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

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Contributors

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- Boeing Commercial, Seattle
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- 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
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Scope

- Motivation & Key Issues – a Review of the complete project
- 2009 focus: Experimental aeroelastic capabilities for testing degraded and damaged composite airframes
  - Development
  - Status

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.

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
(the 2008-2009 focus highlighted)

- 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.

Program Approach
(the 2008-2009 focus highlighted)

- Efficient simulation of <u>linear</u> 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)

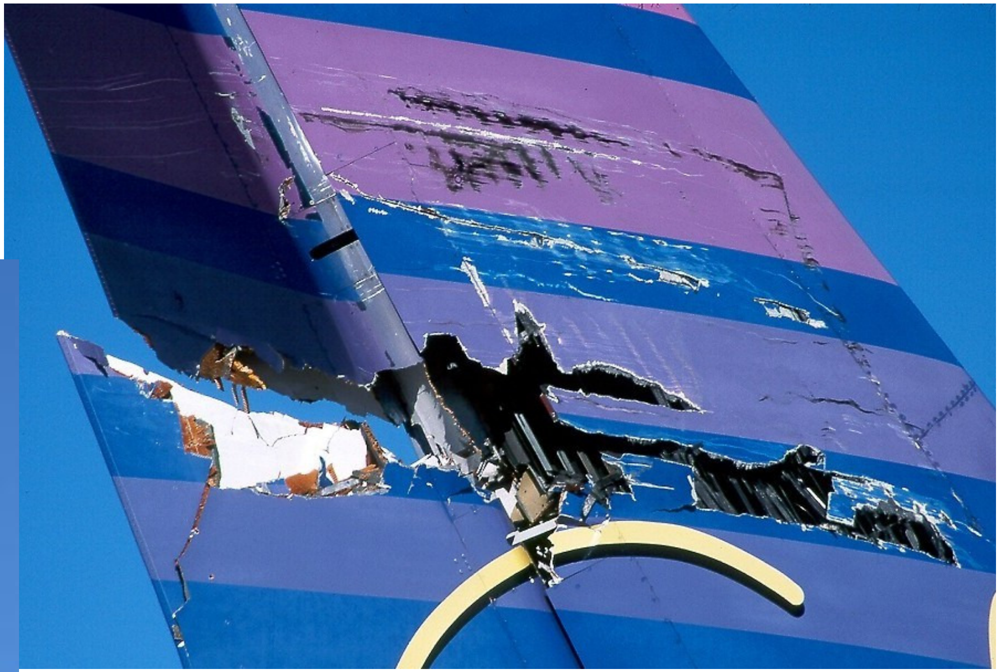
- Efficient simulation of <u>nonlinear</u> aeroservoelastic behavior, including limit cycle oscillations (LCO):
  - Tools development for basic research and physics exploration: simple, low order systems
  - Tools development for complex, large-scale aeroelastic systems with multiple nonlinearities

- 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.**

2008-2009 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.

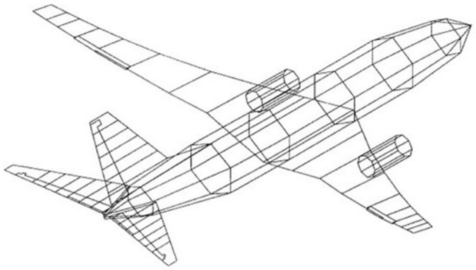
Aeroelastic Experimental Capability
and
Flutter Experiments

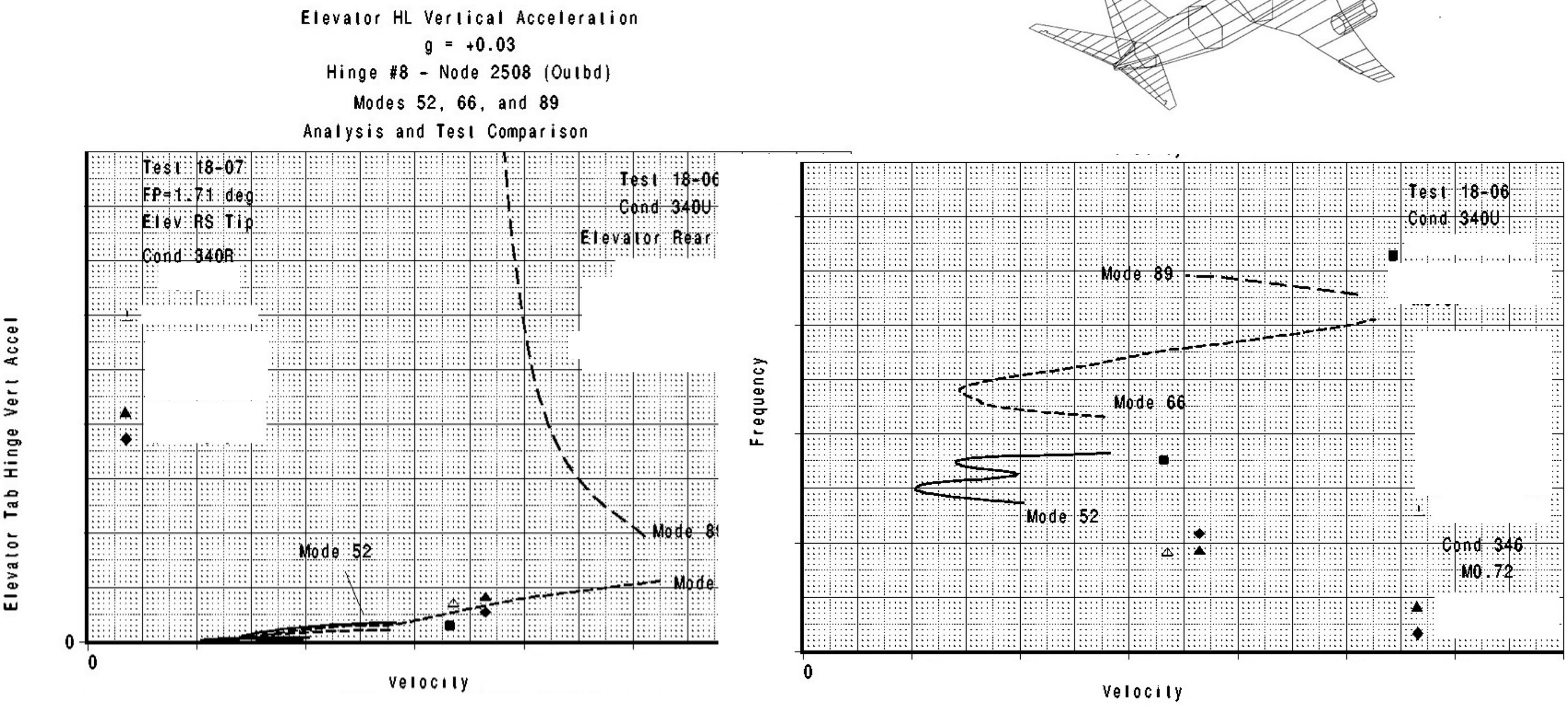
The goal: Provide test data and insights (using simple models) to help validate industry simulation capabilities used to certify composite airplanes with freeplay and other structural nonlinearities

