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

Presented by Professor Eli Livne
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Focus Topic:

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

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Contributors

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- 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)

Scope of Presentation

Motivation & Key Issues – a Review of the complete project (slides 5-8 are included in the Power Point file for completeness but will not be covered in the talk)

2010 focus - Experimental aeroelastic capabilities for testing degraded and damaged composite airframes:

Wind tunnel tests of a Tail / Rudder configuration with no hinge stiffness and with a velocity-square damper

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 2009-2010 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 in areas of importance to the FAA and industry.

Program Approach
(the 2009-2010 focus highlighted)

- 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.

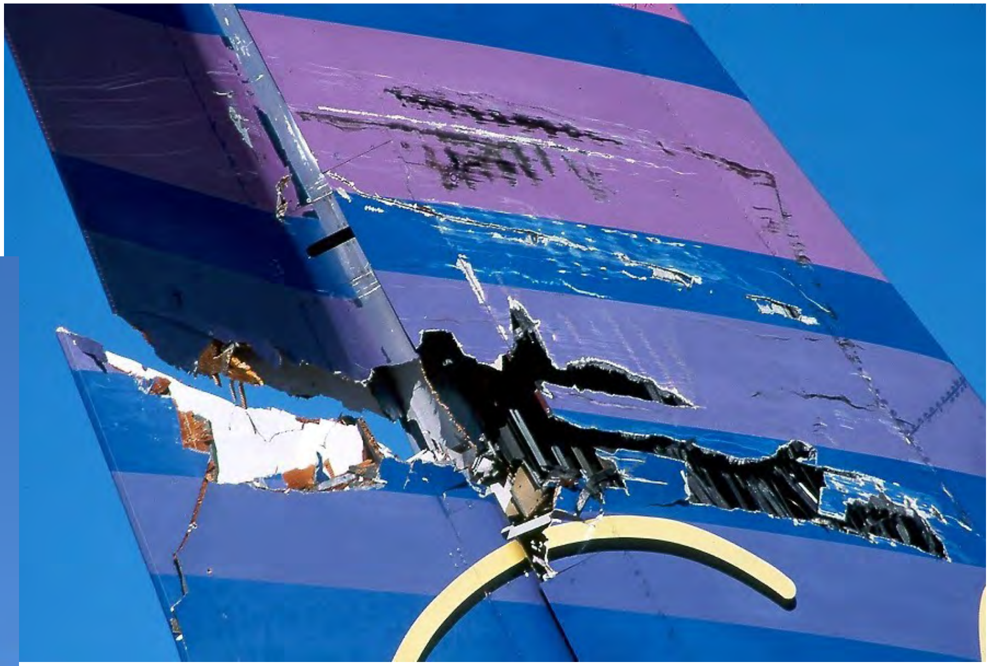
- Structural dynamic and future aeroelastic tests of aeroelastically scaled models to support aspects of the simulation effort described above.

The 2009 – 2010 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:

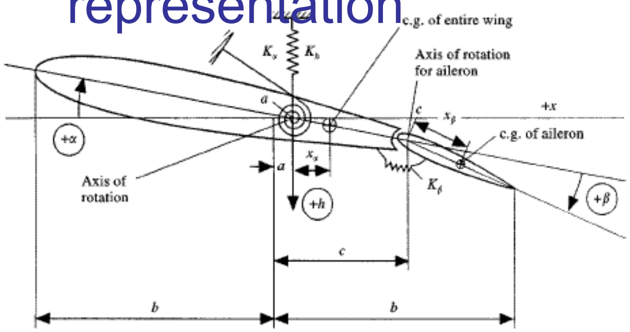
- Actuator / Actuator attachment hinge nonlinearities:
  - Freeplay / bilinear stiffness (hardening nonlinearity)
  - Buckling tendency (softening nonlinearity)
  - Hinge failure (coupled rudder rotation / rudder bending instability)
  - Actuator failure – nonlinear behavior with nonlinear hinge dampers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

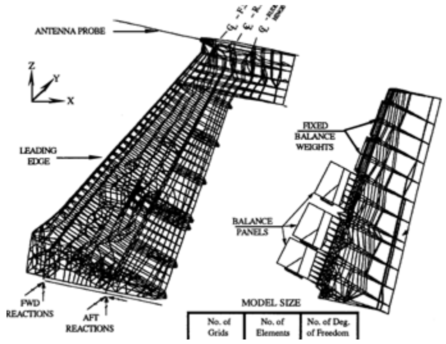
Important Notes:

