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AMTAS
Advanced Materials in Transport Aircraft Structures

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

Presented by Dr. Eli Livne
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Contributors

Department of Aeronautics and Astronautics

- Dr. Eli Livne – PI, Professor

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
- Additional Boeing Dynamics&Loads Engineers (in development)

FAA Technical Monitor

- 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

Scope

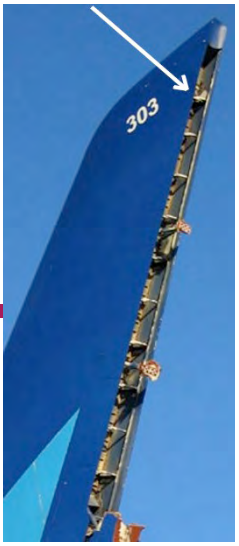
Probabilistic approach to the aeroelastic reliability of damaged composite aircraft (including maintenance)

Automated simulation capabilities for uncertainty analysis:

- Linear structural dynamics
- Nonlinear structural dynamics

Experimental aeroelasticity

- Capabilities
- Experiments



2.5.3.2 Flutter

The lateral load signals recorded, the damage to the VTP main attachment fittings, the damage to the rudder hinge arms at positions 5 and 6, as well as the noise and vibrations felt during the event are consistent with flutter.

2.5.4 Possible Causes of Flutter

2.5.4.1 Flutter without Prior Structural Deviation

Flutter analysis confirmed that a rudder with no structural deviations will not flutter within the design envelope. The investigation showed that the rudder was operated within the design envelope; therefore, the rudder did not experience flutter without a prior structural deviation.

2.5.4.2 Flutter Following Structural Deviation

The investigation revealed that rudder imbalance and hinge free play would not have led to flutter. It was determined that the most probable cause of flutter was a large disbond-type damage. The presence of additional minor factors such as possible water trapped in the honeycomb and excess paint would marginally reduce the size of the disbond necessary to cause the flutter.

2.5.5 Growth of Rudder Damage

Vacuum cycling tests conducted resulted in damage growth. Therefore, the pressure differential between the air inside the honeycomb and the reduced external air pressure at cruise altitude might have acted as the driving force for the growth of core/face sheet separations or in-plane core fractures.

This particular rudder design does not include any damage growth arrest features in the side panels such as a mechanical barrier. Once damage starts to grow, it can continue to grow until it reaches critical size. Such a feature was not specifically demanded for certification.

Air Transat Airbus A310-308 AMS Amsterdam [Schiphol], Netherlands

PlanePictures.net // Copyright by Vincent de Koning // 16-August-2003 // AMS // 1061145329

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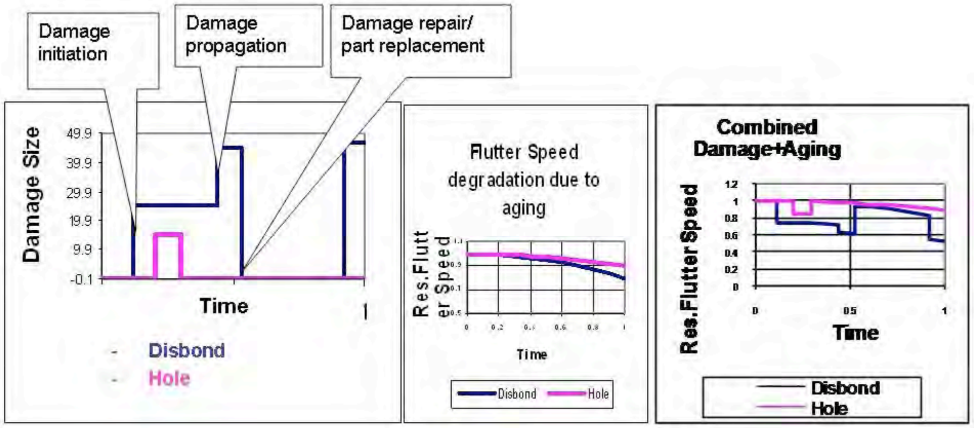
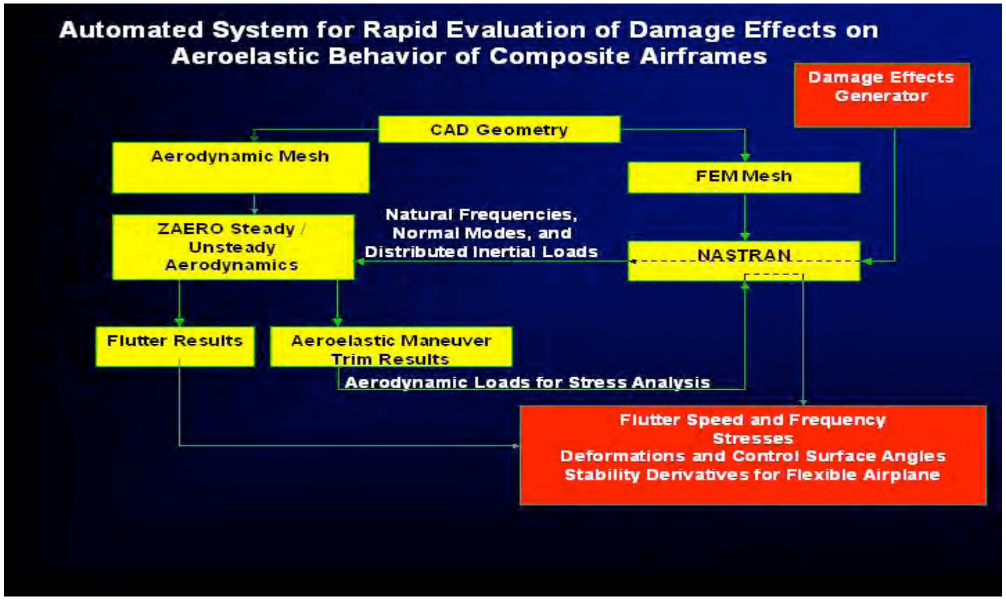
AP PHOTO/NINOY AQUINO INTERNATIONAL AIRPORT

Probabilistic Reliability Assessment of Actively Controlled Composite Airframes Including Damage Statistics, Damage Effects, and Maintenance Procedures Dr. Andrey Styuart (now with Stirling Dynamics, Inc.)