Representative Describing Function Limit Cycle Predictions and Flight Test Results (Boeing)

δ_{fp} = ±1.71 deg

g = +0.03





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

Experiments and experimental capabilities development

General Approach:

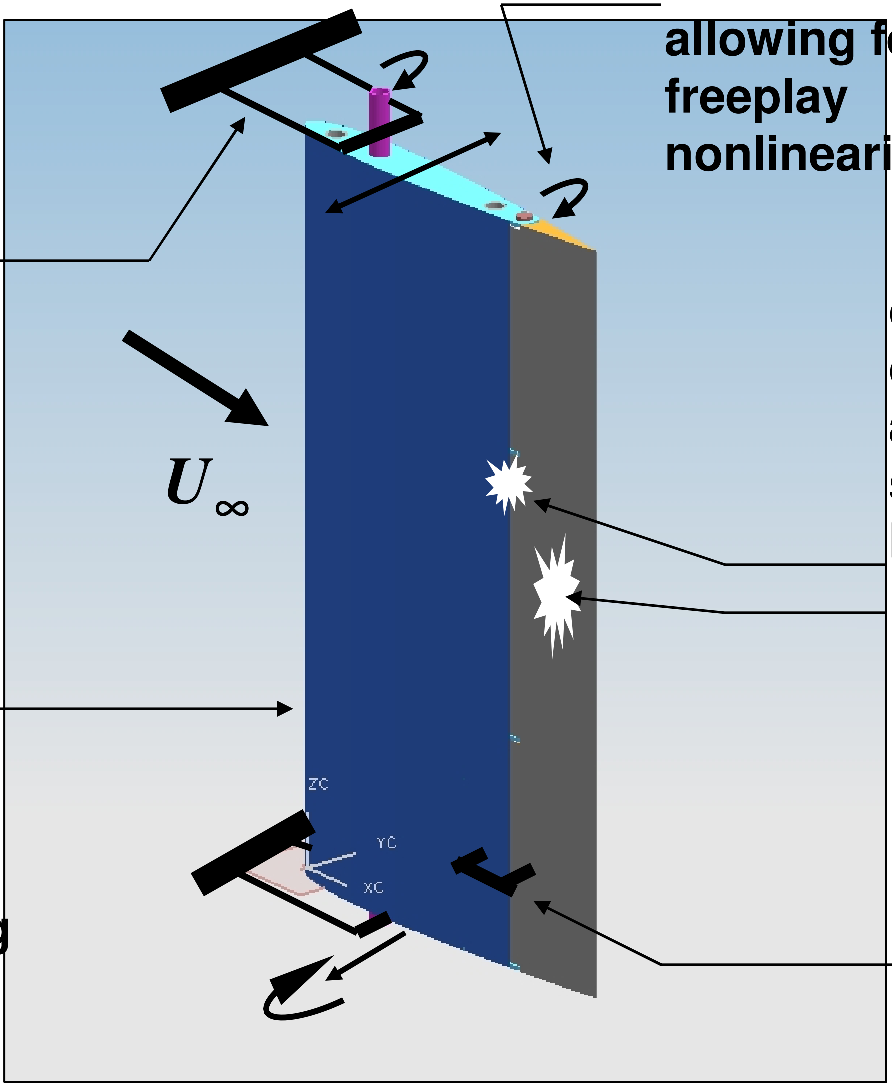
- Start with simple models for which experimental and theoretical results already exist – the Duke U wing / control surface LCO model

- 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



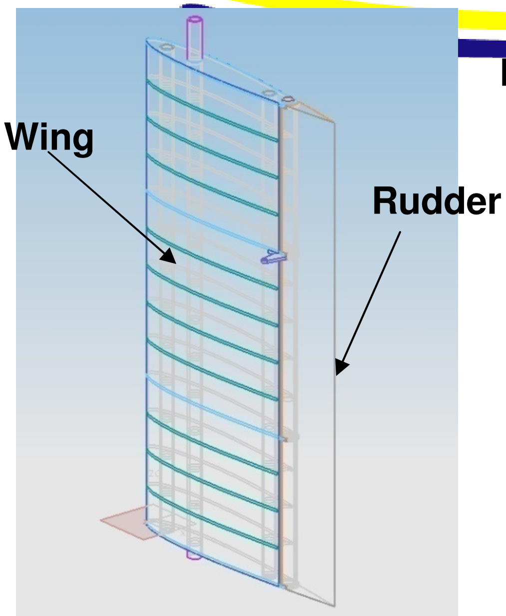
Simulated actuator allowing for freeplay nonlinearities