- 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



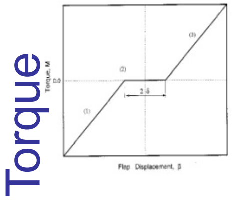


Local degradation / damage

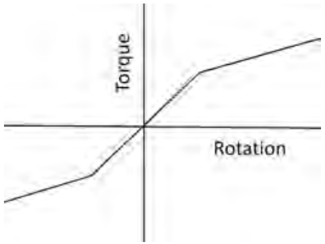
Hinge stiffness

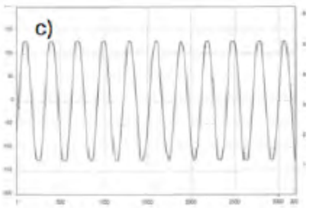
Hardening

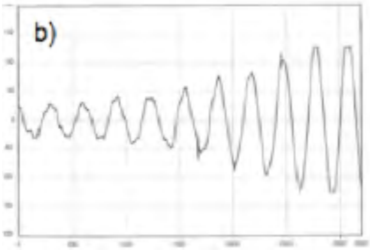
softening



Flap Rotation



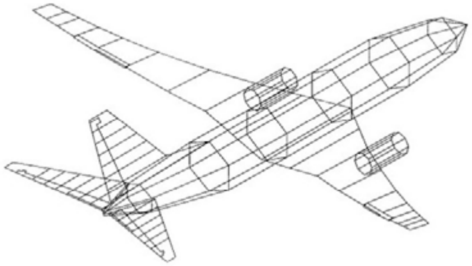




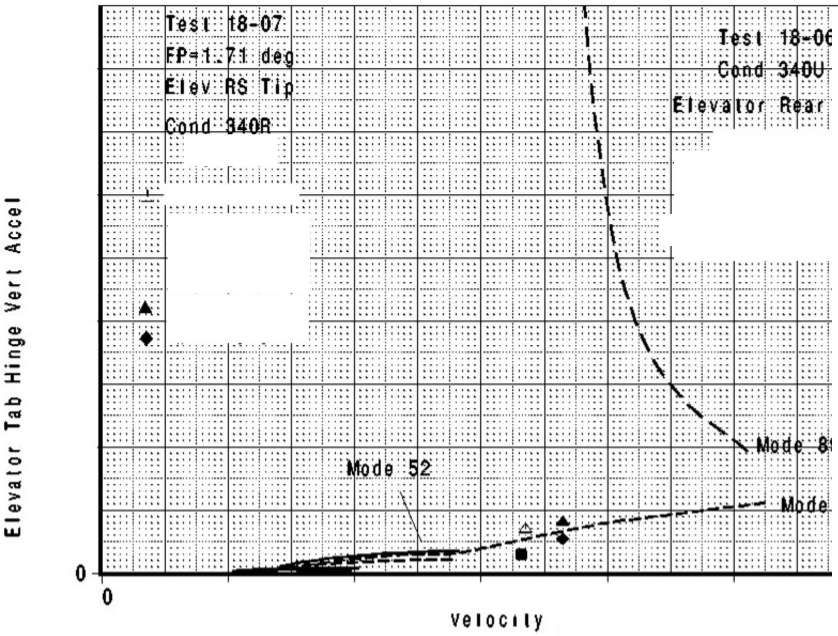
Representative Describing Function Limit Cycle Predictions and Flight Test Results (Boeing)

