detection, Repair, Effect of Residual Strength & Stiffness (and mass)

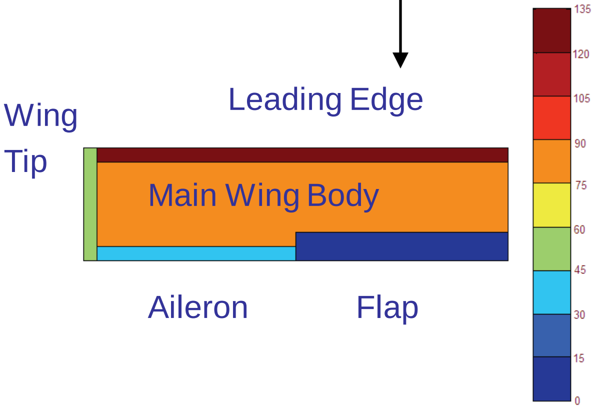
Probability of damage vs. Location



Detailed

Damage maps:

Discrete



Damage probability vs. size

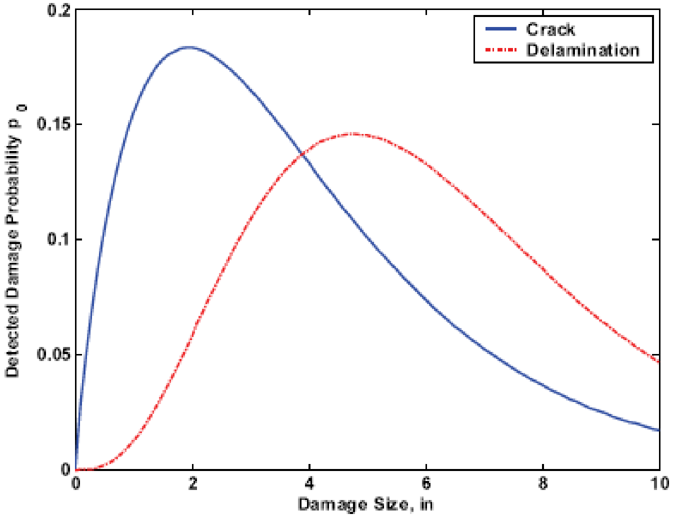


Figure 3. Detected Damage Size Gamma Distribution of Rectangular Wing Aileron

Probability of damage detection vs. size

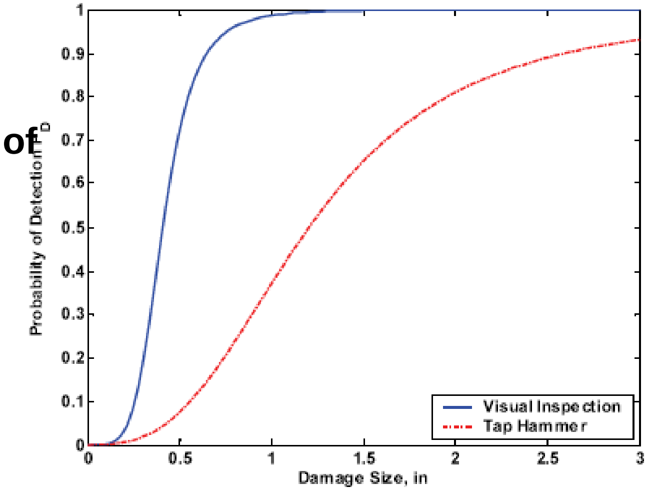
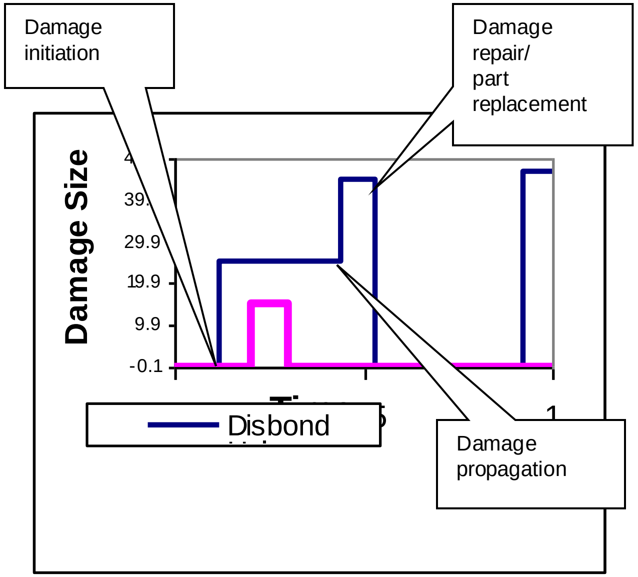


Figure 4. POD for Visual and Tap Hammer Inspection Methods

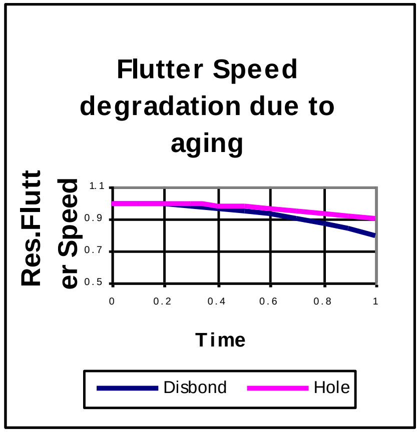
Residual Flutter Speed over Service Life

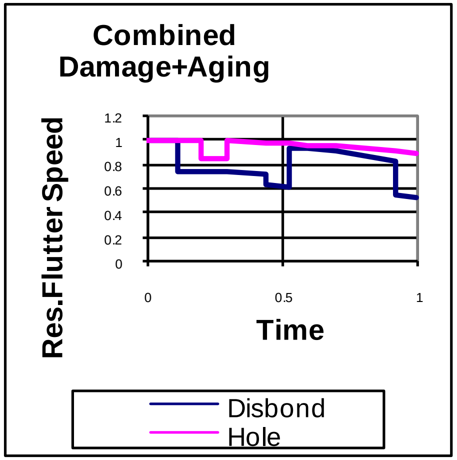


Damage initiation

Damage repair/ part replacement

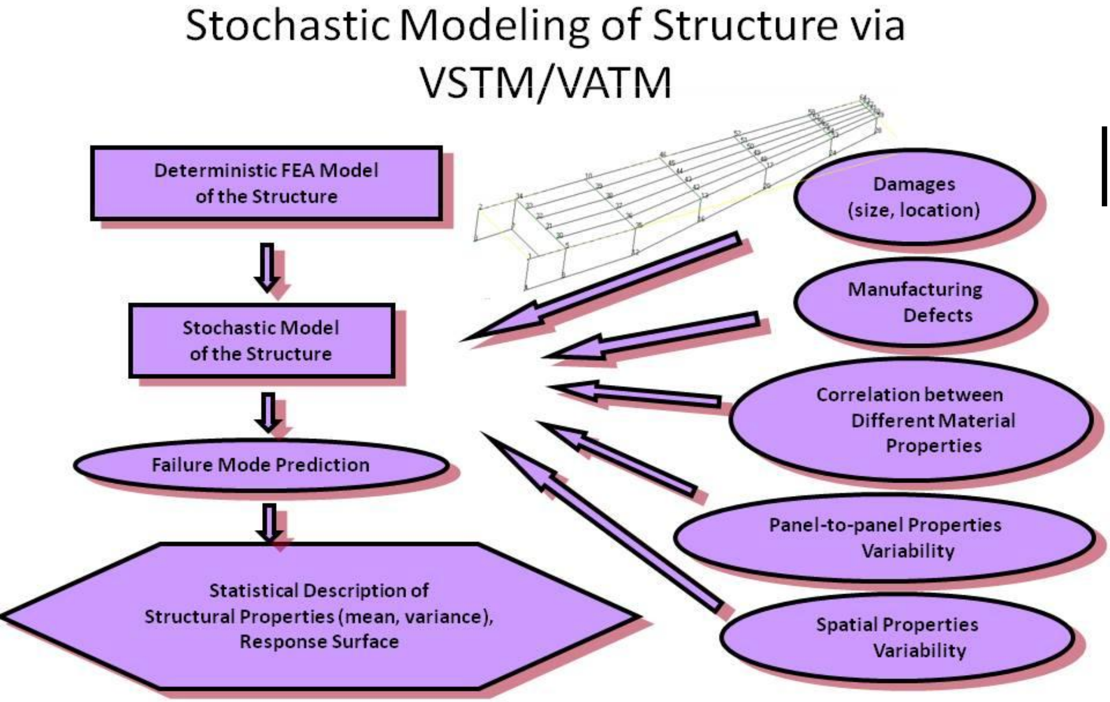
Damage propagation





In addition to residual strength, residual stiffness and residual flutter speeds are tracked over time of service, and the probability of flutter events due to uncertainty in flutter characteristics AND operational speeds / dynamic pressures is assessed.

