Combined Local → Global Variability and Uncertainty in the Aeroservoelasticity of Composite Aircraft

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Motivation and Key Issues

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

- Sources of uncertainty in composite structures: damage, delamination, environmental effects, joint/attachment changes, 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.
– Build a structural dynamic / aeroelastic testing capability and carry out experiments.
– Integrate aeroelasticity work with work on damage mechanisms and material behavior in composite airframes.
– 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.
Approach
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 Simulation:
Automated for Carrying Out Fast Repetitive Analyses
Development of an In-House Design Oriented Aeroservoelastic Modeling Capability (May 2005 slide)

Variable Local Structure: Modulus of Elasticity (E) of certain skin panels

Active Aileron

Variation of the Real (damping) And Imaginary (frequency) Parts of a Typical Pole
Development of an In-House Design Oriented Aeroservoelastic Modeling Capability (June 2006)

• Development of the in-house capability continues:

• Extensions under development:
  – Linear buckling analysis (and sensitivities).
  – Non-linear structural behavior (local nonlinearities due to damage or wear, large structural deformations).

• Complete control of the simulation software is necessary for:
  – Studies of non-standard approximation techniques (used for accelerating the large number of repeated analyses needed to cover structural uncertainties).
  – Insight.
  – Better integration with an array of different commercial packages.
  – Creating a comprehensive design optimization / reliability assessment tool that will also allow development of best repair practices and fleet retrofits, if needed.
Linear Aeroelasticity of Full Scale Composite Aircraft: Computational Array using Commercial Codes
Modeling Case: The Fighter-Type Wing with Control Surfaces

NASTRAN Structural Dynamic Mesh

LE Flap
Electric actuation

TE flaperon
Servo-hydraulic actuation
Modeling Case: The Fighter-Type Wing with Control Surfaces

Flaperon mode

- Panel damage $\rightarrow$ 7% reduction in flutter speed
- Added mass near trailing edge due to repair $\rightarrow$ 6% flutter speed reduction (added mass at TE: 1% of TE mass)
Modeling Case: The UW Low-Speed Dynamically-Scaled All Composite Supersonic Business Jet (SSBJ) UAV

Structure:
Kevlar/Epoxy Skins
Graphite/Epoxy Frames
Kevlar/Graphite/Epoxy spars and local reinforcements
Aluminum hard points for landing gear
Wood engine mounts
Balsa/Fiberglass canards and horizontal tails

Length=9.5 ft
Span=4.5 ft
Weight=26 lbs
Structure=13 lbs
The UW Dynamically Scaled SSBJ UAV

The complete vehicle and selected structural details
Modeling Case: The UW Low-Speed Dynamically-Scaled All Composite Supersonic Business Jet (SSBJ) UAV

- Coupon tests
- CAD geometry
- Material properties
- Nonstructural weights
- NASTRAN FE Model
Effect of Damage Size on Flutter Frequency and Speed

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Aeroelastic Reliability
Considering Linear Aeroservoelastic Failure Modes

- Linear stability results: flutter speed
- Linear stability results: damping and frequency of aeroservoelastic poles at given flight conditions
- Cover variations in all system’s parameters

Gather statistics of failure:
- Flutter
- Fatigue
- Ride comfort

Response to atmospheric gusts (stable system)
Nonlinear Behavior Simulation: Automated for Carrying Out Fast Repetitive Analyses
Free-Play Induced LCO: Intuitive Concepts

- 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.
LCO Simulation Methods

- Describing Function Method
  - Solve the aeroelastic equations in the frequency domain.
  - Assume existence of simple harmonic motion. Find the speed, frequency, and amplitude at which it will happen (if at all).
  - Map: LCO amplitude and frequency vs. speed.
  - Method determines if LCO can or cannot exist. Different initial conditions are not used to create the LCO maps.

