Lessons from Modeling Flexible Aircraft for Active Flutter Suppression

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Active Flutter Suppression (AFS)

Reducing structural weight
- Standards require flutter to be 115% of maximum airspeed (Vne)
- Control system could be used to increase flutter speed without structural weight

Addressing design issues
- Predicted flutter speed can drop as design matures
- AFS could avoid expensive redesigns

X-56A Multi-Utility Technology Testbed
- Designed for testing active flutter suppression
- Flexible wings have unstable flutter modes
- AFRL Funded
- Lockheed Martin Built
- NASA has flown slightly past the flutter speed
Objective

Generate models useful for the design and evaluation of control laws for active structural control and flutter suppression that are able to accurately predict body freedom flutter.

For design
- Form of the models
- State-space models
- Interpolation between flight conditions
- Full envelope design

For evaluation
- Uncertainty
- Piloted simulation

Prediction
- Physically based models
- Using information typically available before flight
- Predictive accuracy insufficient/inconsistent
- Using flight test results to determine where we went wrong
### Challenges with Aeroservoelastic Modeling

<table>
<thead>
<tr>
<th>Category</th>
<th>Challenges</th>
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<td><strong>Challenging Dynamics</strong></td>
<td>- Unstable</td>
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<td></td>
<td>- Closed Loop</td>
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<td><strong>Model Complexity</strong></td>
<td>- High Order</td>
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<td></td>
<td>- Multiple-input</td>
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<td>- Multiple-output</td>
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<td><strong>Nonlinearities</strong></td>
<td>- Difficulty in prediction</td>
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<td>- Difficulty in interpreting</td>
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<td><strong>Uncertainty and Noise</strong></td>
<td>- Turbulence</td>
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<td>- Limited Knowledge</td>
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<td>- Variability</td>
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### Types of models being used

<table>
<thead>
<tr>
<th>NDoF model</th>
<th>Low Order Equivalent System (LOES) models</th>
<th>Parameter estimation models</th>
<th>Frequency responses</th>
</tr>
</thead>
</table>
| • Preflight models  
  • Did some updates from stiff wing data  
  • Very high order  
  • ~300 states  
  • Integrated into piloted simulation | • Transfer functions  
  • Different from handling qualities LOES  
  • Lower order system  
  • Do have structural modes  
  • Flight derived  
  • Time domain system ID | • Lower order  
  • Flight derived  
  • More physical parameters  
  • Still in development | • Flight derived  
  • Non parametric (high order) |
Maneuvers Used

Use air density in place of altitude
- Small effect for low subsonic conditions

Use ID multisines for updating
- Better excitation for system ID

Use margin multisines for validation
- Keeps data independent of tuning
- Plenty of test points for comparison
- Compares specific input/outputs of interest
Model Complexity: “Curse of dimensionality”

HIGH ORDER MODELS

MIMO SYSTEM
Aeroelastic models have lots of parameters

• Parameters arranged in a matrix

\[
\begin{bmatrix}
A & B \\
C & D
\end{bmatrix}
\]

• 22 Outputs
• 12 Inputs

• Estimate of parameters for multiple model types

<table>
<thead>
<tr>
<th></th>
<th>Rigid longitudinal model</th>
<th>Parameter ID models</th>
<th>Aeroelastic Plant</th>
<th>Full Aeroelastic Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>States</td>
<td>4</td>
<td>6</td>
<td>155</td>
<td>234</td>
</tr>
<tr>
<td>Max parameters</td>
<td>416</td>
<td>504</td>
<td>33,807</td>
<td>62,976</td>
</tr>
<tr>
<td>Typical parameters</td>
<td>135</td>
<td>270</td>
<td>10,299</td>
<td>14,958</td>
</tr>
</tbody>
</table>

• System order causes many parameters
  • Inputs and outputs also mean a lot of parameters
  • Physical modeling requires more parameters then identifiable from flight
Preflight Flutter Model Tuning

Flutter model uses a lifting surface method
- Similar to vortex lattice
  - potential flow without boundary layer or thickness effects
- Good for unsteady aerodynamics
- Poor for steady coefficients

Refining flutter aerodynamic model
- AIC matrices relate local velocity to pressures

Common techniques exist for refining these matrices
- Tuning to match wind tunnel/CFD results
- Effectively changing the shape to reflect the boundary layer and thickness.
  - Downwash correction
- Fairly easy to implement
- Fairly easy to create problems

Currently only matching steady coefficients
Issues in flutter model tuning

Correction reflects error in relative change in local velocity

CFD/Wind tunnel includes physics not in potential flow models
- Cannot tune to match physics not in the model
- Requires replacement of coefficients

Coefficients may not be consistent
- Matching lift and moment may require unrealistic center of pressure
  - Mostly an issue in control surfaces
- Causes unrealistically large corrections
- Can only match a limited number of coefficients

Smoothness of corrections
- Giesing, Kalman, and Rodden used weighted RMS
  - Limits total variation
  - Large changes between neighbors is possible
- We have implemented smoothness based on difference between neighboring panels

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CFD Based Correction Factors

Final Correction Factors
Direct Tuning with Flight Data

Low order PID results have different model structure
- Lower order means the parameters are biased
- Requires an adjustment to parameters