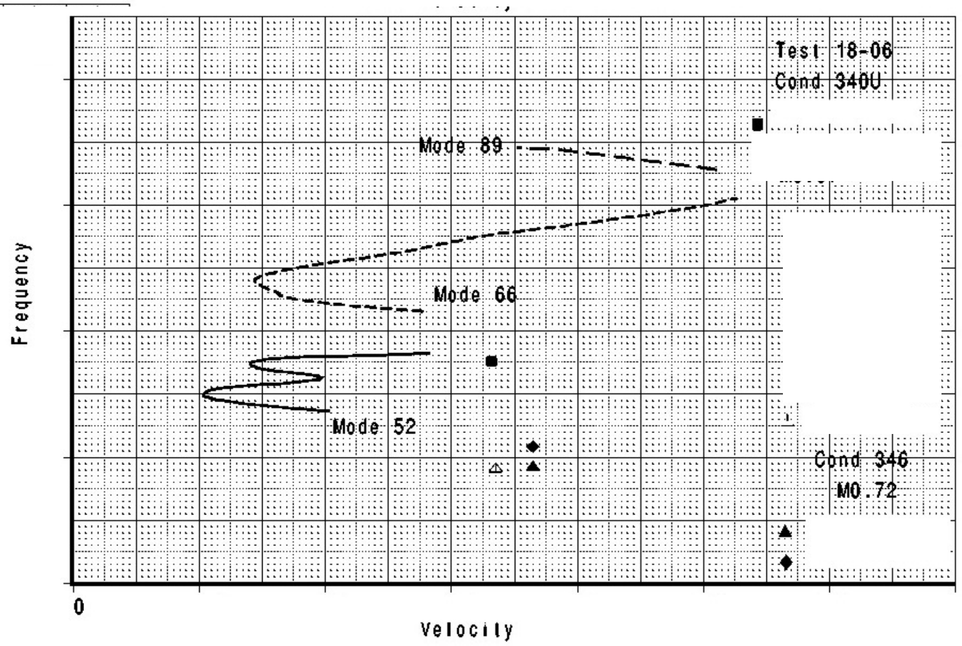
$\delta_{fp} = \pm 1.71$ deg

$g = +0.03$



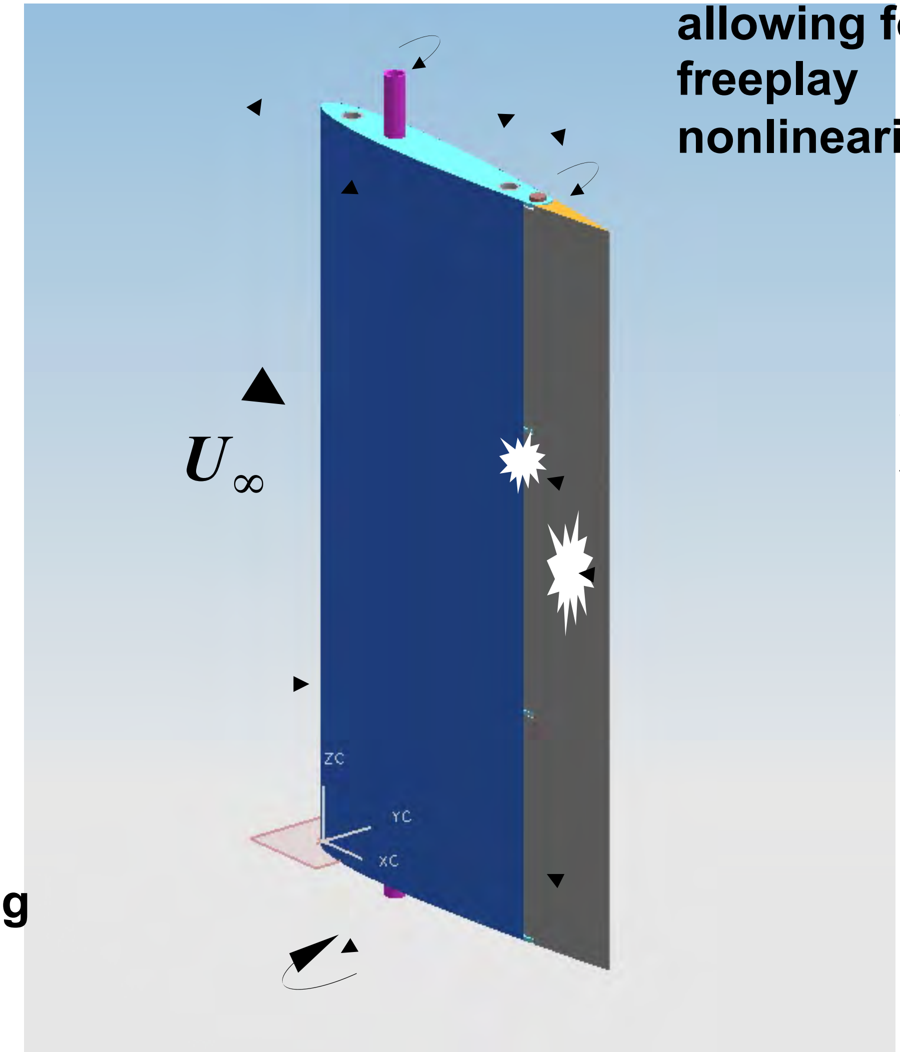
Elevator HL Vertical Acceleration
g = +0.03
Hinge #8 - Node 2508 (Outbd)
Modes 52, 66, and 89
Analysis and Test Comparison





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

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

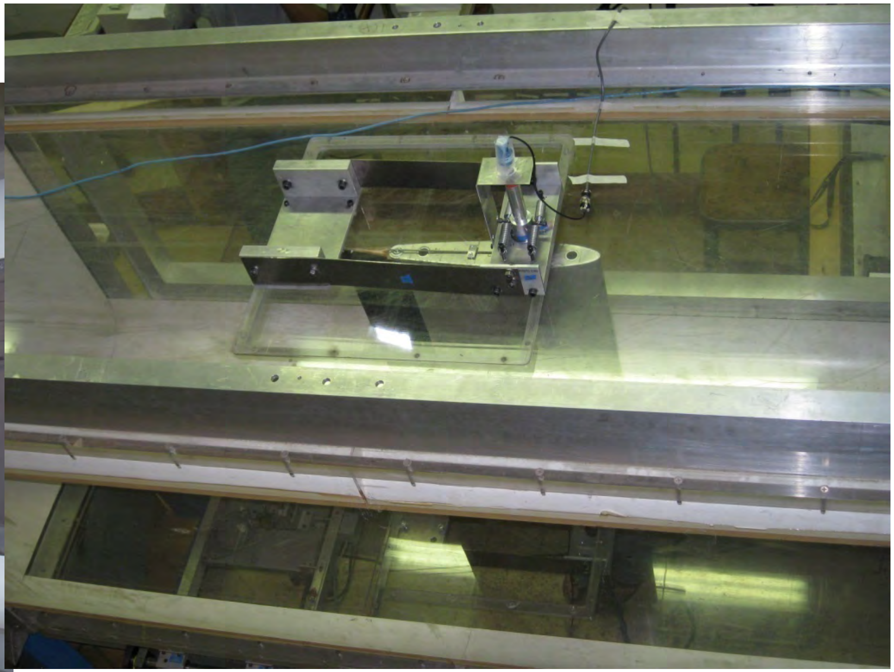
Wing - wind tunnel mount
Providing linear Plunge
And torsional pitch stiffnesses