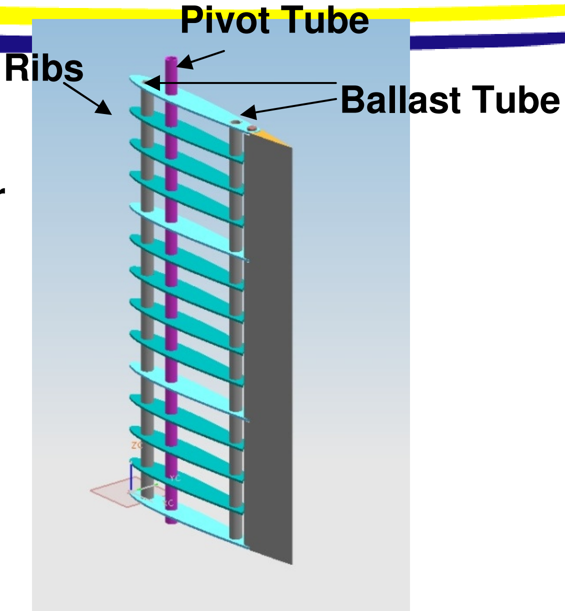
Wing - wind tunnel mount
Providing linear Plunge
And torsional pitch stiffnesses

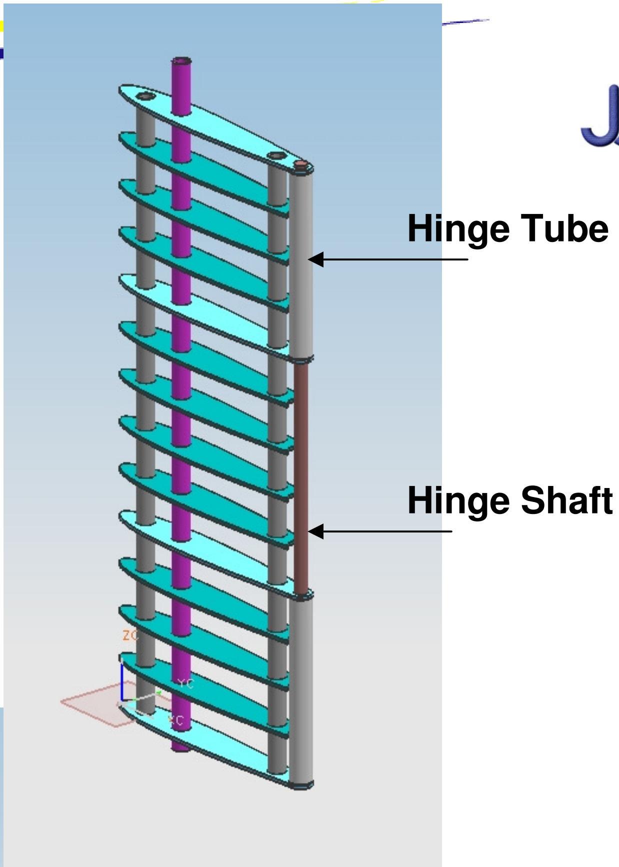
Rudder – composite construction allowing for simulations of hinge failure and Rudder damage

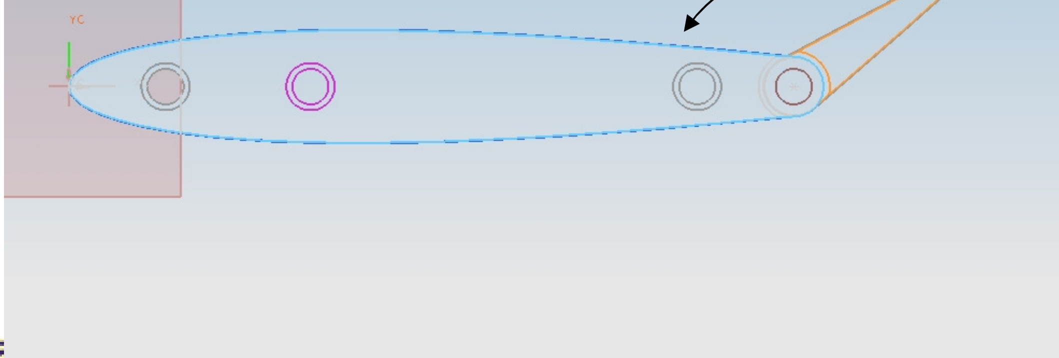
Aluminum wing allowing for variable inertia / cg properties