Virtual Testing



Stochastic Modeling of Structure via VSTM/VATM

Deterministic FEA Model of the Structure

Stochastic Model of the Structure

Failure Mode Prediction

Statistical Description of Structural Properties (mean, variance), Response Surface

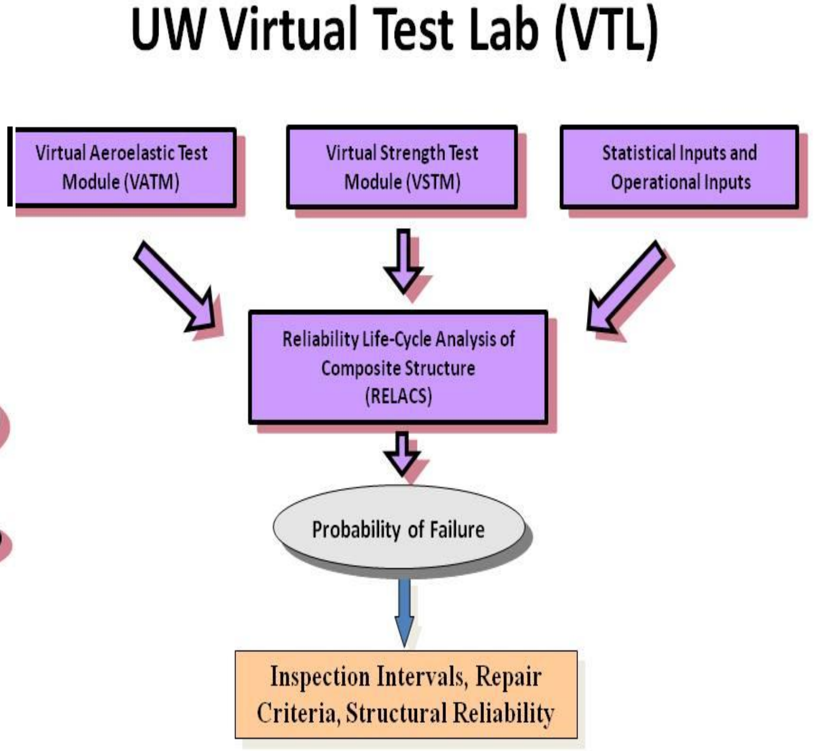
Damages (size, location)

Manufacturing Defects

Correlation between Different Material Properties

Panel-to-panel Properties Variability

Spatial Properties Variability



UW Virtual Test Lab (VTL)

Virtual Aeroelastic Test Module (VATM)

Virtual Strength Test Module (VSTM)

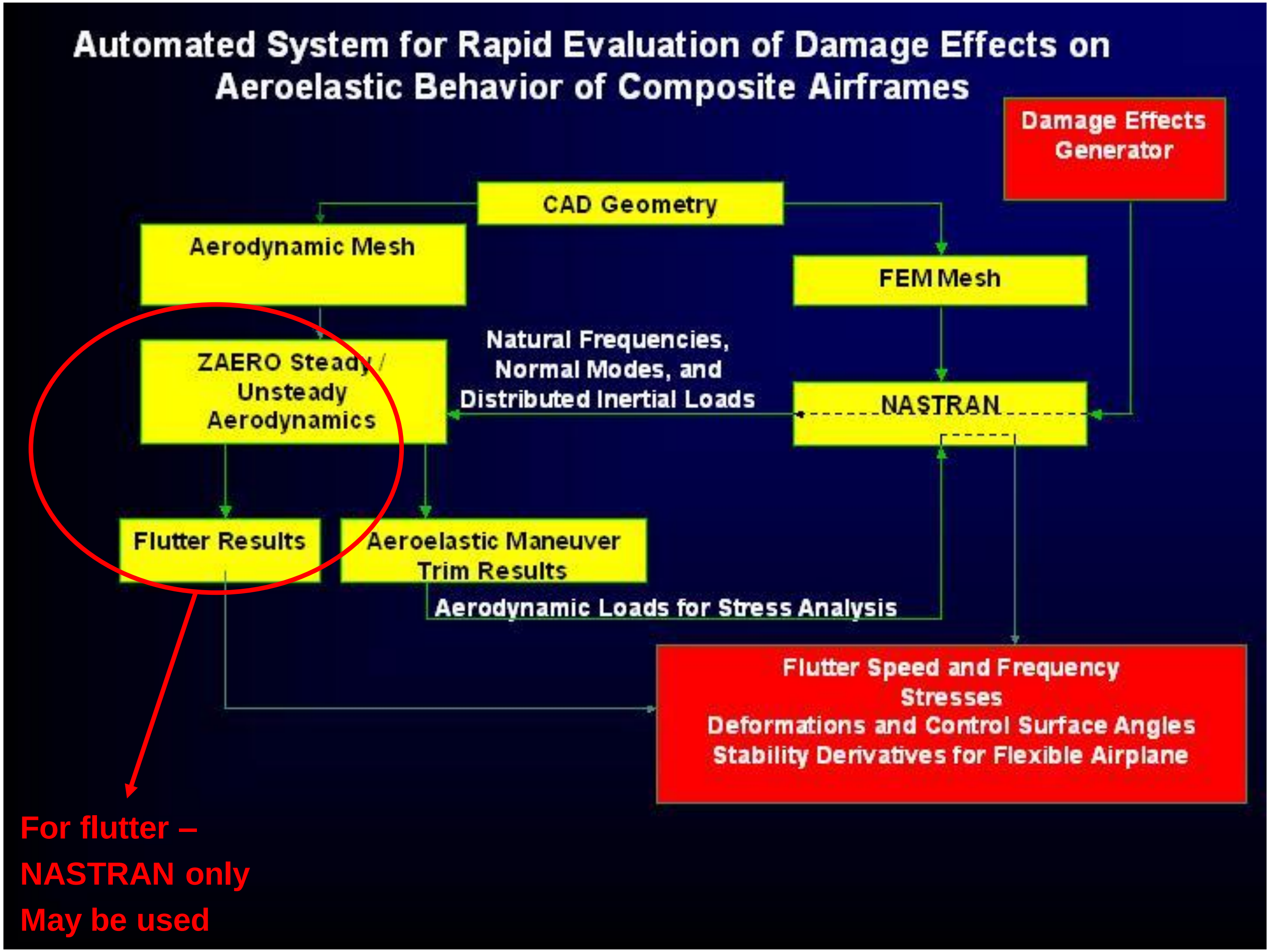
Statistical Inputs and Operational Inputs

Reliability Life-Cycle Analysis of Composite Structure (RELACS)