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

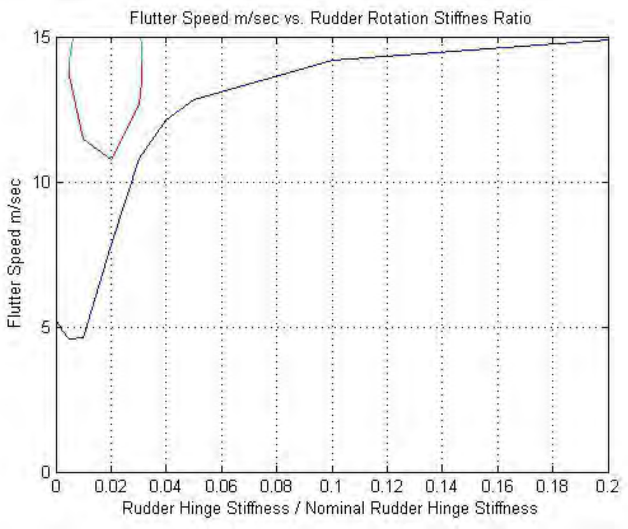
Aluminum wing allowing for variable inertia / cg properties

Simulated actuator / damper attachment allowing for different nonlinearities

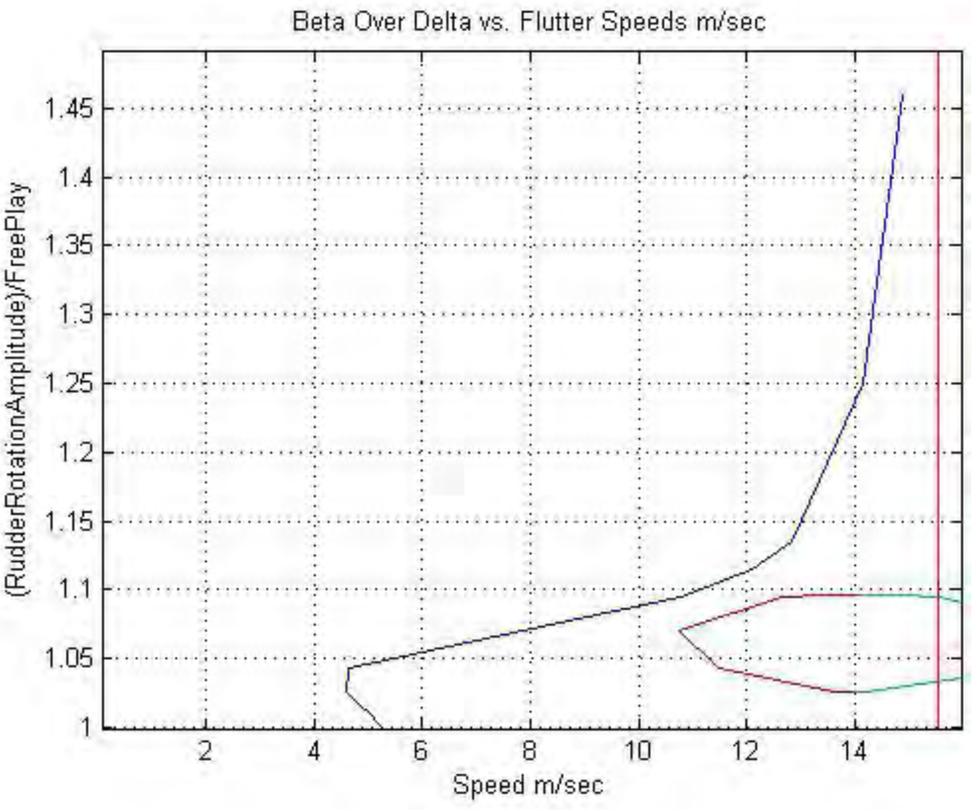
The tail / rudder model at the UW's 3 x 3 wind tunnel 2009-2010