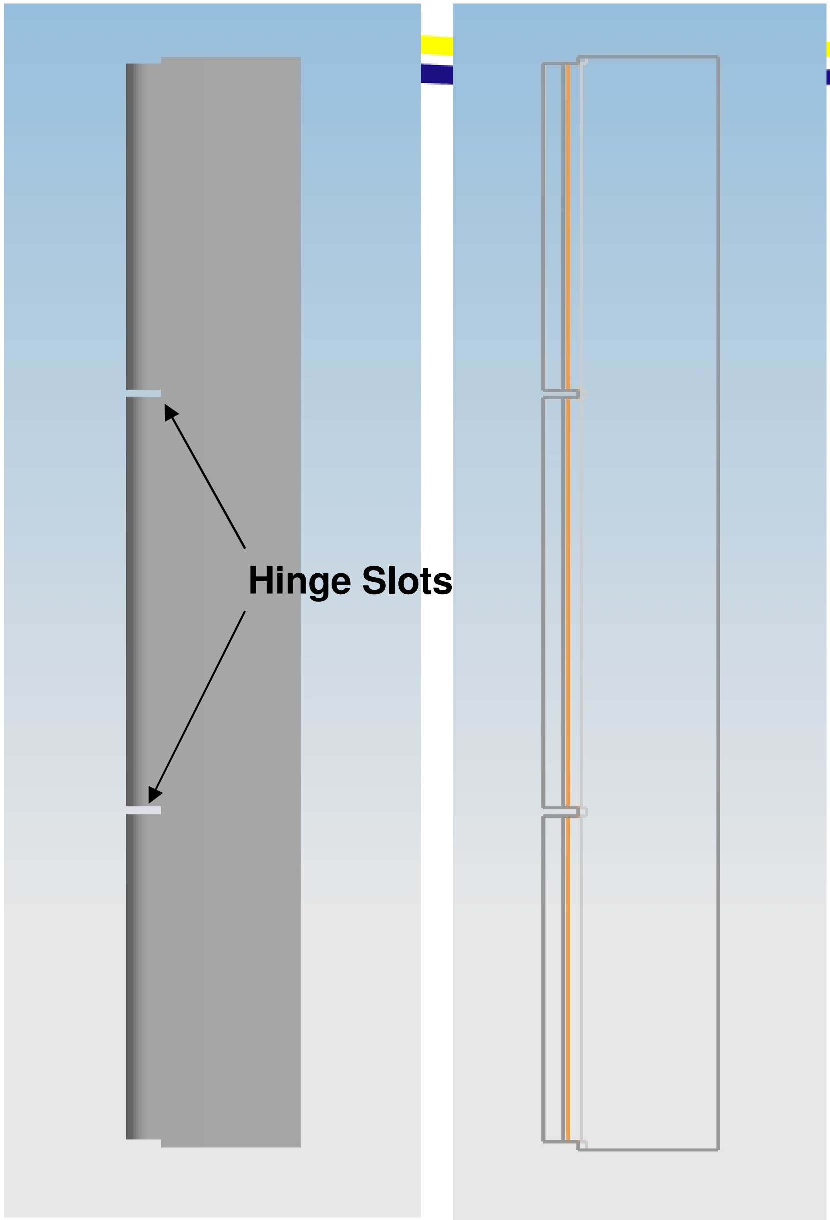
Simulated actuator / damper attachment allowing for different nonlinearities

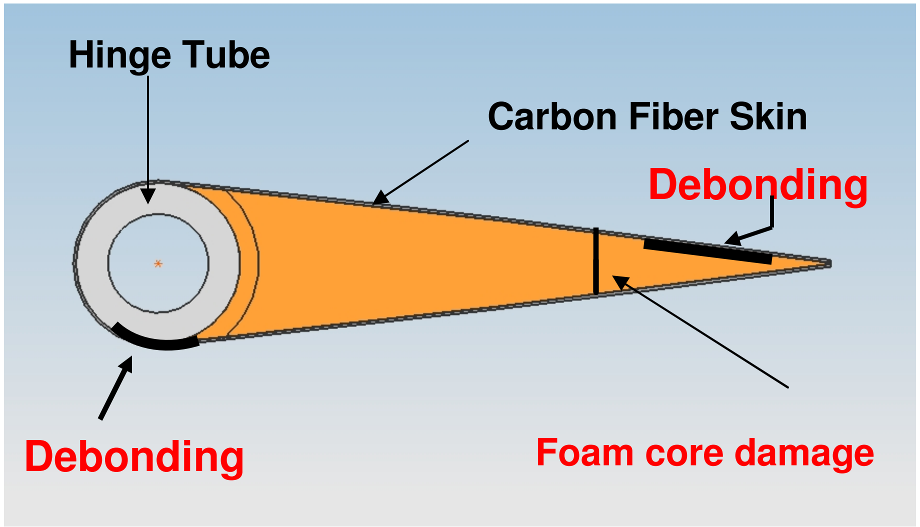

Wing
Rudder


Pivot Tube
Ribs
Ballast Tube


Hinge Tube
Hinge Shaft


35 °

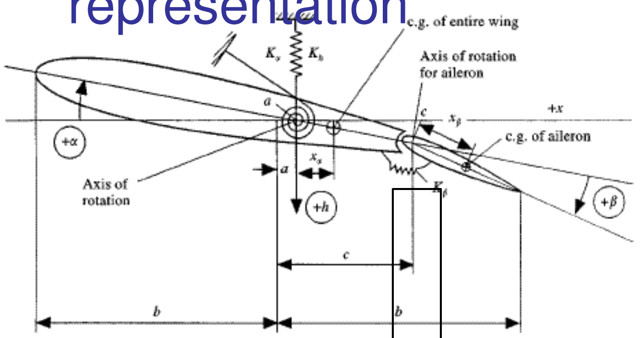


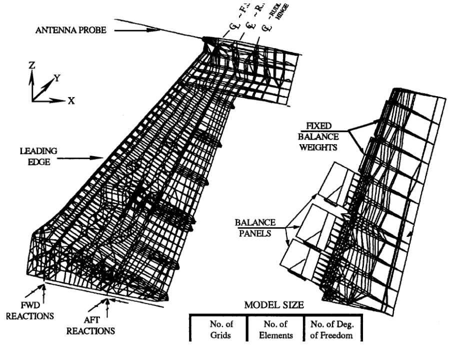


- Damage modes
  - Debonding.
  - Delamination
  - Core cracking
  - Hinge failure