- Time Domain Simulation
  - Solve the aeroelastic equations in the time domain.
  - Obtain time histories.
  - In theory: there is a need to cover all possible initial conditions and excitations to get a complete map of all possible aeroelastic time responses.
Computational tools for both Describing Function frequency-domain simulations and time domain simulations were developed and validated using a simple case: The Tang-Dowell 2D 3dof airfoil / aileron low-speed aeroelastic model.

Describing Function results were also validated using independent University of Washington simulation results.
LCO Amplitudes for the Tang-Dowell Airfoil / Flaperon 3dof System

All system parameters: nominal values

Note: abrupt changes in LCO amplitudes (with speed) can correspond to change on oscillation frequency also.
Describing Function LCO Analysis in the Case of Control Surface Free-Play: Concept

Amplitude of oscillation determines an equivalent effective linear spring.

Carry out linear flutter analysis for that spring value and find flutter speed(s) and frequency(ies).

Linear flutter solutions correspond to the system oscillating in simple harmonic motion, with the flaperon moving on its hinge with the assumed amplitude (used to determine the equivalent spring).

Create a map of possible simple harmonic oscillation amplitudes versus speeds and frequencies that allow them.
The Iterative Nature of Flutter Solutions

Oscillation damping

Flutter point: system moves in simple harmonic motion

unstable

stable

speed

Iterative solution: non-dimensional frequency is varied and aeroelastic modes are tracked to find flutter crossings automatically
The Double-Iterative Nature of Free-Play
LCO Flutter Solutions

Vary assumed stiffness to model different levels of oscillation

Find possible LCO speeds and frequencies

Track LCO speeds and frequencies vs. oscillation amplitudes
To create LCO maps and identify the most critical LCO conditions
Aeroelastic Reliability
Considering LCO-Related Failure Modes

LCO results – Describing Function Maps

Assess failure Modes: fatigue, Ride comfort, Possibility of Destructive Linear flutter

Gather Statistics Of Failure

Cover variations In all system’s parameters

LCO results – Extract amplitudes / frequencies From Time Histories of Response to excitation And initial conditions

Gather Statistics Of Failure
3DOF aeroelastic system – Probabilistic Analysis

**Damage may lead to:**
- 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
Nominal parameters (LCO results obtained from response time histories)

Note: the response amplitudes are normalized
Monte-Carlo Simulation Results (obtained from response time histories)
Scatter band

Scatter of LCO Amplitude

Flap LCO Amplitude

-0.0050 0.0000 0.0050 0.0100 0.0150 0.0200 0.0250 0.0300 0.0350 0.0400 0.0450

Mean
Mean+Sigma
Mean-Sigma

Speed, m/s

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A Probabilistic Approach to Aeroservoelastic Reliability Estimation

General
The Next Step – Link Statistical Variability Models with Variability and Damage Models of Actual Aircraft

• With capabilities to rapidly find statistics of aeroelastic behavior and failure due to variability of system’s parameters, add:
  – Models of actual damage types
  – Information regarding damage variability for actual aircraft in service

• Develop tools for assessing aeroelastic reliability measures

• Use the statistics of the resulting behavior to evaluate aeroelastic reliability

• Use the technology to affect design practices, maintenance procedures, and optimal retrofits
Deterministic Approach

- For normal conditions without failures, malfunctions, or adverse conditions: no aeroelastic instability for all combinations of altitudes and speeds up to max design conditions + 15%
- In case of failures, malfunctions, and adverse conditions: no aeroelastic instability within operating conditions + 15%
- Parametric studies used extensively to find and cover all worst case scenarios
- 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.
- Extension of damage tolerance concepts to aeroelasticity: residual stiffness in the presence of damage and no catastrophic aeroelastic failure.
General probabilistic approach

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

\[ P_f = \int_0^\infty (1 - F_{V_a}(V)) f_{V_f}(V) \, dV \]

\( F_{V_a} \) is a Cumulative Probability Function of maximum random airspeed per life

\( f_{V_f} \) is Probability Density Function of the random flutter speed
Failure types considered