Uncertainty is the result of

- material and manufacturing variability (in-panel, panel-to-panel);
- Material degradation over time;
- Damage statistics (type, size, location),
- Maintenance procedures (frequency, type, detection, repair);
- Statistics of airplane operations (flight conditions)



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

Monte Carlo simulations of aeroelastic behavior

- Variability in composite structures,
- extendable to Airframe / controls / aerodynamics system level variability statistics evaluation capability.

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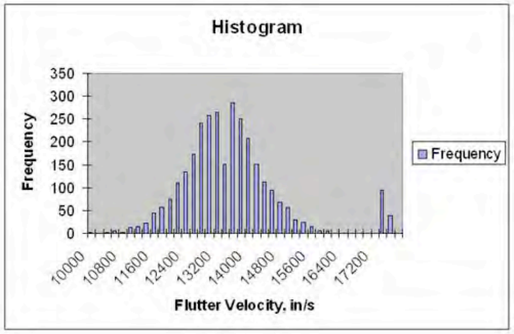
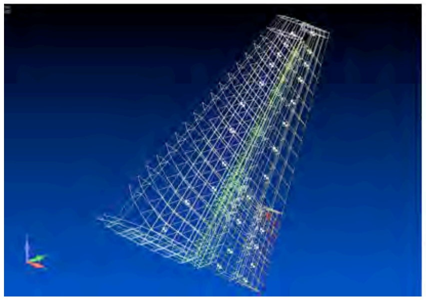
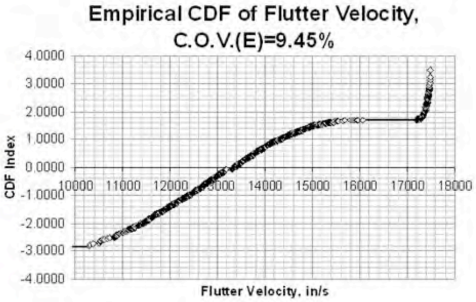
Probabilistic Reliability Assessment of Actively Controlled Composite Airframes Including Damage Statistics, Damage Effects, and Maintenance Procedures

FE Model of Composite 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







<u>Qualifications!</u>
Not a real flying structure;
Flutter analysis carried out for a cantilevered tail
and not for empennage/tail system;
Results – problem dependent

Flutter speeds uncertainty in a transport-type
Composite vertical tail/rudder system.
Note the possible switch in flutter mechanisms
For certain combinations of system parameters.

Accounting for damage statistics:
the effect on probability of flutter failure
per life of the flutter design safety margin used.
To obtain the same flutter reliability in the
accounting-for-possible-damage case
Compared to no-damage case, the flutter design margin
Has to increase from 1.15 to 1.2 (in the vertical tail case).

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.

Status and Plans

- Note: Limited FAA funding for 2009

Recently (October 2008):

- The work (and capabilities) were presented at the ICAS conference in Anchorage, Alaska, and at the Aeroelastic Certification Workshop in Sedona Arizona.

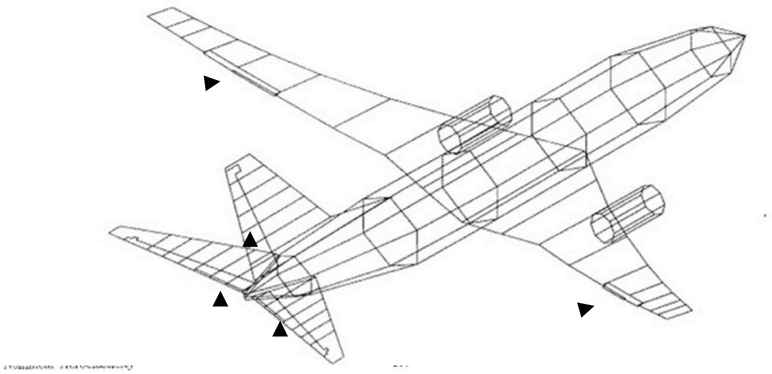
Future:

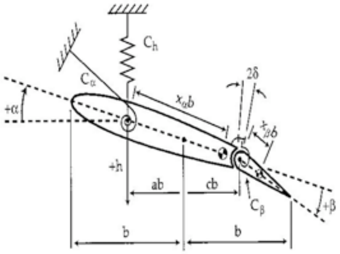
- Seek support for implementation from additional sources: industry? US Air Force? NASA?

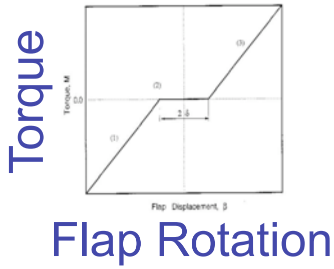
Structural Nonlinearities in Aeroelasticity

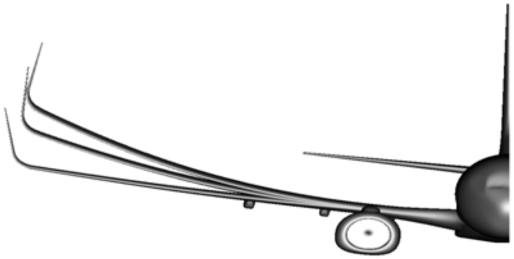
Nonlinearities in the Aeroelastic behavior of lifting surface configurations can be the result of structural or aerodynamic effects or both

For airplane configurations flying at *low angles of attack with attached flow* that is predominantly linear – structural nonlinearity is the determining nonlinear aeroelastic behavior factor