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



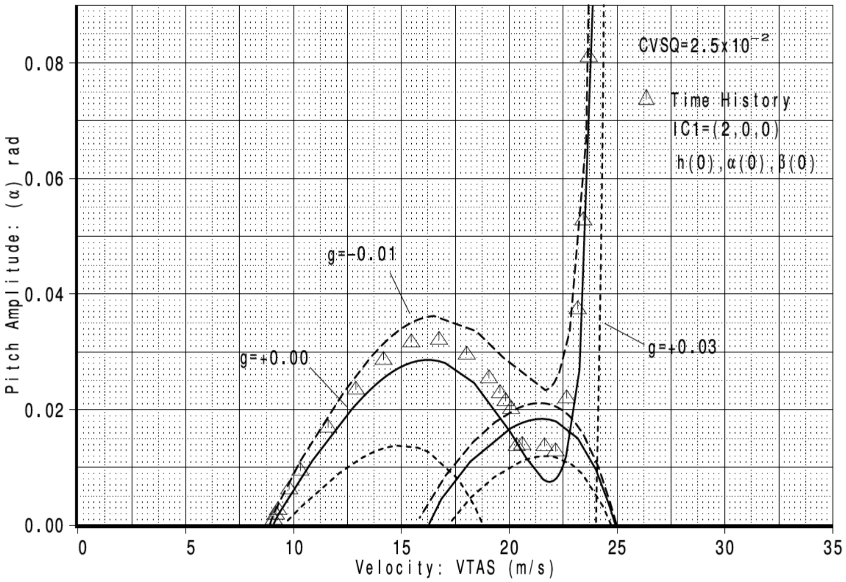
The effect of reduction of rudder rotational stiffness on the flutter speed

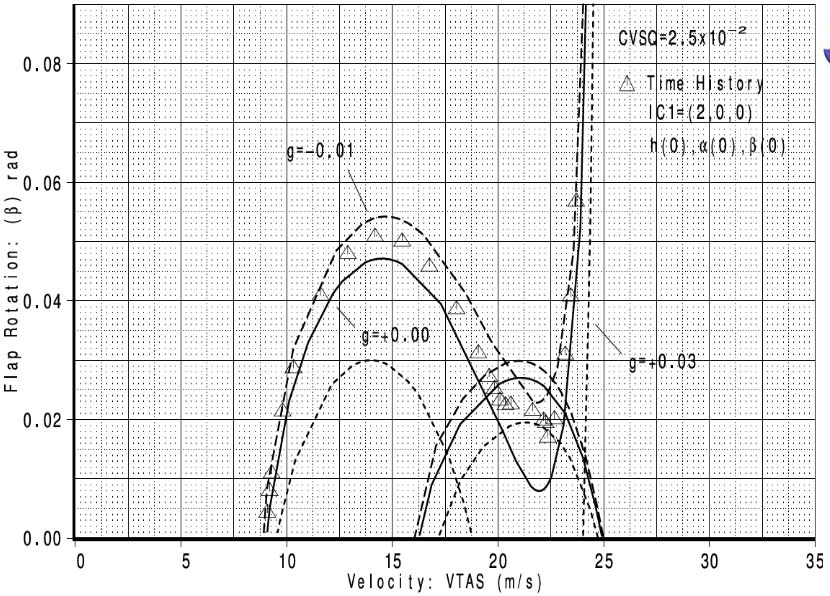


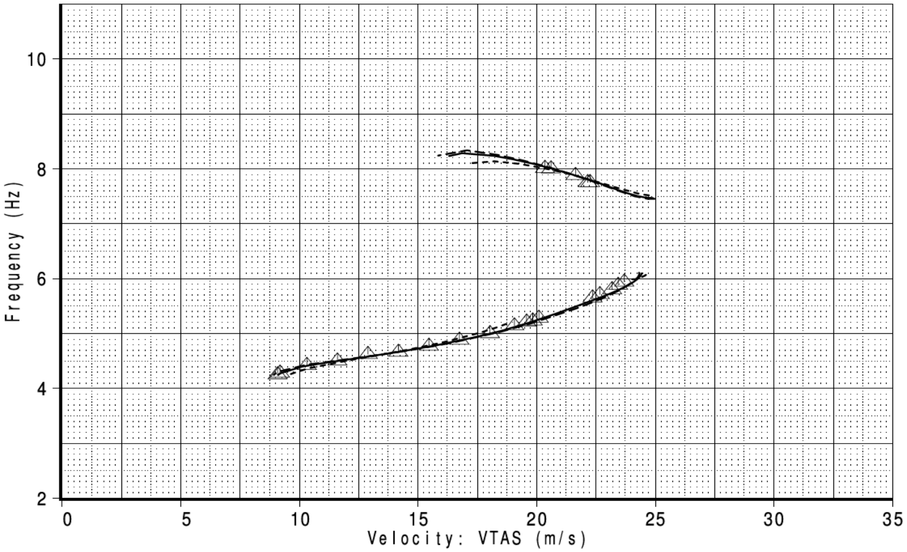
Predicted Limit Cycle Oscillation amplitudes of rudder rotation at speeds below the flutter speed of the no-freeplay system