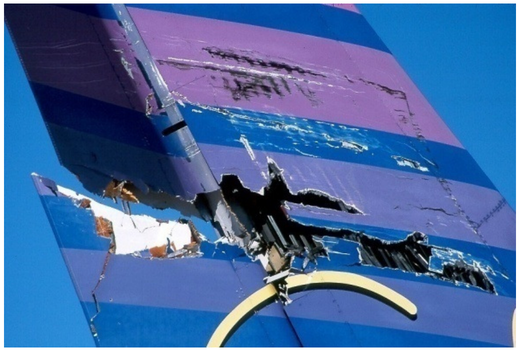
Limit Cycle Oscillations and flutter due to control surface hinge stiffness nonlinearity

Basic aeroelastic model representation





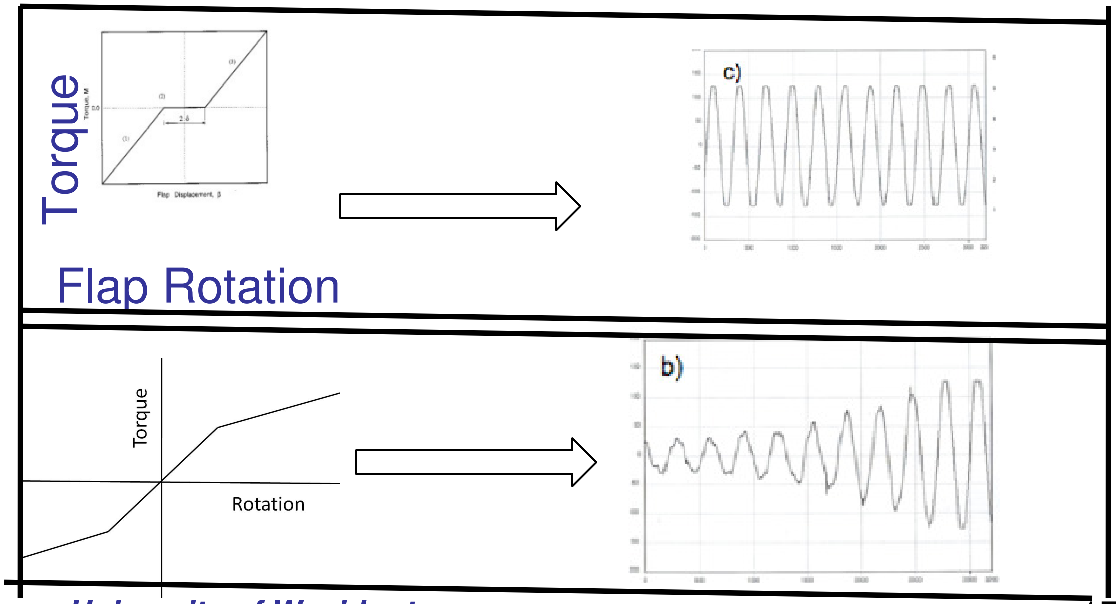
Local degradation / damage



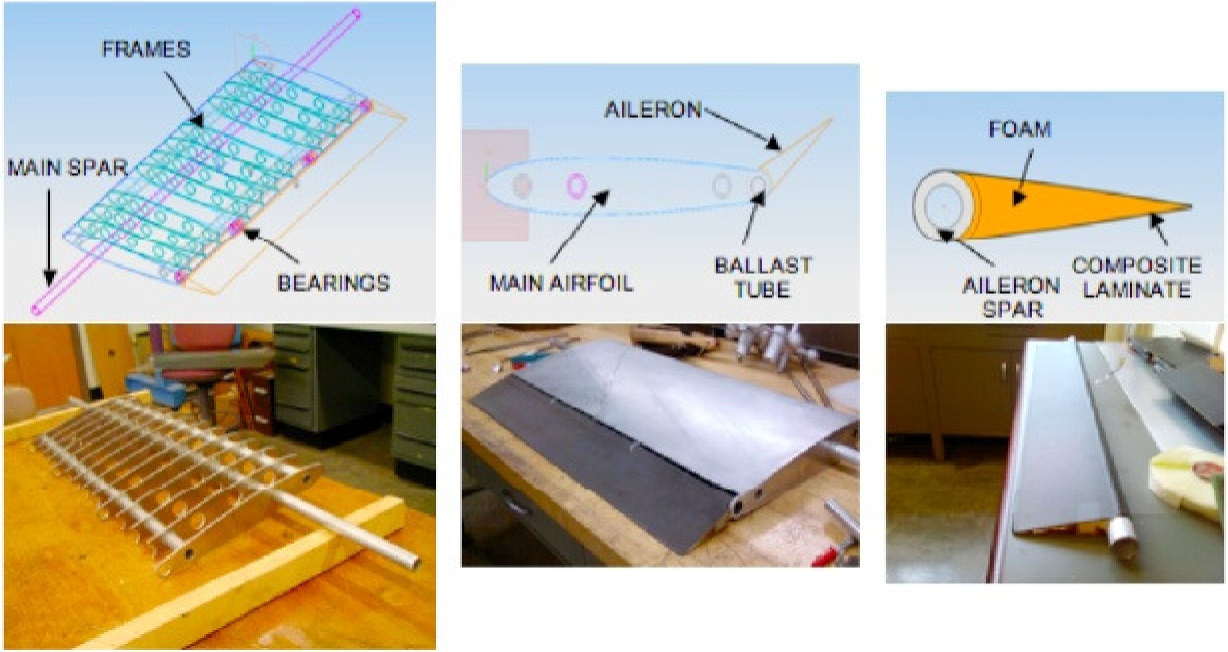
Hinge stiffness

Hardening

softening

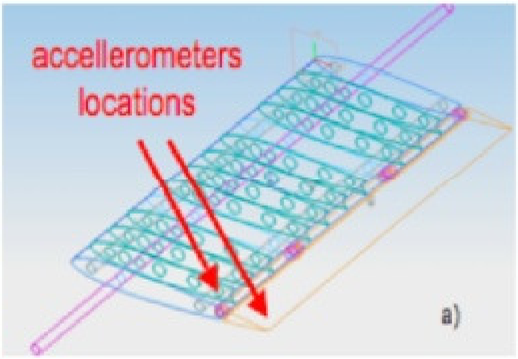


The Aeroelastic UW Tail / Rudder Model



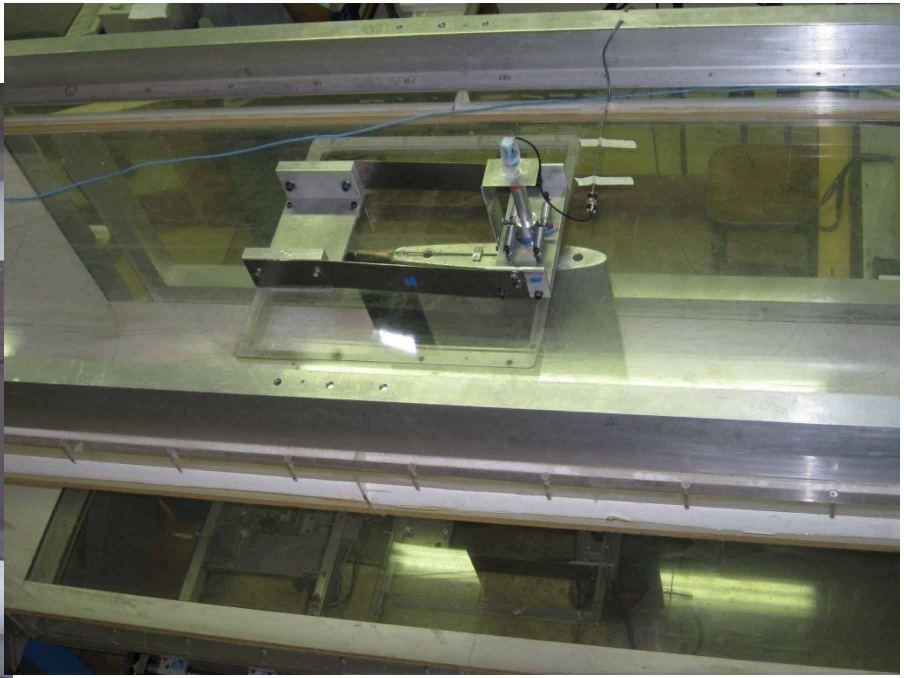
Design and manufacturing of the model

Support Blocks



Accellerometers Location

The tail / rudder model at the UW’s 3 x 3 wind tunnel 2009

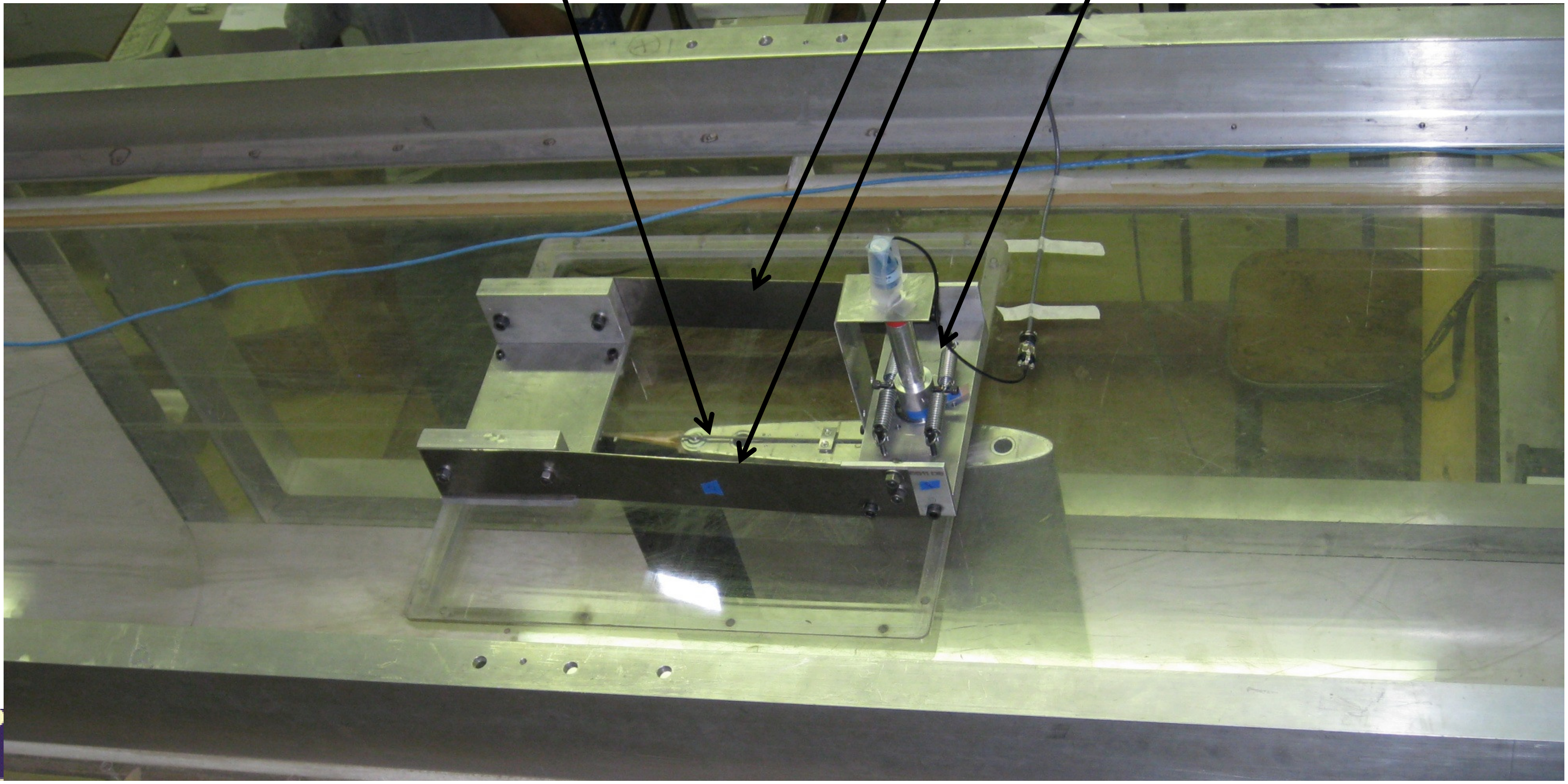