Probability of Failure

Inspection Intervals, Repair Criteria, Structural Reliability

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



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

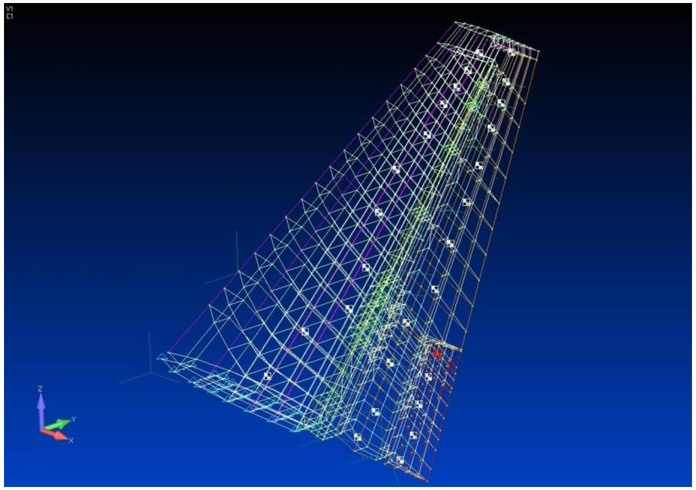
For flutter –
NASTRAN only
May be used

An Example: Evaluation-Model of a Vertical Tail / Rudder System

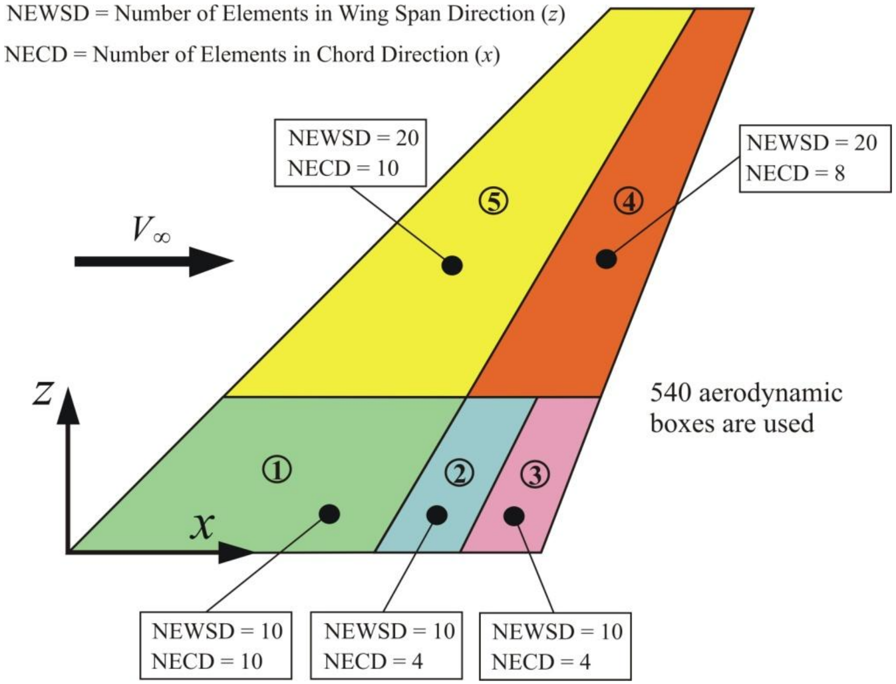
Structure:

- Number of grid points =1268
- Number of CBAR elements = 309
- Number of CBUSH elements = 45
- Number of CONM2 elements = 28
- Number of CQUAD4 elements = 1409
- Number of CROD elements = 1056
- Number of CSHEAR elements = 91
- Number of CTRIA3 elements =187
- Number of RBE2 elements =16
- Number of RBE3 elements = 28

Caution: this case does not represent any airplane in service.



Unsteady Aerodynamics – Doublet Lattice

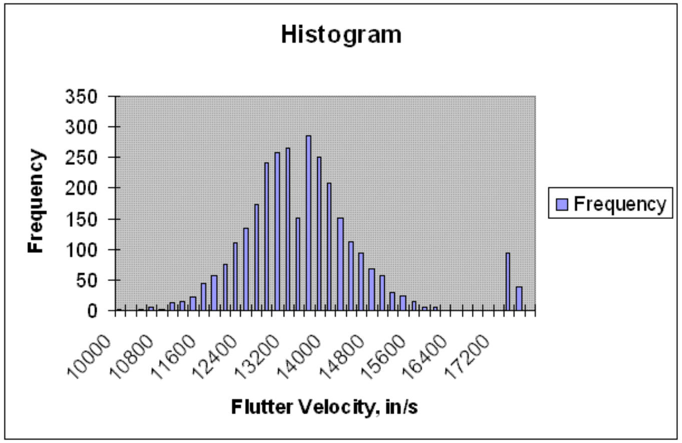


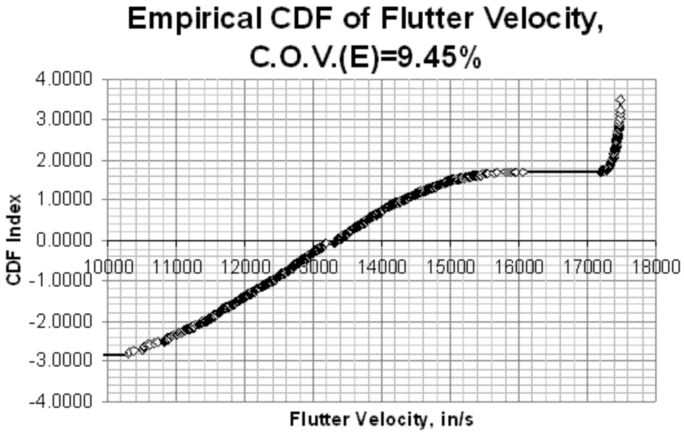
Statistical Flutter Results for the Tail / Rudder System
No Damage

- Structural Variability (Construction. Assumptions are for illustration of the methodology)

Property	Panel-to-panel C.O.V.	Element-to-element C.O.V.	Radius of Correlation, in
Thickness *t*	0.03	0.01	10
G11	0.05	0.02	100
G22	0.05	0.02	100
G12	0.05	0.02	100

- Flutter results





- Note: The flutter PDF is multi-modal. Some members of the fleet may have flutter due to mechanisms different from those of others.
- The variance of *VF* is noticeably greater than variances for input parameters (in this case)

Damaged Vertical Tail – Flutter Speed Statistics

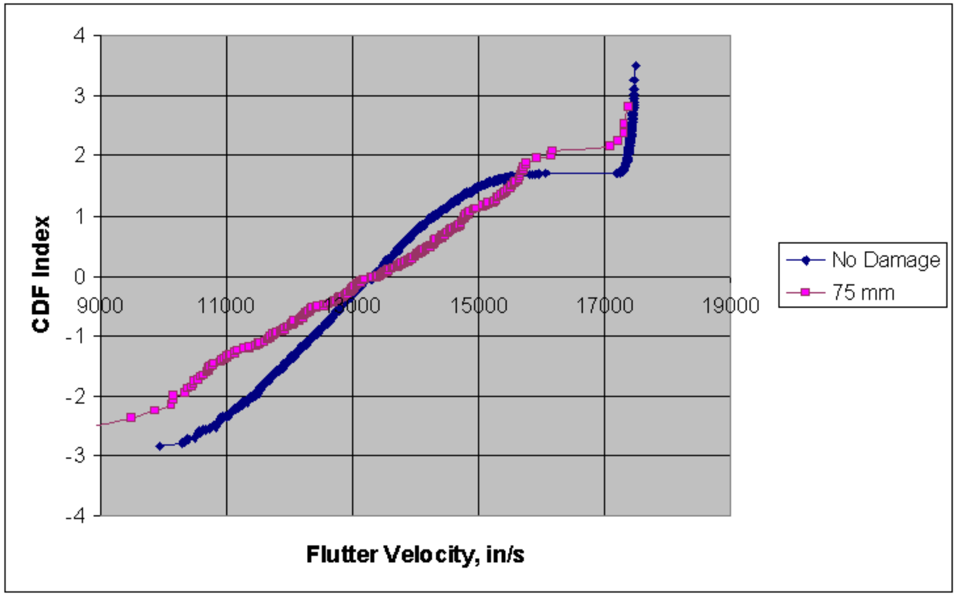
Residual stiffness (tension & compression) based upon a

rule-of-mixtures

for constant thickness panel

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

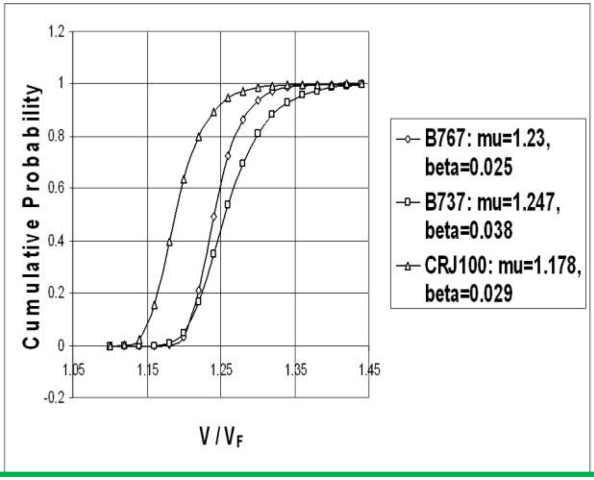
$$\kappa_C = \left(\frac{W-W_D}{W}\right)\kappa_{C(U)} + \left(\frac{W_D}{W}\right)\kappa_{C(D)}$$



Locations of damaged elements have been chosen randomly for this study with uniform distribution over the tail box skin area.

VATM – RELACS Studies for the Vertical Tail Example

- Statistical flutter results from the VATM simulations - now combined with flutter runs for damaged structures using RELACS.
- Number of Design Cases = 1; Subsonic flight.
- Number of Damage Types = 2; Hole and Delamination.
- Number of Inspection Types =2; Visual and Instrumental.
- The CDF of maximum airspeed per life
- The probability of damage detection model described previously by Styuart, Mor, Lin & Livne.
- Exceedance data of damage occurrence:
- Report DOT/FAA/AR-01/55, 2002
- recalculated for 60000 flight hours and torsion box skin



Damage exceedence curve

Probability of failure vs. design safety margin

Note: results are case dependent. Results also depend strongly on damage scenarios and maintenance practices

VATM – RELACS

A Unique Capability for Monte-Carlo Based Assessment of Aeroelastic Reliability in Damaged and Undamaged Composite Airframes

Combine:

- Statistical generator of FE models for composite airframes subject to manufacturing variation, material degradation, and damage effects.
- Statistics of flight operations (flight speeds exceedances)
- Statistics of inspections and repair.
- Automated rapid aeroelastic model generation, flutter simulations, results extraction and storage.
- Monte Carlo simulations.