- 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 Nonlinear Aeroelastic Behavior with No Rudder Hinge Stiffness and with a Velocity-Squared Damper (Boeing)



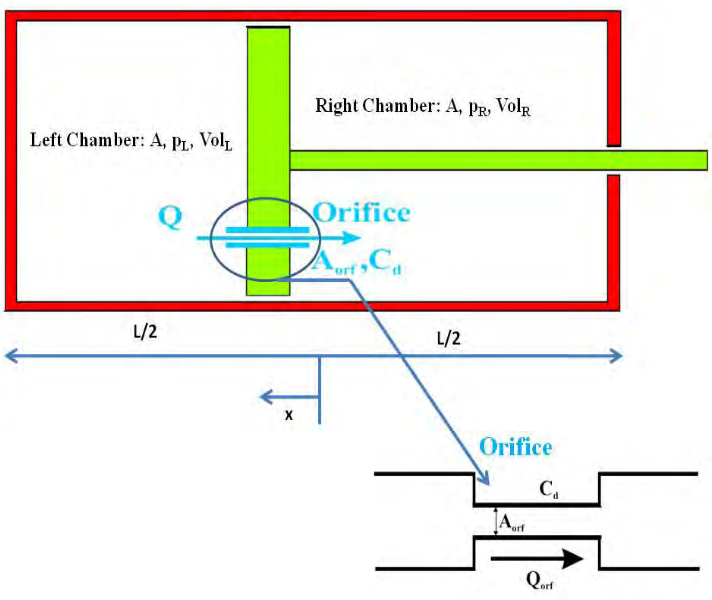


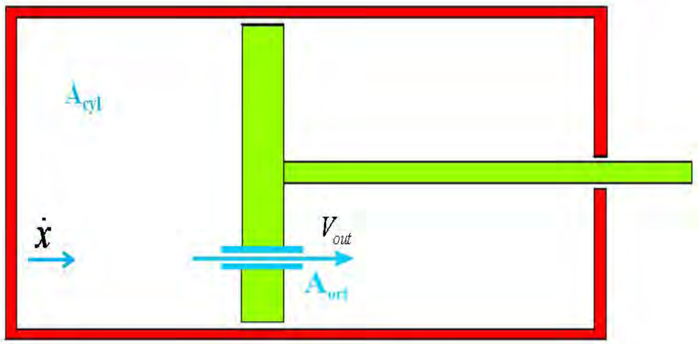


Notes: The system is the Duke University Tail/Rudder System

Results: from work by Dr. James Gordon, Boeing

The Design of a Small Velocity Squared Damper





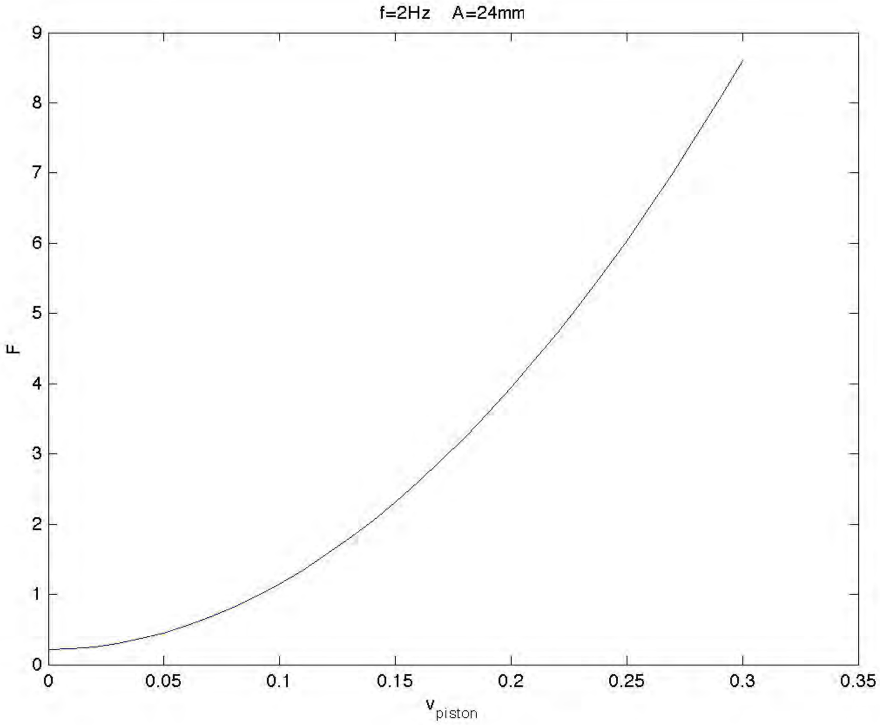
Axes chosen so that
Piston at rest
with respect to them