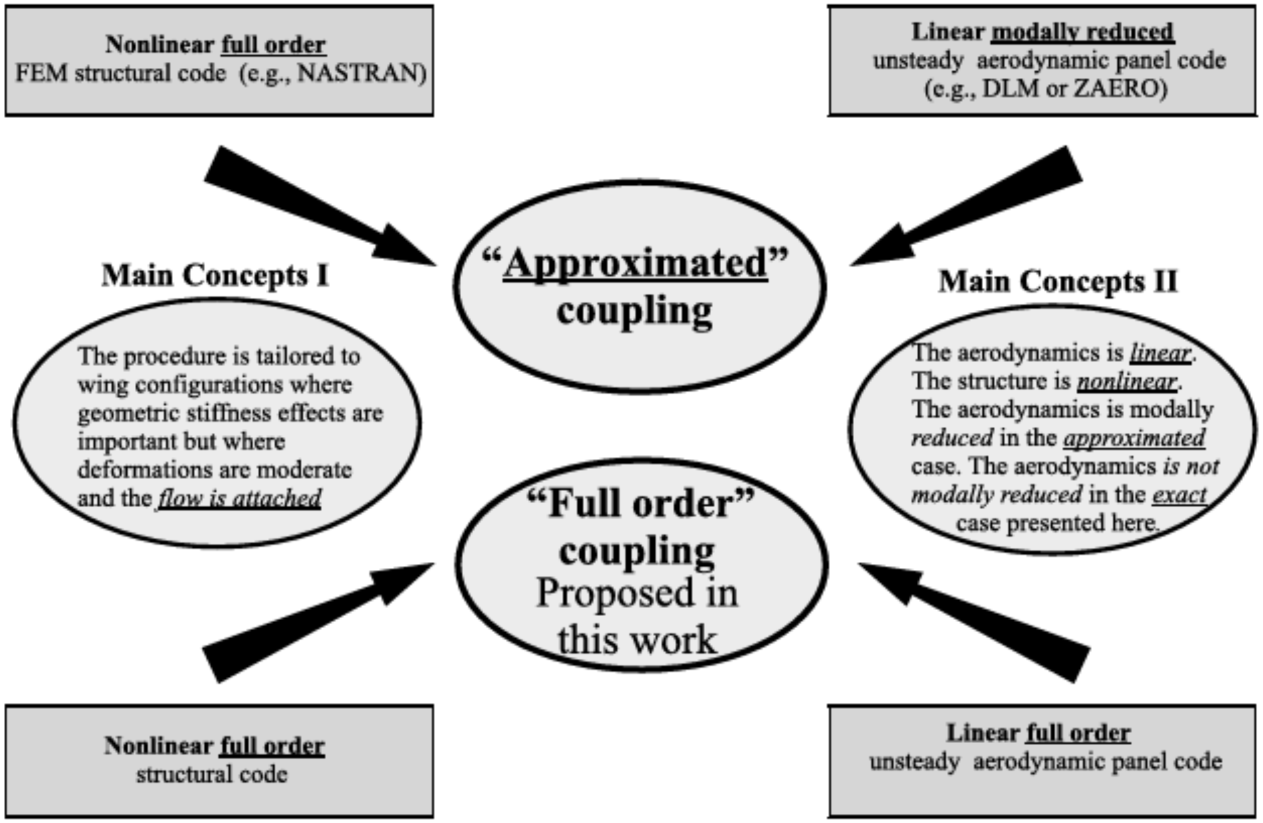


Localized “point” structural nonlinearities

“Distributed” geometric structural nonlinearities

Proposed Approach for Geometrically Nonlinear Aeroelastic Time Domain Simulations

Dr. Luciano Demasi (now at San Diego University)



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

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

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*

"Approximated" coupling

Main Concepts II

The aerodynamics is *linear*.
The structure is *nonlinear*.
The aerodynamics is modally *reduced* in the *approximated* case. The aerodynamics *is not modally reduced* in the *exact* case presented here.

"Full order" coupling
Proposed in this work

Nonlinear full order
structural code

Linear full order
unsteady aerodynamic panel code

Figure 1. Conceptual description of the procedure presented in this work.

Aeroelastic Simulations for Structurally Nonlinear Composite Airframes – Status and Plans

<u>Recent:</u>

- Presentation at the Flutter and Dynamics Council Meeting in Arizona, October 2008.

<u>Future:</u>

- Further development of the technology, with emphasis on improved computational efficiency and on analysis / test correlations.
- Integrate into the aeroelastic loads / flutter process in industry
- Pursue implementation in commercial codes (NASTRAN? ZAERO?)