To obtain:

- Flutter statistics and flutter reliability assessment for composite airplanes.
- Statistical sensitivities to all input parameters.

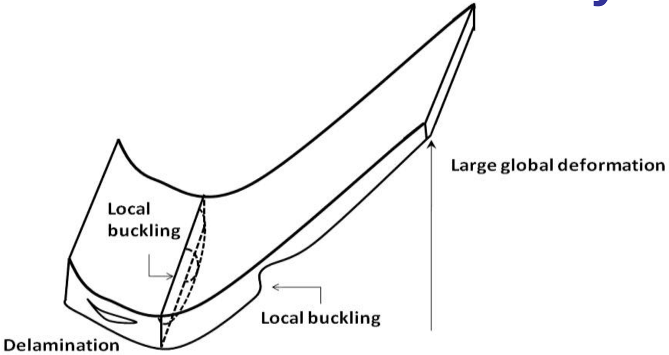
To yield:

- Understanding of the complex composite airplanes flutter variability problem and its key mechanisms and influences.
- Design and maintenance procedures.
- Guidance for research and development.

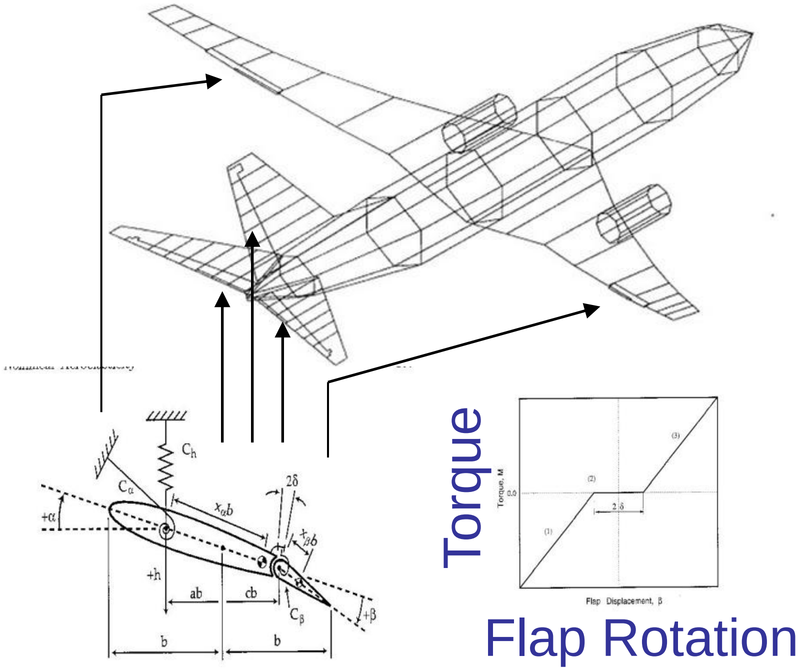
Dynamic Aeroelasticity of Structurally Nonlinear Airplane Configurations Using Linearized Unsteady Aerodynamic Models

JAMS Meeting,
April 2011

Local and Global Nonlinear Structural Effects in Composite Airframe Aeroelasticity

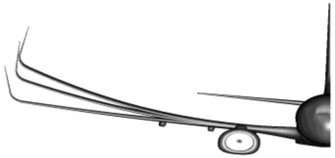


Localized “point” structural nonlinearities



“Distributed” geometric structural nonlinearities

Optimized composite airframes



New Configurations

Truss Braced Wings

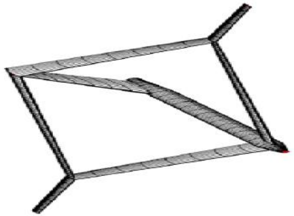
Joined Wings

Aeroelastic Modeling Detail & Complexity

Complexity, Fidelity, Modeling &Computational Costs

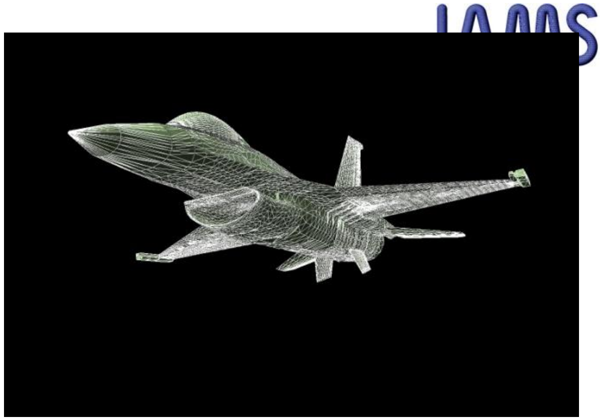

Daedalus

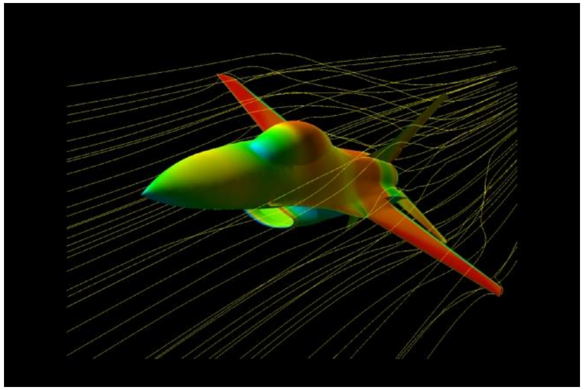

Helios


Sensorcraft Model - Cesnik

Nonlinear 3D beams (Hodges, Patil, Cesnik, Drela, Dowell)
Strip (incompressible: Peters, Modified Theodorsen)
DLM (Patil&Hodges: Application to HALE)
Nonlinear VLM (Mook, incompressible)
+ Nonlinear FEs (ZONA)

Useful
Mid-level
Modeling
(Physics Based)
???





CSD/Nonlinear FEs + CFD/NS
(Farhat et. al.)

The Fundamental Idea

- Modes (reduced basis) may be adequate for capturing the global deformation of a nonlinear structure: Thus, for coupling with unsteady aerodynamic loads
- To capture structural behavior (internal stresses, geometric stiffness), however, a full order FE model is required.
- March a full order nonlinear FE code forward in time:

$$\boxed{\left[K\left(\{u\}\right)\right]\{u\}=\left\{F\left(\{u\}\right)\right\} \quad \leftrightarrow \quad [M]\left\{\ddot{u}(t)\right\}+[C]\left\{\dot{u}(t)\right\}+\left[K\left(\left\{u(t)\right\}\right)\right]\left\{u(t)\right\}=\left\{F(t)\right\}}$$

- Fit a modal base generalized coordinate set $\{q\}$ to FE every deformation vector $\boxed{\{u\} \quad \rightarrow \quad [\Psi]\{q\}\approx\{u\} \quad \rightarrow \quad \{q\}}$
- And use modal based aerodynamics