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

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

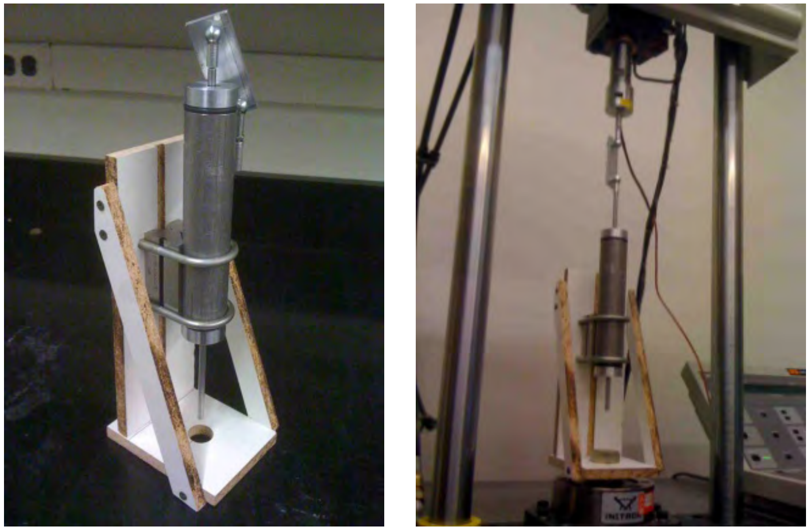
$$F_{tot} = F_{pressure} + F_{viscosity} + F_{inertial}$$

The Design of a Small Velocity Squared Damper



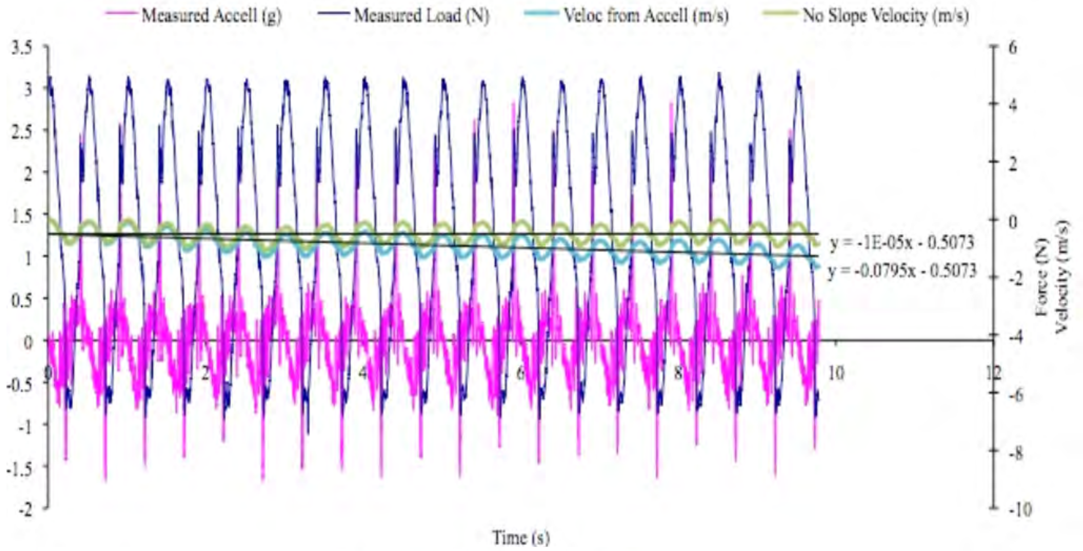
Ground Tests of the Damper

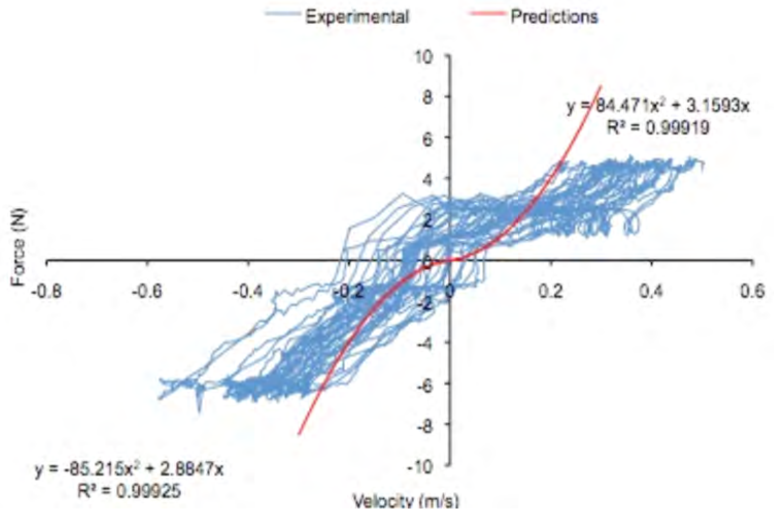
Direct attachment to the
Instron Machine



Attachment to the
Instron Machine through a lever system
To increase testing stroke

Exploratory Damper Test Results – Work in Progress





Test Fixture Problems:

Flexibility of lever system

Nonlinearity of the piston rod
Buckle (tendency to buckle
In compression)

Short Term Plans

- Improve damper test fixture and carry out damper characterization tests
- Use CFD to simulate the internal flow field in the damper and optimize orifice shape and distribution.
- Attach dampers to the tail/rudder system and carry out aeroelastic wind tunnel tests at the UW’s 3 x 3 low speed wind tunnel.
- Correlate with Boeing results and validate Boeing and UW simulation codes.