Modifications and Improvements of the Model for the 2009 Limit Cycle Oscillation (LCO) Tests

- Improved hinge bearings for reduced hinge damping to represent typical flight vehicle structures.
- Improved pitch spring system.
- Addition of RVDT sensors for direct measurement of pitch and rudder rotations.
- Revised bending, pitch, and rudder rotation stiffness values leading to coupled plunge, pitch, and rudder rotation frequencies representative of actual airliner bending / torsion / rudder rotation frequencies.
- A new rigid jig attachment system for carrying out modal tests of the model cantilevered in the lab.

Modifications and Improvements of the Model for the 2009 Limit Cycle Oscillation (LCO) Tests

- New pitch springs & RVDTs
- Plunge (heave) stiffness
- Rudder rotation stiffness



Tests 2009

- **Modal tests & correlation with the analytical predictions**

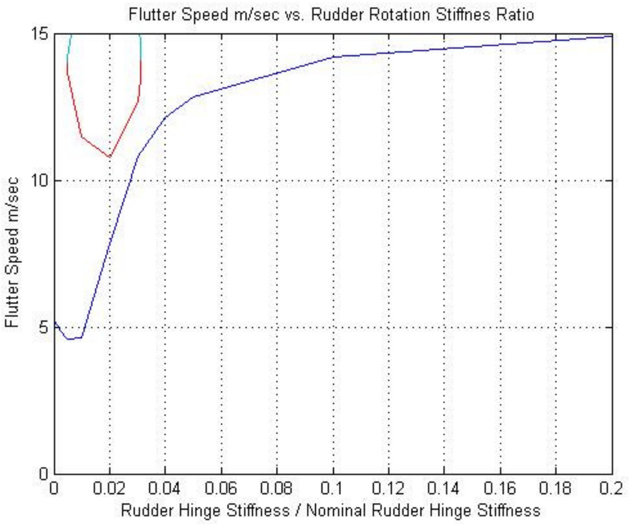
- **Ground Vibration Tests (GVT): Model mounted in the 3 x 3 wind tunnel:**

Mode	Damping ratio	Frequency(measured)	Frequency(predicted)
plunge	0.075	2.19 Hz	2.11 Hz
pitch	0.11	3.59 Hz	3.62 Hz
rudder	0.0075	20.62 Hz	20.66 Hz

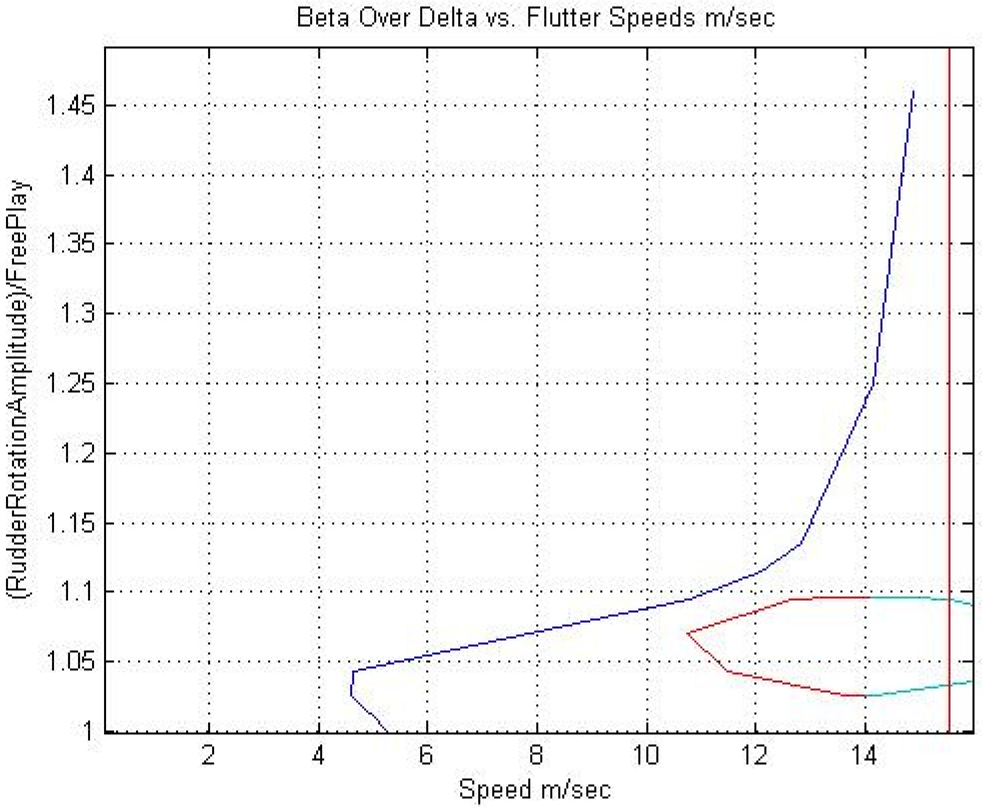
- **Flutter Test of the Nominal System (no nonlinearities introduced)**