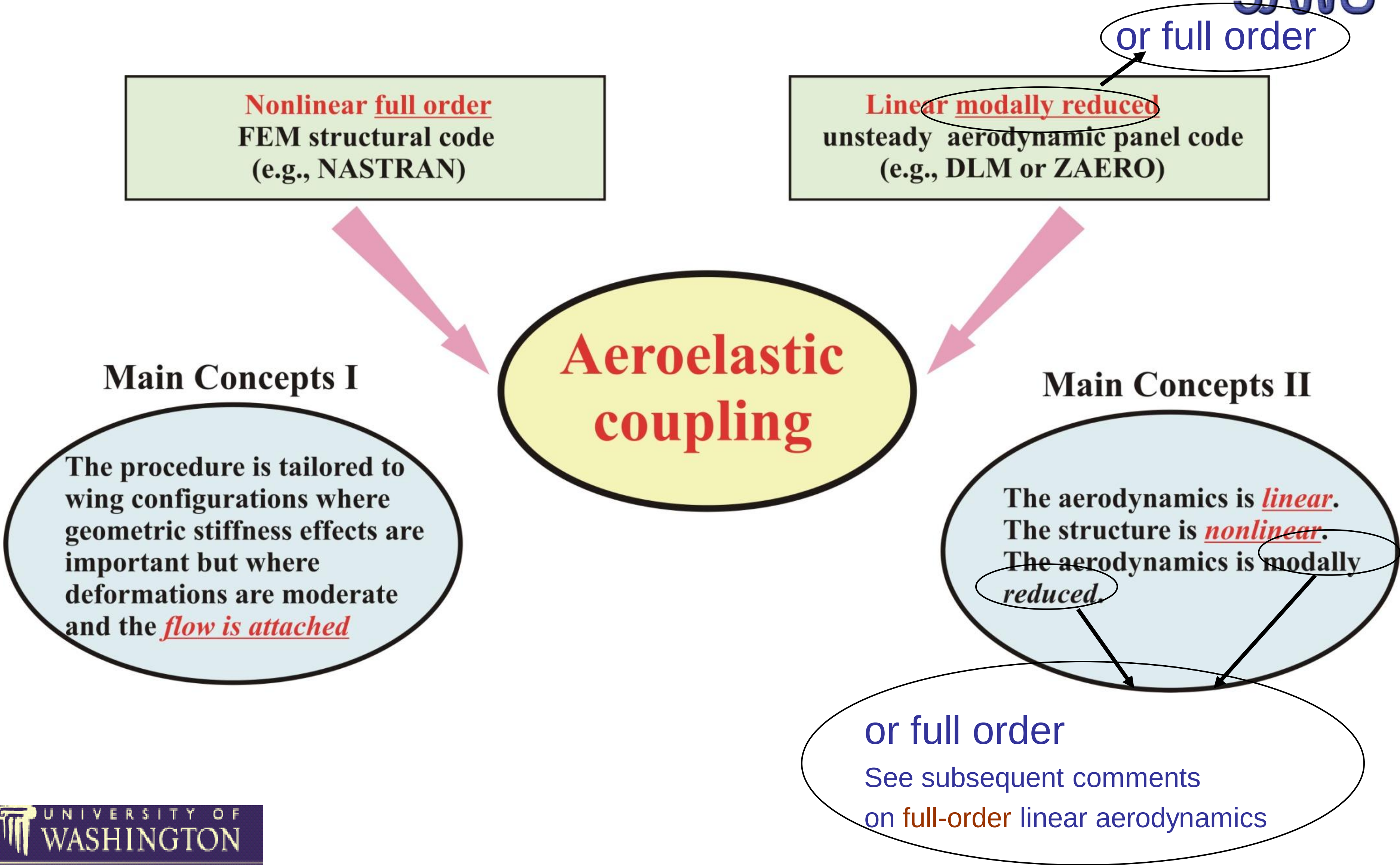
$$\boxed{\left\{Q(t)\right\}=\left[P_0\right]\left\{q(t)\right\}+\left[P_1\right]\left\{q(t)\right\}+\left[P_2\right]\left\{q(t)\right\}+\left[P_3\right]\left\{r_1(t)\right\}+\left[P_4\right]\left\{r_2(t)\right\}+\ldots}$$

- To generate the aerodynamic inputs to the full order structural model

$$\boxed{\left\{Q(t)\right\} \quad \rightarrow \quad [\Phi]^T\{F\}\approx\{Q\} \quad \rightarrow \quad \left\{F(t)\right\}}$$

- Structures / Aerodynamic Coupling is done analytically – No staggered time marching

A Physics Based Nonlinear FE/Linear Aero Approach for Geometrically Nonlinear Aeroelastic Time Domain Simulations



or full order

Nonlinear full order
FEM structural code
(e.g., NASTRAN)

Linear modally reduced
unsteady aerodynamic panel code
(e.g., DLM or ZAERO)

Aeroelastic coupling

Main Concepts I

The procedure is tailored to wing configurations where geometric stiffness effects are important but where deformations are moderate and the *flow is attached*

Main Concepts II

The aerodynamics is *linear*.
The structure is *nonlinear*.
The aerodynamics is modally *reduced*.

or full order

See subsequent comments
on full-order linear aerodynamics

Prototype Capability: Modeling. Static Aeroelasticity

Structure:

- Nonlinear Updated Lagrangian Formulation: the coordinates of the structural nodes are updated at each iteration (Newton-Raphson procedure)
- Element: flat triangular shell element with 18 DOF (3 rotations and 3 translational displacements per node)
- A particular procedure is used in order to remove the rigid body motion and calculate the unbalanced loads as the analysis progresses (Levy, Gal, Computers & Structures 2005)
- The tangent stiffness matrix

$$\left[\boldsymbol{K_T}\right]=\left[\boldsymbol{K_L}\right]+\left[\boldsymbol{K_G}\right]$$

Aerodynamics:

- Doublet Lattice Method (DLM) - 1998 “Quartic” Rodden version
- Fixed Aerodynamic Mesh

Prototype Capability: Modeling. Static Aeroelasticity. (Continued)

- Motion transformation from FE mesh to aerodynamic panel mesh: Infinite Plate Spline method

- Transformation of aero panel loads to the FE structural mesh: by finding the triangular element which contains the load and by using the area coordinates

- Aerodynamic linearity: all transformation matrices are assumed constant

- Aerodynamic forces change magnitude but not direction: small deformation where nonlinear effects are due to internal stresses in the structure, or large deformation where linear aerodynamic modeling is still adequate

Text Case: JW Results – Full Order Aerodynamics

Static aeroelastic solution:
incremental increase of airspeed

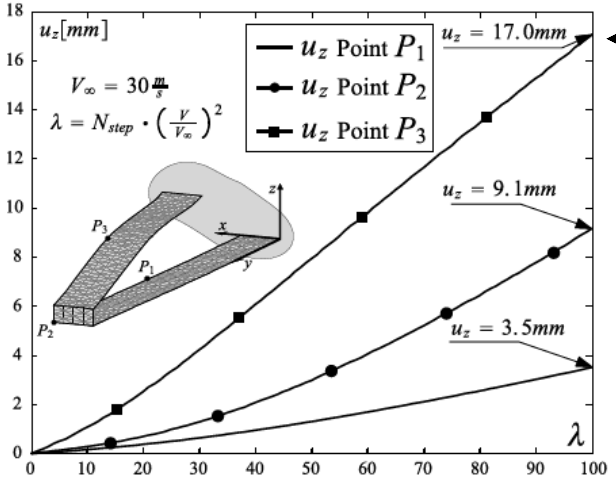


Figure 16. **Nonlinear steady state solution (present capability,** $V_\infty = 30\ m/s$, **present capability, MESH4). Lower wing, joint and upper wing have thickness** $h_L = 2.0\ mm$, $h_J = 2.0\ mm$ **and** $h_U = 0.5\ mm$ **respectively.** $P_1 \equiv (a, 5a, 0)$; $P_2 \equiv (a, 10a, 0)$; $P_3 \equiv (2a, 5a, \frac{3}{5}a)$; $a = 50\ mm$.

Dynamic aeroelastic solution:
Time marching

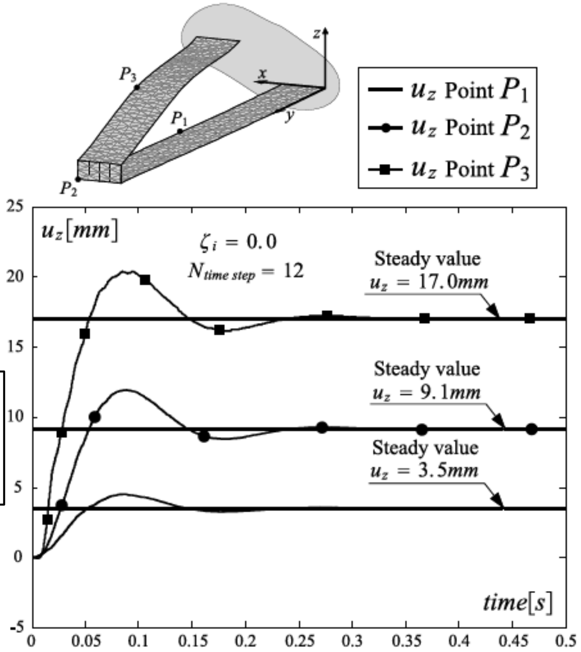


Figure 17. **Nonlinear time-domain simulation (sub-critical case,** $V_\infty = 30\ m/s$, **present capability, MESH4). In all cases** $\zeta_i = 0$. **Lower wing, joint and upper wing have thickness** $h_L = 2.0\ mm$, $h_J = 2.0\ mm$ **and** $h_U = 0.5\ mm$ **respectively.** $P_1 \equiv (a, 5a, 0)$; $P_2 \equiv (a, 10a, 0)$; $P_3 \equiv (2a, 5a, \frac{3}{5}a)$; $a = 50\ mm$.