Longer Term Plans

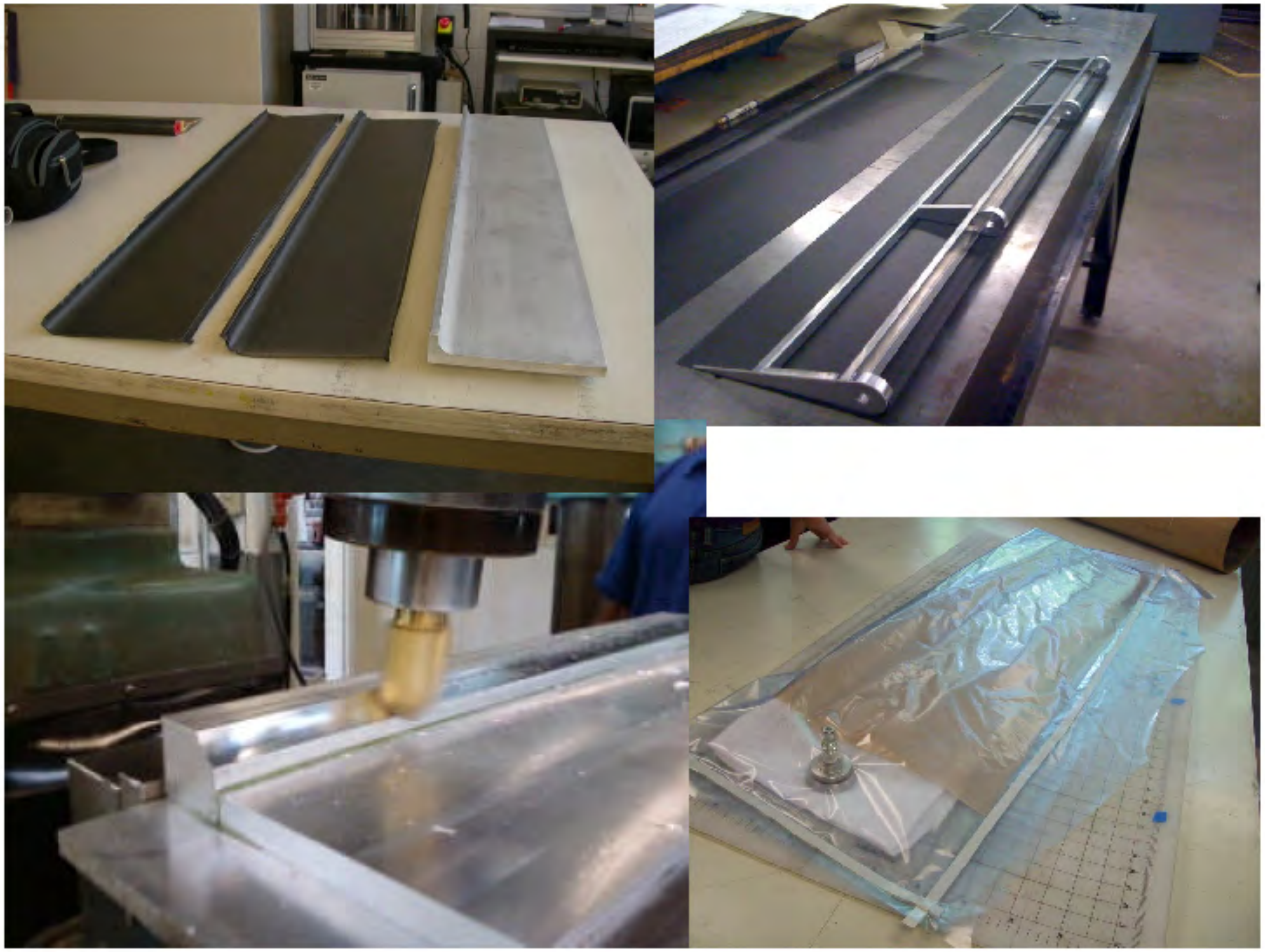
- Test Tail/Rudder systems with composite rudder with various structural damage scenarios leading to local stiffness nonlinearity.

- Test Tail/Rudder system with small actuators and various hinge nonlinearities.

- Correlate with aeroelastic and aeroservoelastic simulation codes at Boeing and the UW.

- Proceed to more complex aeroelastic wind tunnel tests of composite airframe models.

New Composite Rudder Designs



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 and is undergoing ground tests currently.
- 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 2010 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.