Experiments and Experimental Capability

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

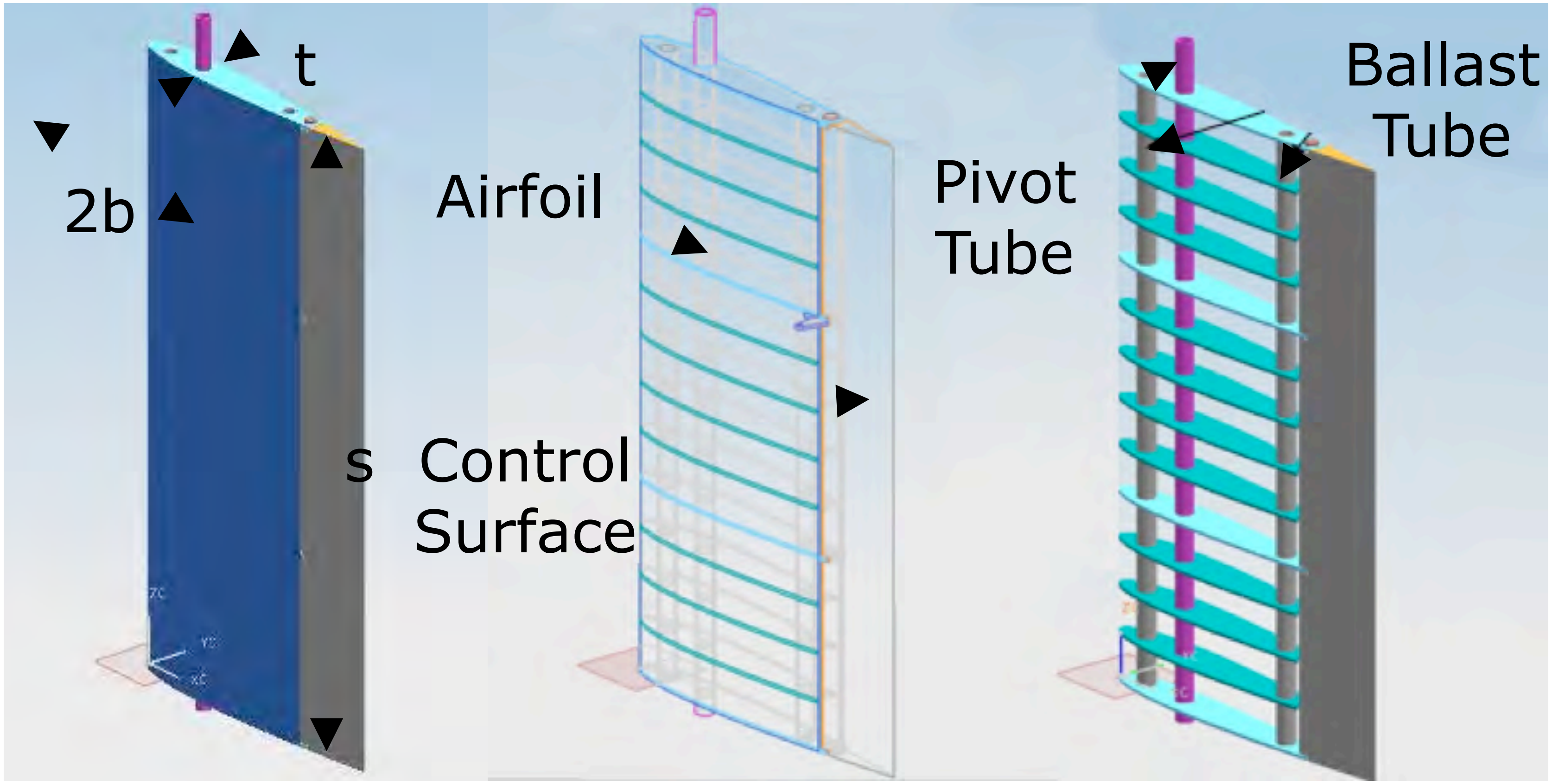
Use tests to validate and calibrate numerical models