Conclusion

- A unique methodology was developed for the aeroelastic simulation of composite airframes subject to local and global geometric nonlinearity

- A set of coupled structure / aerodynamic aeroelastic equations are solved simultaneously (with no staggering), coupling detailed nonlinear FE models with linearized panel or linearized CFD aerodynamic models

- The methodology leads to high efficiency in problem formulation and solution, because currently used NASTRAN / Panel Aero models used in industry can be converted no nonlinear structural modeling and run with a change of a single input parameter.

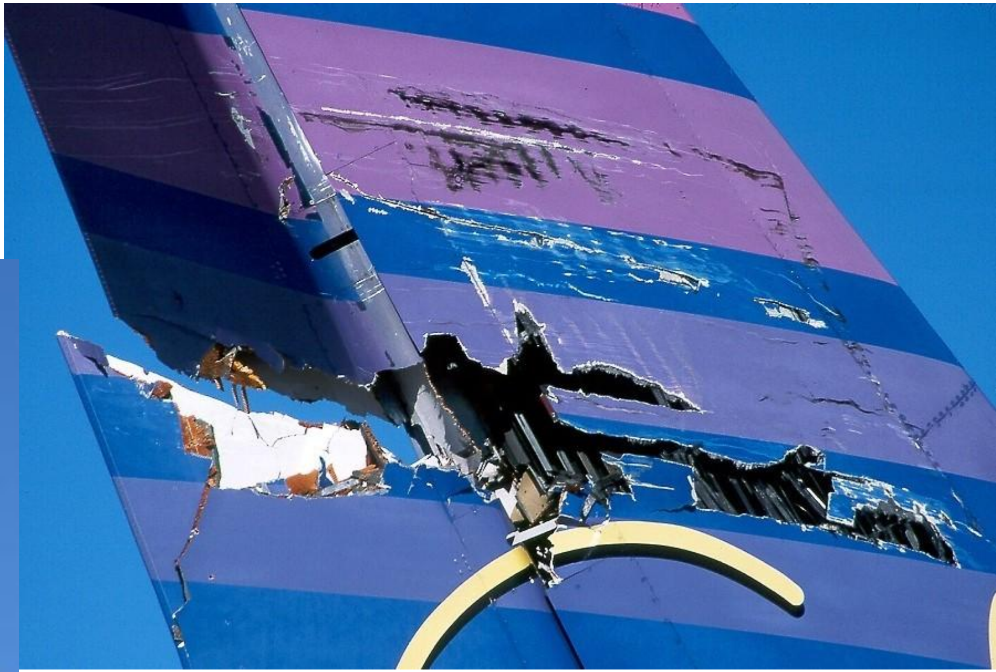
- A prototype simulation code was created and tested successfully on one of the most demanding structurally-nonlinear aeroelastic problems: the Joined Wing problem.

The 2009 – 2011 Focus

Wind Tunnel Model Development for Aeroelastic Tests of Wing / Control-Surface Systems with Hinge Stiffness Loss and with a Velocity-Squared Damper

2009-2010 Focus: Tail / Rudder Systems

Air Transat 2005



Damaged A310 in the hangar
(picture found on the web)

Experiments and experimental capabilities development

Interests:

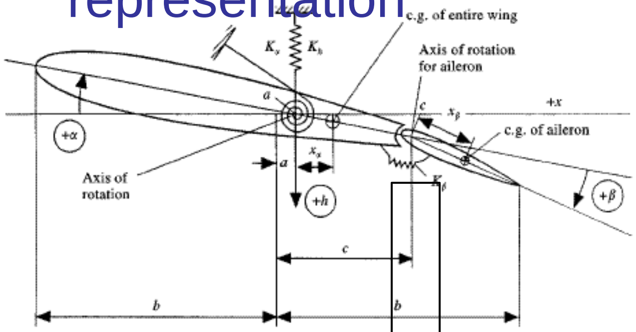
- Actuator / Actuator attachment hinge nonlinearities:
  - Freeplay / bilinear stiffness (hardening nonlinearity)
  - Buckling tendency (softening nonlinearity)
  - Hinge failure (coupled rudder rotation / rudder bending instability)
  - Actuator failure – nonlinear behavior with nonlinear hinge dampers
  - Flutter / Limit Cycle Oscillations (LCO) of damaged rudders
- Use tests to validate and calibrate numerical models – a UW / Boeing / FAA collaboration.

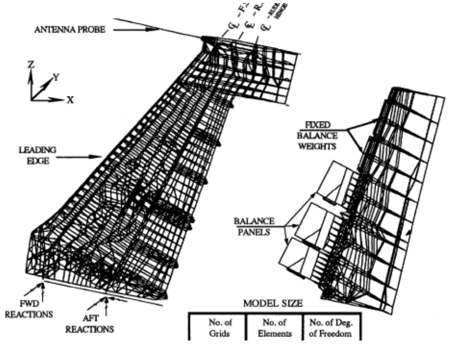
Important Notes:

- Rudder hinge stiffness nonlinearities and hinge failure can be caused by actuator behavior or by failure of the composite structure locally and globally.
- Wind tunnel model designs and tests will start with simulated hinge nonlinearities using nonlinear springs and then proceed to composite rudder structure with actual composite failure mechanisms.

Limit Cycle Oscillations and flutter due to control surface hinge stiffness nonlinearity