- **Flutter speed / frequency prediction: 15.7 m/sec / 2.6 Hz**

- **Flutter speed / frequency test: 16.2 m/sec / 2.5 Hz**

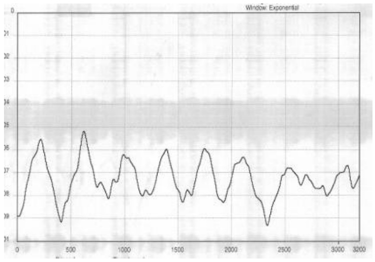


The effect of reduction of rudder rotational stiffness on the flutter speed

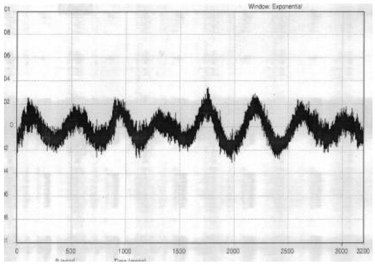


Predicted Limit Cycle Oscillation amplitudes of rudder rotation at speeds below the flutter speed of the no-freeplay system

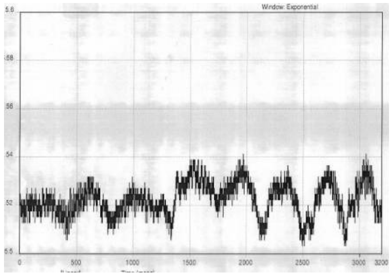
Limit Cycle Oscillations with a 1 deg rudder freeplay at 13.2 m/sec (81% of the no-freeplay flutter speed)



Laser vibrometer at rudder mid-chord



Laser vibrometer plunge velocity at elastic axis

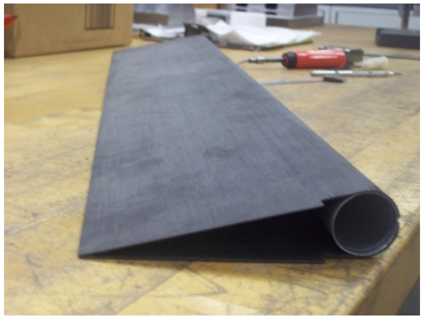


RVDT tail pitch angle

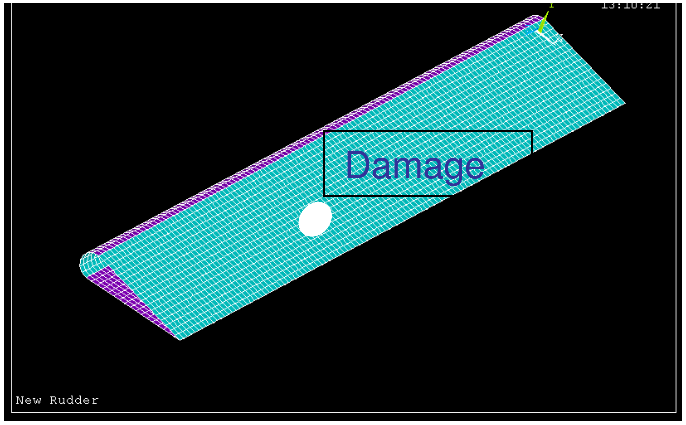
LCO Tests Status

- Modification of model to allow tests with larger freeplay magnitudes
- Improvement of instrumentation and data processing equipment.
- Modification of model to allow rapid changes in system’s characteristics
- Search for / design hinge dampers for tests involving complete loss of actuator stiffness (to allow validation of UW and Boeing computational tools)

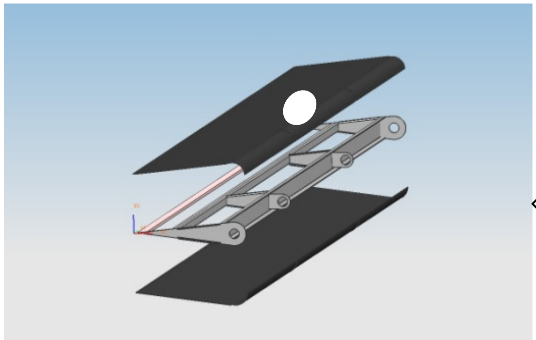
Design / Construction of Composite Rudders for Flutter Simulations / Tests of Damaged Rudders Representing Realistic Rudder Designs: In Progress



Highly flexible rudder model for exploratory flutter / LCO studies of Pristine and damaged structures with more complex dynamics (including Rudder torsion and bending)



Detailed finite element / Unsteady aerodynamic modeling, including 3D and Local effects



Rudder models reflecting Actual composite rudder Designs with various internal Structural arrangements And damage mechanisms

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.
- Correlation with Boeing flutter and LCO simulation runs – underway. 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.

Benefits to Aviation
(general program and 2009 experimental work)

- 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.