Use tests to support FAA / NTSB work

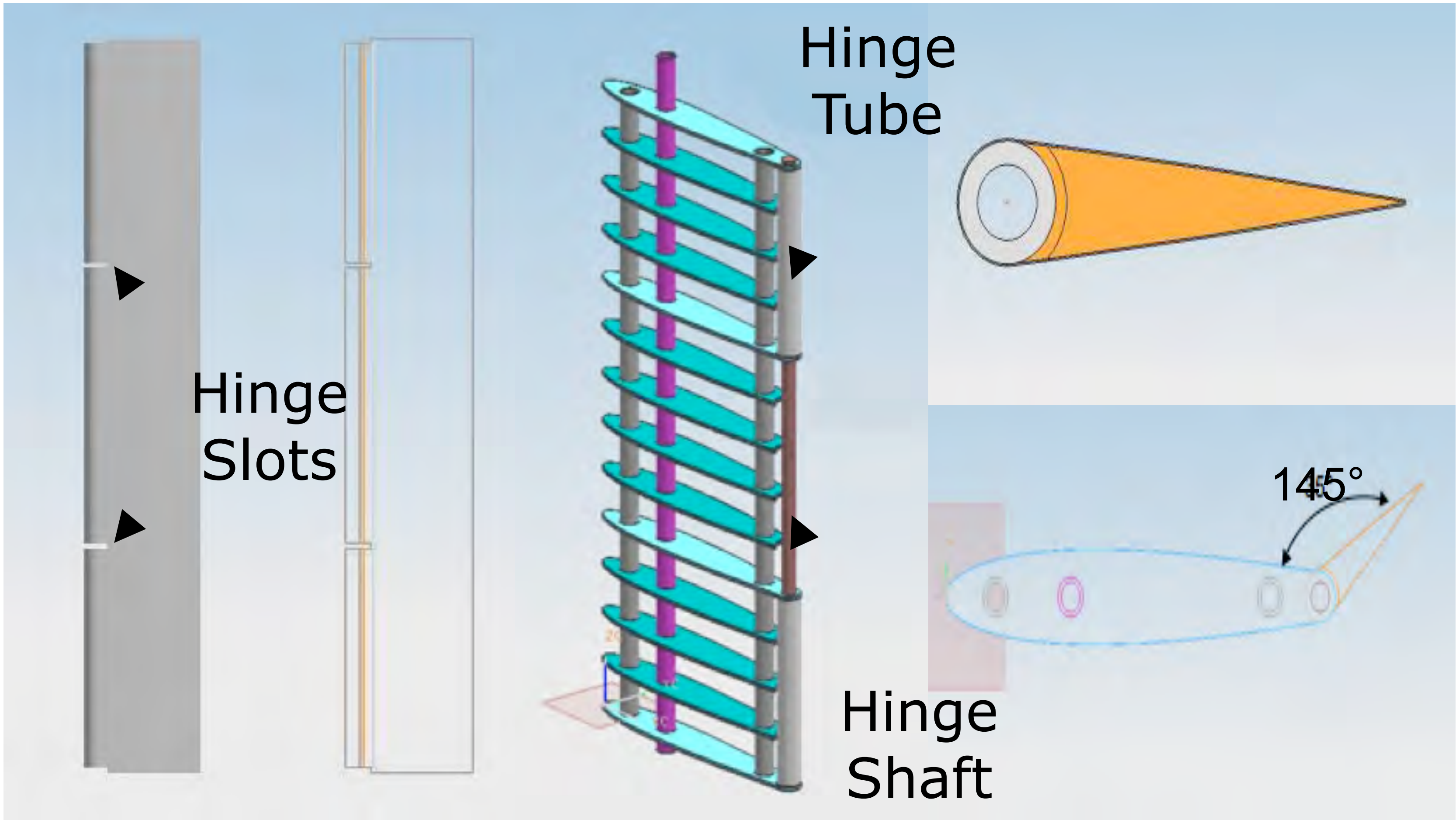
Prototype Aeroelastic System

UGS Unigraphics; NACA 0012;

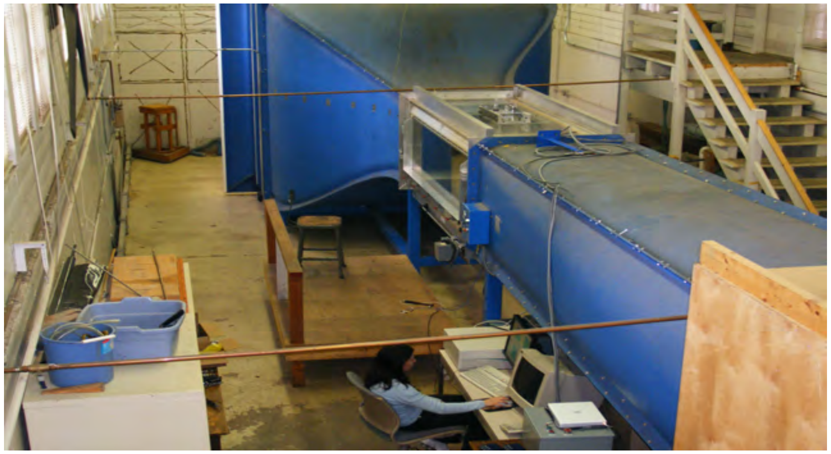
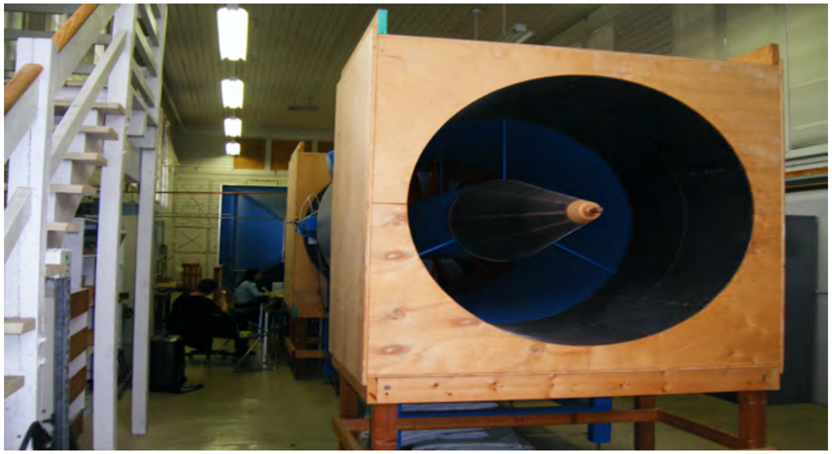
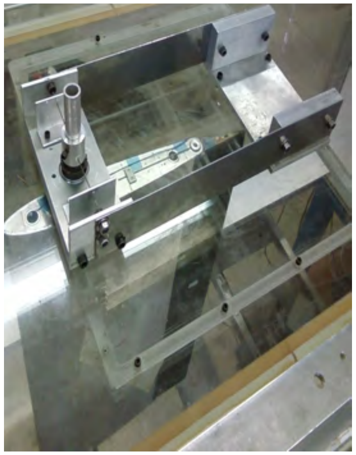
2b = 0.508 m (20 inches); t = 0.06 m (2.35 inches); s = 0.9 m (35.5 inches)