Basic aeroelastic model representation





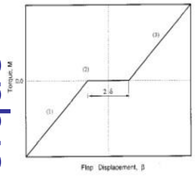
Local degradation / damage

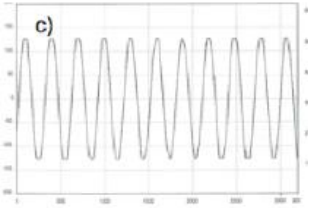
Hinge stiffness

Hardening

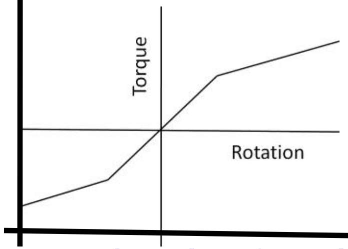
softening

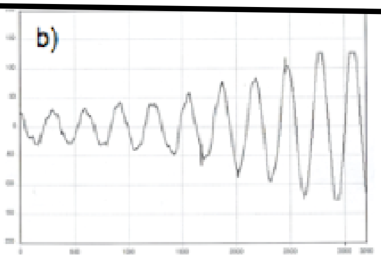
Torque



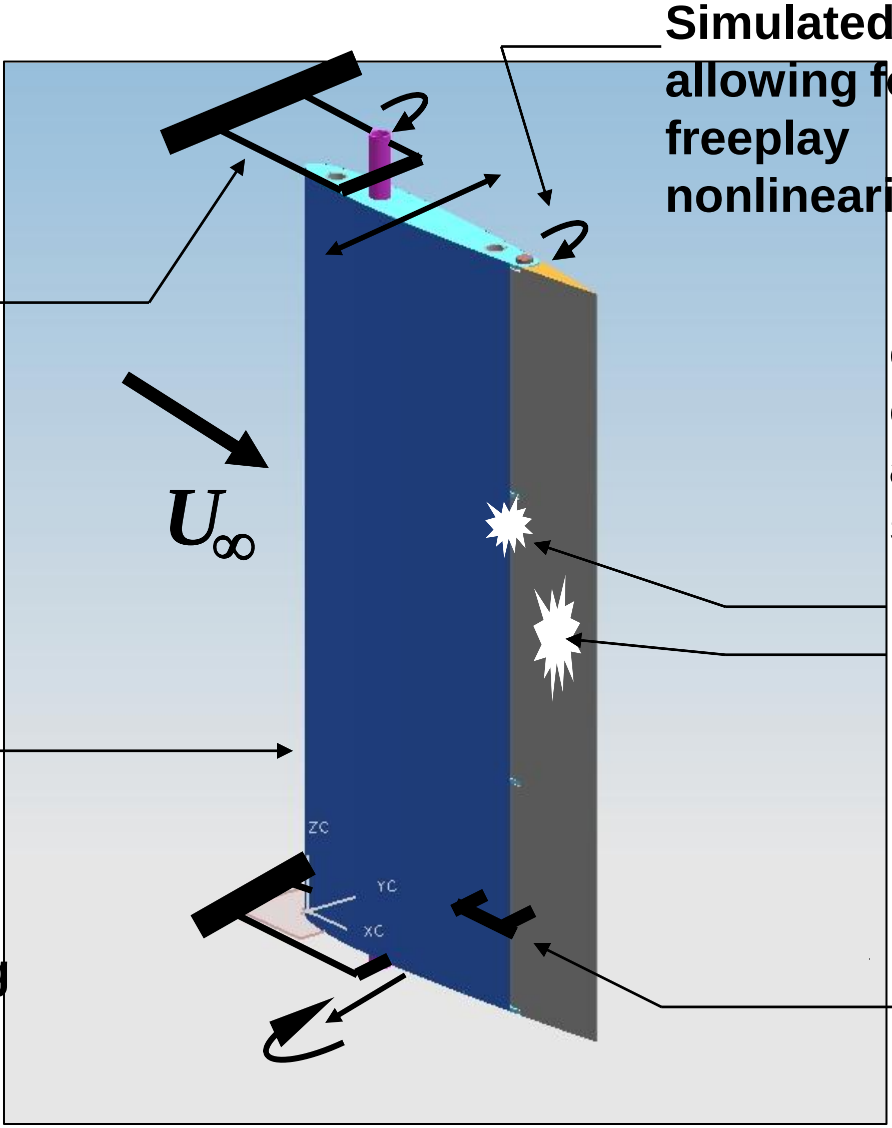


Flap Rotation





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



Simulated actuator allowing for freeplay nonlinearities

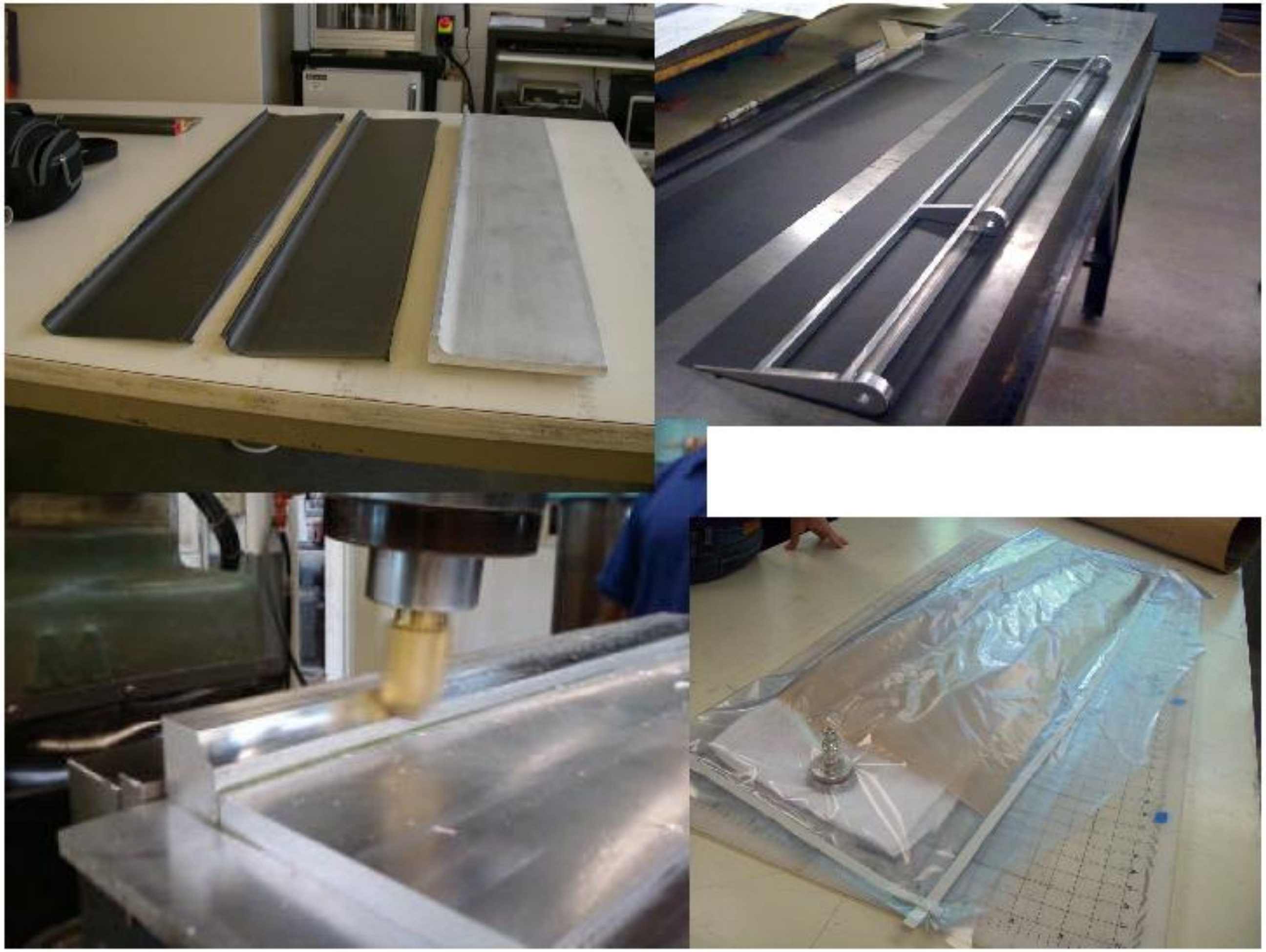
Wing - wind tunnel mount
Providing linear Plunge
And torsional pitch stiffnesses

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

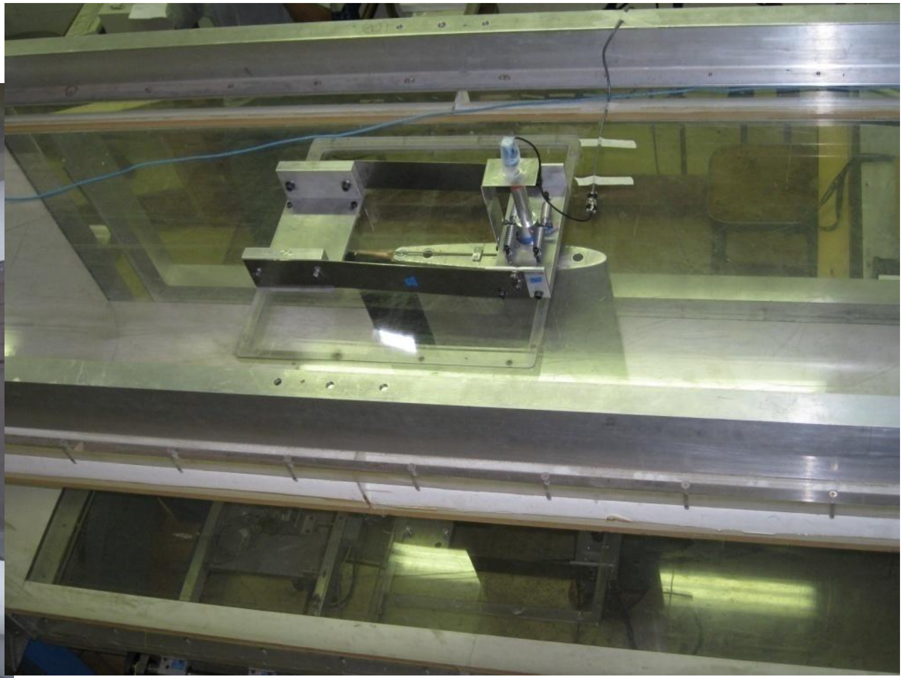
Aluminum wing allowing for variable inertia / cg properties