- Excessive deformations
- Flutter: airspeed exceeds the flutter speed of damaged structure
- High amplitude limit cycle oscillations: the acceptable level of vibrations is exceeded
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Probability of Failure Formulation 1

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

<table>
<thead>
<tr>
<th>Interval #</th>
<th>Probability of Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (new structure)</td>
<td>8.0E-04</td>
</tr>
<tr>
<td>2 (damaged structure)</td>
<td>8.9E-03</td>
</tr>
<tr>
<td>3 (repaired structure)</td>
<td>6.33E-03</td>
</tr>
<tr>
<td>Total POF =</td>
<td>1.60E-02</td>
</tr>
</tbody>
</table>
Multiple damages / times / repairs

Effects of aging on Flutter speed

Effects of Damage on Flutter Speed

Total degradation for both damages

VF/VF0
Probabilistic Model

Combine statistics of flutter speed (due to damage and structural changes, as simulated by the aeroelastic modeling capabilities described here) with statistics of speed excursions.

The methodology is built on:

Lin, K., and Styuart, A.,
“Probabilistic Approach to Damage Tolerance Design of Aircraft Composite Structures”,

extended to include Aeroelastic failure modes.
Describing Function Analysis of Multi-Degree of Freedom Aircraft

The step from a simple 3 dof system to the case of a complete passenger airplane
The step from a simple 3 dof system to the case of a complete passenger airplane makes the problem more complex by orders of magnitude:

- Many more modes of vibration must be included in the aeroelastic analysis in order to capture all global and local motions of importance
- Many limit cycles are possible
- Automation of the analysis process is challenging
- A major challenge: Automation of probabilistic analysis / LCO simulations of systems covering large numbers of possible system variations
Boeing 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

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The Challenging Case of Many Dofs and closely-spaced Frequencies

Effective tab rigid rotation stiffness = 0

Growth Rate vs Velocity

Frequency vs Velocity
The Challenging Case of Many Dofs and closely-spaced Frequencies

Effective tab rigid rotation stiffness - High

Growth Rate vs Velocity

Frequency vs Velocity
$\delta_{fp} = \pm 1.71 \text{ deg}$

$0 < g < +0.03$
\[ \delta_{fp} = \pm 1.71 \text{ deg} \]

\[ g = +0.03 \]
Development of Experimental Capabilities

- New Modal testing system: arrived and installed.
- Training: June-July 2006.
- Test articles: small composite UAVs & components: nominal and with different types and level of damage.
Conclusion

• Progress in all major areas of this R&D effort:
  – Efficient simulation tools for uncertain airframes covering flutter and LCO constraints
  – 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: Equipment arrives; Up to speed in the next few weeks.
  – 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

- **Flutter**
  - Continue development of the UW in-house simulation capability to include buckling (geometric nonlinearity) effects.
  - Continue development of the integrated NASTRAN / ZAERO simulation environment:
    - test using models with complexity representative of real passenger aircraft, and
    - improve automation of analysis and computational speed to allow efficient execution of the large number of simulations needed for probabilistic studies.
  - Use sensitivity analysis and approximations to utilize design optimization technology to address issues of reliability and optimal maintenance.
Plans

- LCO
  - Extend time-domain LCO simulation capability to complete airplanes and their finite element model.
  - Integrate with probabilistic / reliability analysis.
  - Continue development of LCO simulation tools for large-scale aeroelastically complex flight vehicles.
  - Develop a probabilistic approach to nonlinear LCO problems using Describing Function simulation techniques.
  - Design nonlinear small scale models (with different sources of service life and damage-related nonlinearity), carry out numerical simulations, correlate with structural dynamic tests, and prepare for aeroelastic wind tunnel tests.
Plans

- Probabilistics & Reliability
  - Link structural variation over time and damage modes to structural stiffness and inertia variations (including statistics).
  - Develop a comprehensive reliability methodology for composite airframes (with design and maintenance consequences) covering aeroelastic / aeroservoelastic failure modes.