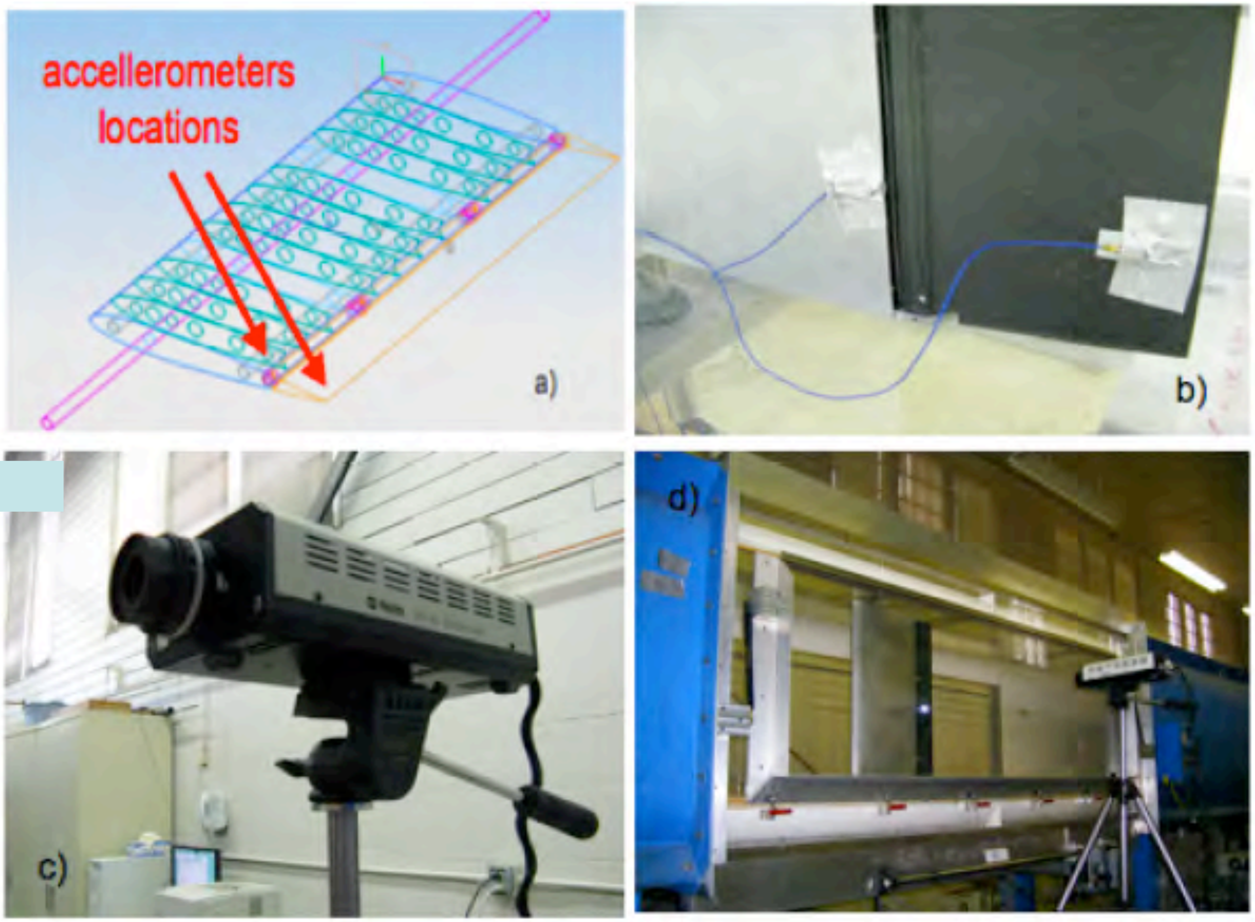
Prototype Aeroelastic Test System



Aeroelastic Tests in the UW's 3 x 3 Low Speed Wind Tunnel


Experimental Instrumentation
Accelerometers and Laser Vibrometer



A new laser vibrometer System has been Purchased (upgradable to Scanning)

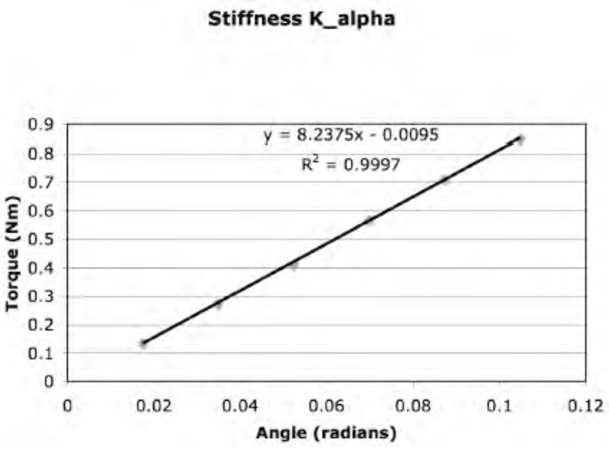
DATA Acquisition
Jaguar System

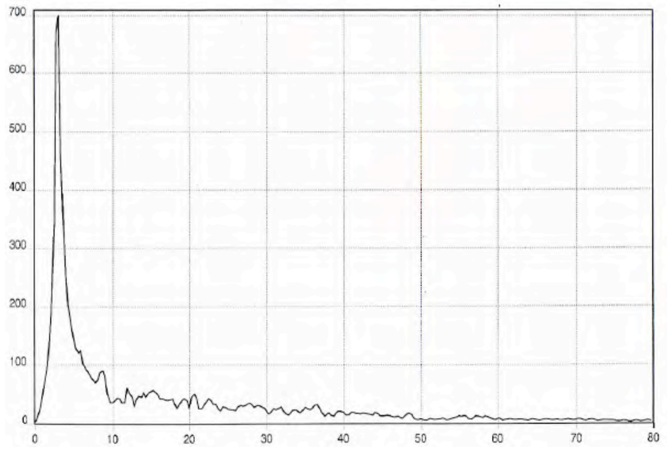
Structural Characterization

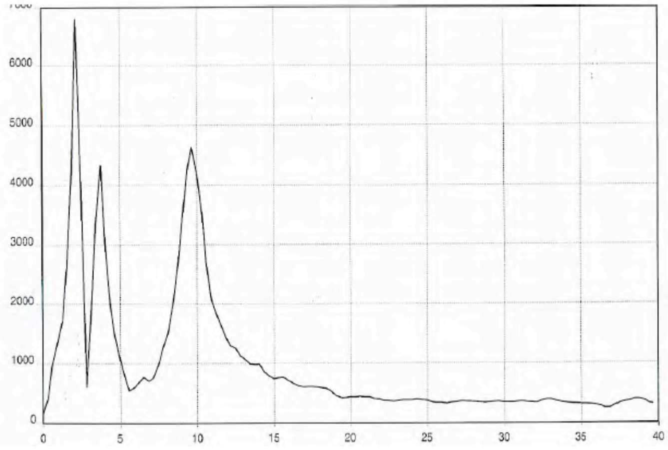
Stiffnesses, Natural Frequencies, Damping Ratios