Simulated actuator / damper attachment allowing for different nonlinearities

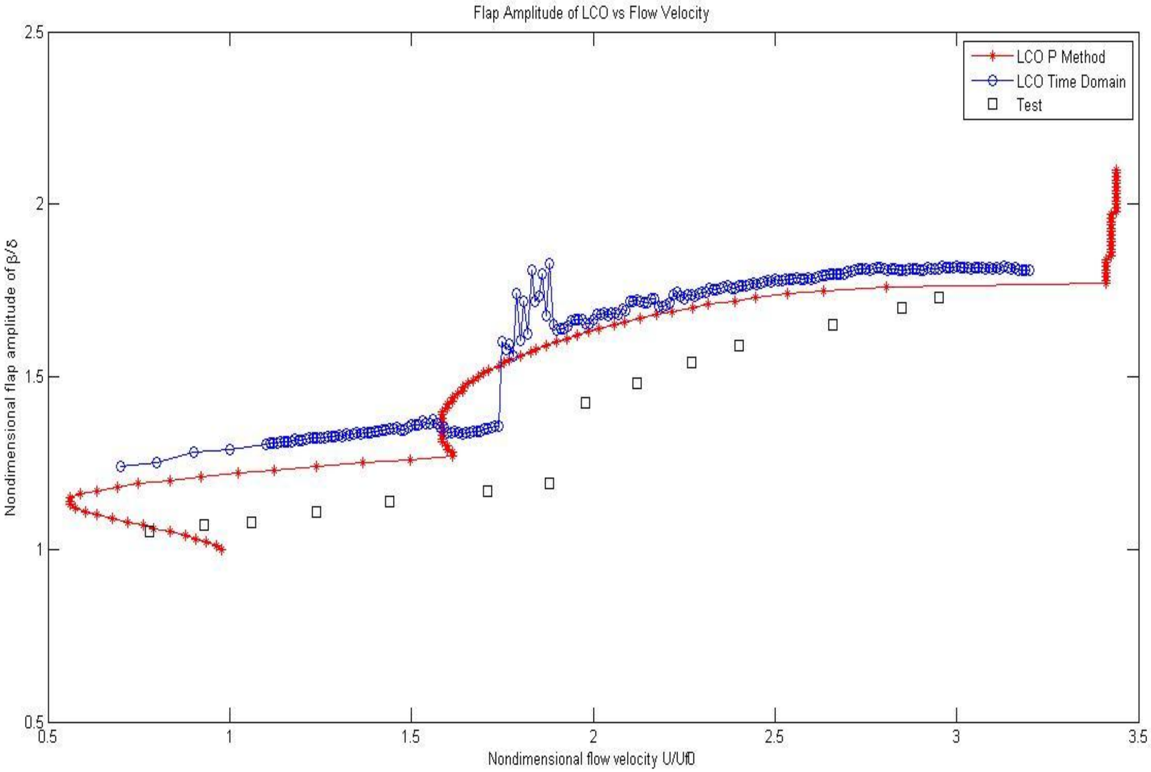
New Composite Rudder Designs



The tail / rudder model at the UW's 3 x 3 wind tunnel 2009-2010



The Complexity of Nonlinear Aeroelastic Behavior with Rudder Hinge Stiffness Free-Play



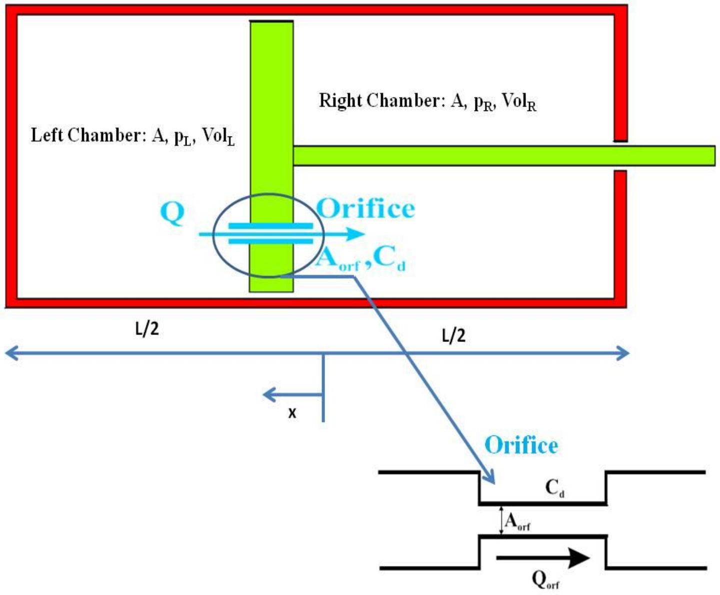
Predicted Limit Cycle Oscillation amplitudes of rudder rotation at speeds below the flutter speed of the no-freeplay system – The Duke University test case

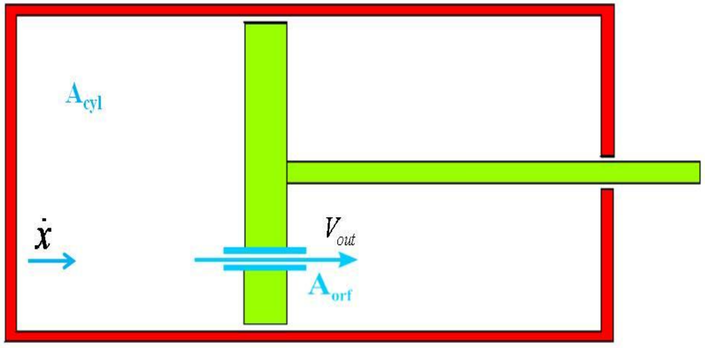
Loss of Hinge Stiffness

- An important condition in the aeroelastic design and certification of lifting-surface / control-surface systems is the case of loss of actuator stiffness, with control surface rotation resisted only by a velocity-square damper.

- No experimental wind tunnel aeroelastic results are available for this case.

The Design of a Small Velocity Squared Damper





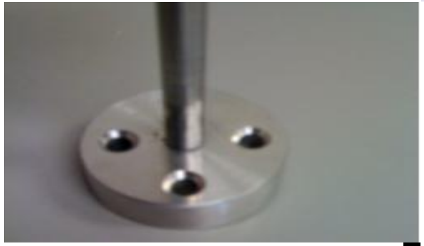
Axes chosen so that
Piston at rest
with respect to them

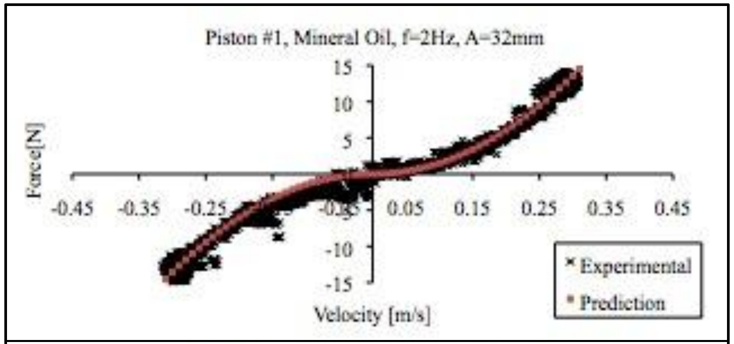
$$p_L + \frac{1}{2}\rho\cdot v_p^2 = p_R + \frac{1}{2}\rho\cdot V_{out}^2 \rightarrow \Delta p = p_R - p_L = \frac{1}{2}\rho\cdot\left(V_{out}^2 - v_p^2\right)$$

$$A_p\cdot v_p = A_{orifice}\cdot V_{out} \rightarrow V_{out} = \left(\frac{A_p}{A_{orifice}}\right)\cdot v_p = \frac{1}{\eta}\cdot v_p$$

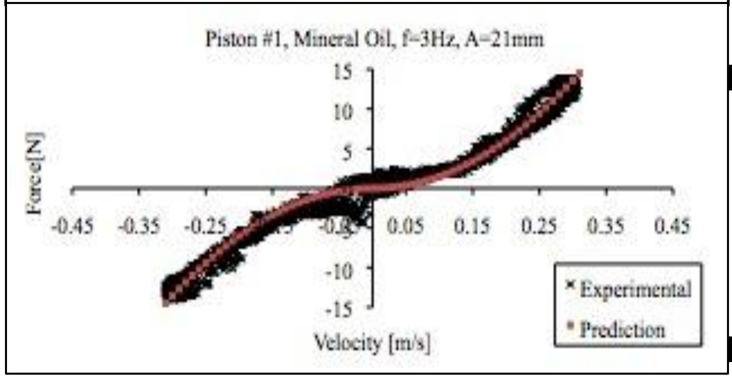
$$F_{tot} = F_{pressure} + F_{viscosity} + F_{inertia}$$

The Design of a Small Velocity Squared Damper





Piston #1, Mineral Oil, f=2Hz, A=32mm



Piston #1, Mineral Oil, f=3Hz, A=21mm

Conclusion

- Major progress in the development of the UW’s aeroelastic wind tunnel capabilities.

- Linear flutter as well as Limit Cycle Oscillations (LC) tested in the UW’s 3 x 3 wind tunnel and used to validate UW’s numerical modeling capabilities.

- A small velocity-squared damper was designed and built.

- Wind tunnel tests of tail / rudder systems with actuator failure and with nonlinear dampers – in development.

- Wind tunnel tests of representative tail / rudder systems with realistic rudder composite structures – in development.

- Results from this effort will provide valuable data for validation of simulation codes used by industry to certify composite airliners.

Future Directions

- Expand the probabilistic aeroelastic reliability methodology and associated capabilities to include dynamic loads due to gusts as well as uncertainty and damage in active flight control and load alleviation systems.
- Implement the new nonlinear aeroelastic simulation capability in commercial FE / aeroelastic packages, extend to include linearized CFD aerodynamics, and improve the capability to capture both local and global failure.
- Complete aeroelastic wind tunnel tests of the tail / rudder system with nonlinear dampers; validate computer simulations and improve them.
- Proceed with simulation / testing work to the case of tail / rudder with failed rudder hinges and rudder structure loss of stiffness due to delamination.

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.