Directly adjusting parameters used in model generation
- No adjustment needed for implementation
- Full envelope correction
- Also applied to generate LOES models

Frequency Domain
- No estimation of states required
- No inclusion of control system needed

Output Error
- Using only accelerometers and strain gauges
- Data directly from flight test instrumentation has more consistent timing
Simplifying the Outputs

Outputs are highly correlated
- Each strain gauge contains essentially the same information
- Turbulence will cause signal errors to be correlated

Principle component analysis (PCA/POD/KLT)
- Combine base on linear relationships
  - Reducing dimension of the outputs
  - Combining outputs to average out the noise
  - Similar to generating modes

Reduced rank regression
- PCA applied to outputs

Tested on generating low order models
- Reduces number of parameters fit
- Improves speed (~100x) and accuracy of the fitting
Direct Tuning with Flight Data

Tuning is improving the fit

Additional improvement is still expected
- Flutter speed is still high
- Unable to get full envelope correction
- Large corrections

Additional parameters may be needed
- Updating 58 parameters
- LOES models have ~200 parameters
- Inertial Parameters
- Structural Parameters
  - Update material properties, rather then frequencies
  - Mode shapes are fixed
  - Output equations are fixed

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Bode Diagram: Wing Flap 4 to Center Forward Accel

Magnitude (dB)

Phase (deg)

Baseline
Tuned
FD LOES

Frequency (Hz)
Nonlinearities

ACTUATORS

TAKE-OFF AND LANDING
Effect of Actuator Nonlinearities

- Actuators do not respond to small commands
- Same flight and input (system ID), different magnitudes (x2)
- Same low airspeed, similar fuel weight
- Smaller magnitude shows more variability, and large error relative to ground test
Take-off Simulation

Rapid decrease in main gear loads with increased throttle
  ◦ Not captured in the simulation
  ◦ Change in load is ~40% of change in thrust

Simulation predicted higher rotation speed
  ◦ Higher rotation speed irritated the pilots
  ◦ Simulation used in training adjusted ground effect
    ◦ Not physical
    ◦ Small detriment to accuracy of landing dynamics
Take-off Simulation

Higher rotation speed causes larger pitch up
Flexibility degrades landing damping

- On touchdown significant energy goes into the wings
  - Wings are very poorly damped
  - Reduces effectiveness of landing gear
- Rigid body simulation did not reliably predict the response
- Out piloted simulation included structural dynamics
Uncertainty and Noise

TURBULENCE
LIMITED KNOWLEDGE (EPISTEMIC)
VARIABILITY (ALEATORIC)
Turbulence

First flex wing flight (flight 9)
  ◦ Encountered light to moderate turbulence

Pilot perception
  ◦ Had simulated similar levels of turbulence
  ◦ Response was more stressful in flight

Structural dynamics
  ◦ Added to piloted simulation before flex wing flights
  ◦ Effects were not added to nose camera motion

Turbulence model
  ◦ Used standard model from loads and handling qualities
    ◦ These primarily excite rigid body motion
    ◦ Higher frequency turbulence caused more structural motion
Limited Knowledge (Epistemic Uncertainty)

Uncertainty often viewed as a lack of knowledge
- More testing could improve knowledge and reduce uncertainty
- More testing not always necessary or practical

Unrelated parameter uncertainty
- Large number of parameters
  - Caused unrealistically large uncertainty in output
  - Error in parameters should be related
  - Down select parameters based on engineering judgement
  - Missed parameters that are important

Mu-analysis was very appealing
- Computational cost was excessive
  - To many parameters to examine
  - Frequency of parameter occurrence
  - Mass parameters and air density effect many parameters
  - LFT format was still useful for Monte Carlo

Flight models show what output uncertainty should be
- Models were sufficient for controller design, once the uncertainty was known
Variability (Aleatoric Uncertainty)

Landing Sensitivity Analysis
- Some uncertainty is inherent, and cannot be reduced

Examined sensitivity of the response to parameters
- To many parameter combinations to consider
- Needed to understand interactions between parameters
- For 26 parameters, $2^{26} \approx 10^8$ possibilities
  - >2 years for a 1 second simulation

Monte Carlo/Polynomial chaos expansion
- Generate surrogate model
- Polynomials orthogonal with respect to parameter probability distribution

Used multiple types of sensitivity
- Linear effect: traditional linear sensitivity
- Main effect: direct nonlinear effect
- Total effect: Includes interaction between parameters
Landing Dynamics

Simulation is capturing initial dynamics
- Nonlinearity of ground contact makes comparison difficult

Having a piloted simulation allowed for the development of an effective landing technique.
Landing Monte Carlo

Flight

Simulation

Pitch rate, deg/s

Time, sec

Flight Interval

Flight Mode

Simulation
Landing Monte Carlo

Flight

Simulation

Pitch attitude, deg

Time, sec

Flight Interval
Flight Mode
Simulation

Pitch attitude, deg

Time, sec
Conclusions
Conclusions

Have generated models of reasonable accuracy
- Used to design control system past flutter
- Used to address and validate takeoff and landing issues
- Challenges do still remain

Developed tools and methods for ASE challenges
- Unstable closed loop system
- Complex dynamics
- Nonlinear behavior
- Uncertainty