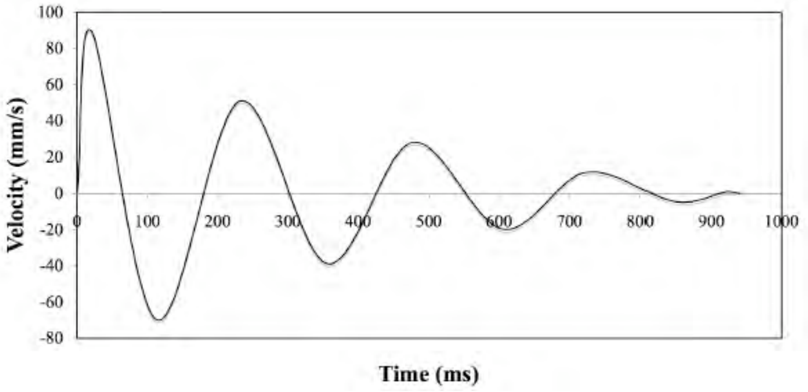
Structural Characterization

Stiffnesses, Natural Frequencies, Damping Ratios





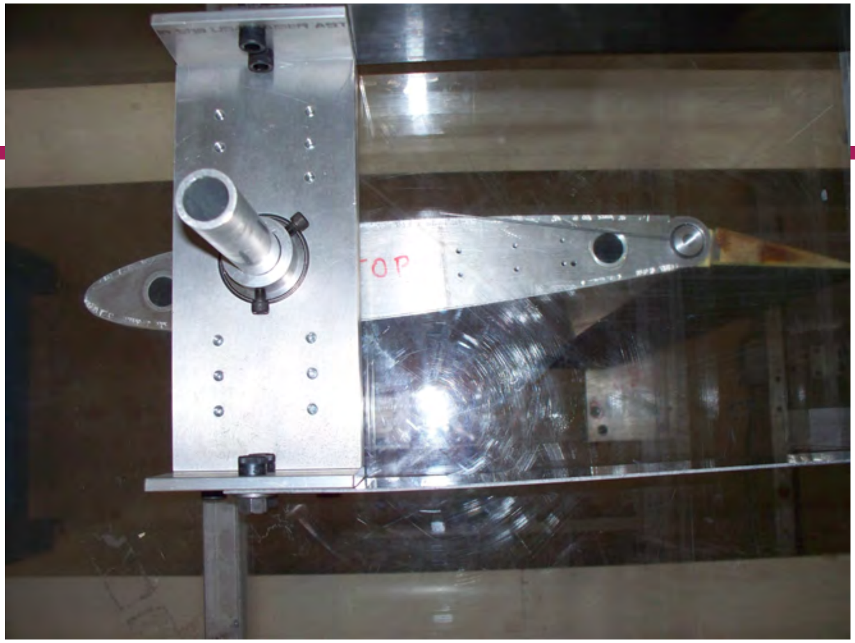


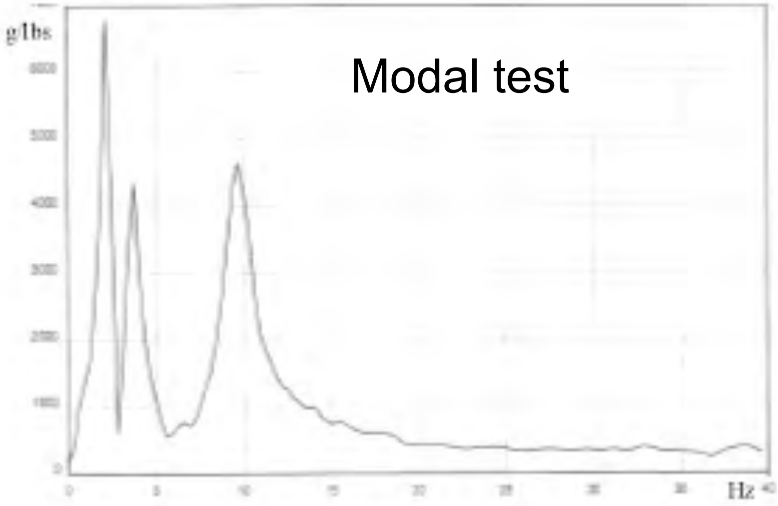


Flutter Tests
Francesca Paltera's MS Work

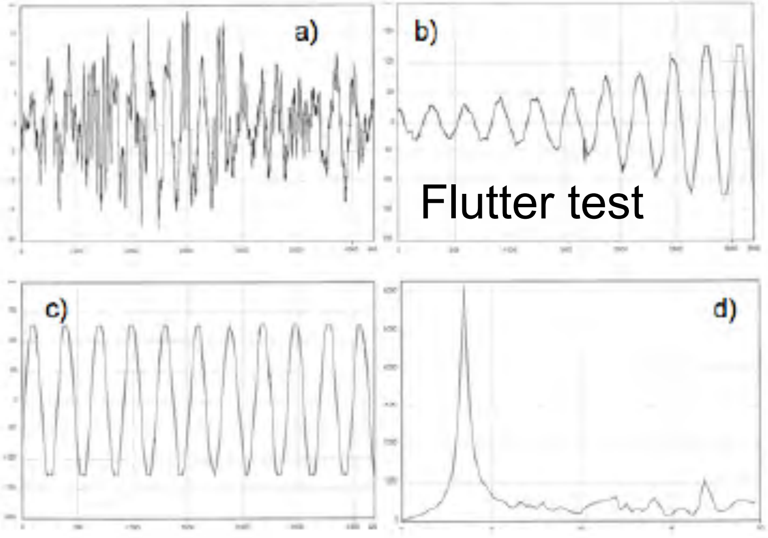
CONTROL SURFACE
Pristine Low-Density
Pristine High-Density
Pristine High-Density with New Springs Set
Low-Density with Teflon
Low-Density with Mold Release
Low-Density with both Teflon and Mold Release
Pristine Low-Density with Broken Hinge
Low-Density with Teflon, Mold Release and Broken Hinge
Pristine Low-Density Free to Move

The tail / rudder model at the UW’s 3 x 3 wind tunnel



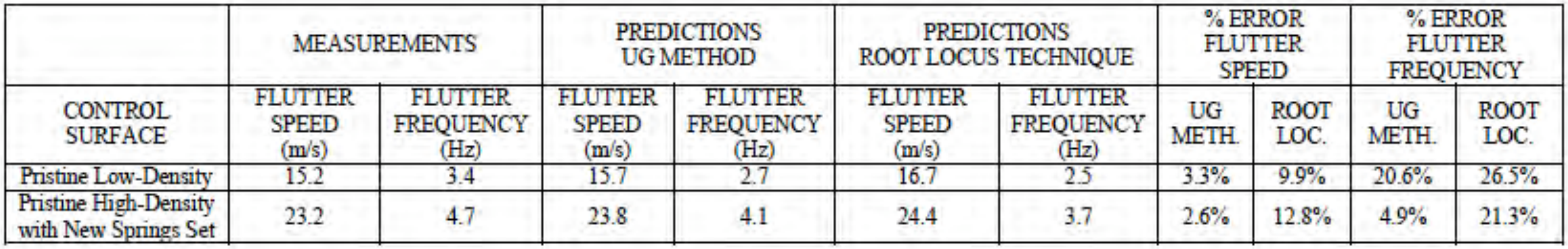


Modal test



Flutter test

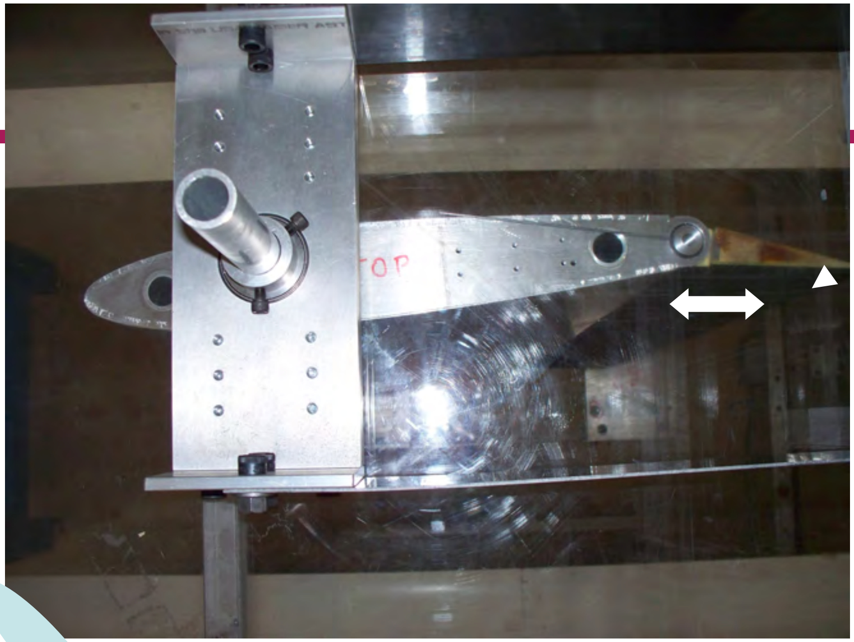
Analysis / Test Correlation: Flutter Speed and Flutter Frequency



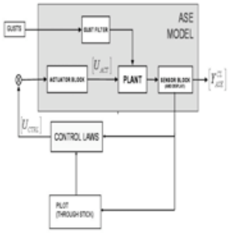
	MEASUREMENTS		PREDICTIONS UG METHOD		PREDICTIONS ROOT LOCUS TECHNIQUE		% ERROR FLUTTER SPEED		% ERROR FLUTTER FREQUENCY	
CONTROL SURFACE	FLUTTER SPEED (m/s)	FLUTTER FREQUENCY (Hz)	FLUTTER SPEED (m/s)	FLUTTER FREQUENCY (Hz)	FLUTTER SPEED (m/s)	FLUTTER FREQUENCY (Hz)	UG METH.	ROOT LOC.	UG METH.	ROOT LOC.
Pristine Low-Density	15.2	3.4	15.7	2.7	16.7	2.5	3.3%	9.9%	20.6%	26.5%
Pristine High-Density with New Springs Set	23.2	4.7	23.8	4.1	24.4	3.7	2.6%	12.8%	4.9%	21.3%

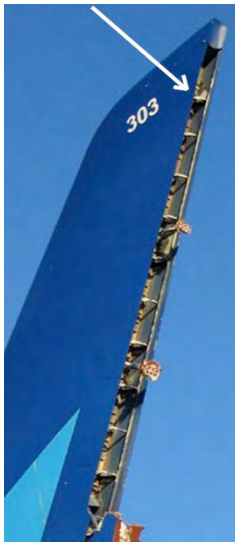
The tail / rudder model at the UW's 3 x 3 wind tunnel

- Validate Duke's Free-Play LCO results
- Test additional actuator/hinge nonlinearities
- Test rudders with hinge failures
- Correlate with analysis



Active Control





Aeroelastic empennage model with multiple free-play nonlinearities

Conclusion

- Aeroelastic reliability capability for composite airframes:
  - Version I ready for implementation
  - Version II, with added gust loads and integrated static / dynamic loads and flutter failure criteria – next in line for development

- Aeroelastic analysis and simulation of structurally nonlinear composite airframes:
  - Technique ready for implementation in commercial codes and the industry’s aeroelastic loads process
  - Improved techniques, with better computational efficiency – in line for development
  - Tests to validate the nonlinear aeroelastic simulation capability (static & dynamic) – underway.

Conclusion

- Flutter and Limit Cycle Oscillation (LCO) wind tunnel tests:
  - Proceed with the tail / rudder system to study LCO due to freeplay and additional hinge nonlinearities (nonlinear dampers, hinge failure, etc.)
  - Improve and expand structural dynamic and aeroelastic testing capabilities
  - Design, build, and test (in collaboration with Boeing) an multiple nonlinearity empennage model with stabilizer and rudder nonlinearities, including those due to damage.