Aeroservoelastic Modeling of Body Freedom Flutter for Control System Design

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Increasing Aspect Ratio

• Improves aerodynamic performance
• Increased flexibility
  • Reduces aeroelastic margin
  • Significant weight penalty to maintain margin
• Greater interaction with the flight dynamics
Active Flutter Suppression

• Use flight controls to maintain stability
  • Does not have a weight penalty
• Past efforts have had mixed results
  • B-52 successfully suppress flutter 1973
  • DAST was unsuccessful
• Body freedom flutter
  • Structural dynamics destabilize flight dynamics
Then and Now

• Found several issues with existing modeling approaches

• Development to date
  • Keep trying to patch issues
  • Inconsistencies between disciplines
    • Coordinate systems
    • Definition of parameters
    • Etc.

• Building upon previous approaches
  • Intentionally similar to existing approaches
  • Addressing inconsistencies between disciplines
The Problem: State Consistency

- Models generally made for specific mass/flight condition
- Full envelope design
  - What happens between these conditions?
- No sign convention in mode shapes
  - The direction of the mode shapes can change
- New modes can appear with masses
- Ordering of the modes can change
  - Finite element models sort by frequency
Previous methods: State Consistency

- Often simply ignored
  - Does not appear on simpler configurations
  - Can be bypassed by specific control architectures
- Corrective transformations
  - Applied to final models
  - Often not robust
  - Are there equivalent states?

Consistent Coefficient

- Airspeed, KEAS
- Fuel Weight, lbs
The Solution: Assumed Modes

- Using an assumed mode method
  - The same mode shapes are used for all conditions
  - Changes are in modal mass and stiffness matrices
    - To match kinetic and potential (strain) energy
    - Aerodynamic coefficients are constant
- Assumed modes method is quite old
  - Using for state consistency is new
- Which mode shapes to use?
  - Are there sufficient mode shapes?
  - Are all of the modes represented?
- This is an issue with any method
The Problem: Low frequency Dynamics

Why do we care?

• Static Instabilities
  • Short-period frequency is reduced
  • Very strong coupling with the phugoid
• Often less control margin
  • MIL-STD-9490 below 0.06 Hz
  • Requires 4.5 dB gain margin
  • Requires 30 deg phase margin

Do not want separate models for these dynamics

What are the primary effects?

• Phugoid mode
  • Dominates low frequency behavior
  • Transfer of energy
    • Kinetic energy
    • Potential energy (gravity)
• Large velocity variations
  • Flutter methods assume constant velocity
Previous method: Apply rigid body model

• **Velocity Variations**
  - Forces change due to changes in dynamic pressure
    - \( \frac{\partial}{\partial V^*} q = \frac{2}{V} \bar{q} \)
  - Applying 6DoF coefficients neglects change in force on the structure

\[
A_{1_{aug}} = S \begin{bmatrix}
-2C_{D_0} & 0 & C_{L_0} & 0 & \cdots & 0 \\
-2C_{L_0} & 0 & -C_{D_0} & 0 & \cdots & 0 \\
2\bar{c}C_{D_0} & 0 & 0 & 0 & \cdots & 0 \\
2C_{\eta_1} & 0 & 0 & 0 & \cdots & 0 \\
\vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\
2C_{\eta_1} & 0 & 0 & 0 & \cdots & 0
\end{bmatrix}
\]

• **Gravity**
  - Can use 6 DoF results
    - If origin is at the center of gravity
  - Assumed modes complicates this
    - Mass matrix is not diagonal
    - Center of gravity moves with structural deformations

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The Solution: Gravitational Forces

• Using the complete mass matrix from the finite element model
  • Modal mass is not diagonal
    • Due to assumed modes method

• For each element
  • \( \mathbf{F}_{\text{gravity}} = m_{\text{element}} \mathbf{g} (\hat{z} + \mathbf{T}(\alpha_0)\theta_{\text{element}}) \)
    • \( \hat{z} \): Vertical vector
    • \( \mathbf{T}(\alpha_0) \): Rotation matrix from trim angle
    • \( \theta_{\text{element}} \): Rotation of element from mode shape
The Problem: Unsteady Aerodynamics

- The structural motions are high frequency
  - On the order of the dynamics of the flow
  - Significant delays in the response
  - Need to model the flow dynamics
- Frequency domain aeroelasticity tools
  - Considering harmonic motions simplifies the dynamics
  - Time histories are required for evaluating closed loop performance
  - No closed form solution from frequency response to time history
Previous method:
Rational Function Approximation

• Rogers Rational Function Approximation
  
  \[ \{q\} \approx (A_0 + A_1 ik + A_2 k^2 + D(ikI - R)^{-1} E ik)\eta \]

• Has been used many times (40+ years old)
• Developed with weak interactions between flight dynamics and aeroelasticity
• Uses a modal coordinate system
  
  • Inertial coordinate system (origin is fixed in space)
  • Does not work for flight mechanics
    • Origin must move with the aircraft
Previous method: Time domain transformation

• Transformation
  • Applied to final model
  • Equivalent to
    • $A_0^* = A_0 T \eta_{2x} + A_1 T \eta_{2x}$
    • $A_1^* = A_1 T \eta_{2u} + A_2 T \eta_{2x} T^{-1} T \eta_{2u}$
    • $A_2^* = A_2 T \eta_{2u}$
  • Results in erroneous coefficients
    • Vehicle heading does not effect aerodynamic forces
    • Issues are emphasized in model reduction
    • Removing increases the error in the RFA
The Solution: Frequency domain Transformation

• Apply transformation directly to frequency domain aerodynamics
  \[ \{ i k \eta \} = \begin{bmatrix} T \dot{\eta} u & T \dot{\eta} x \\ 0 & T \eta 2x \end{bmatrix} \{ u \} \]

• Stability Axis RFA
  \[ \{ q \} \approx A_0 x + (A_1 + A_2 i k + D (i k I - R)^{-1} E) u \]
  • Separate positions \( x \) and velocities \( u \)
  • Euler angles appear only in \( A_0 \)
    • Only need to constrain single matrix
    • Curve fit remains minimum error solution
Applying the method: X-56A MUTT

• Designed for testing active flutter suppression
  • Flexible wings have unstable flutter modes

• Currently have stiff wing data
  • No unstable flutter modes

• Using frequency domain potential flow aerodynamics
Results

Comparing to rigid models

Comparing to flight data

<table>
<thead>
<tr>
<th>Test Case</th>
<th>Fuel Mass</th>
<th>Airspeed</th>
<th>Input</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Low</td>
<td>Low</td>
<td>Pitch</td>
</tr>
<tr>
<td>2</td>
<td>High</td>
<td>Low</td>
<td>Pitch</td>
</tr>
<tr>
<td>3</td>
<td>Low</td>
<td>High</td>
<td>Pitch</td>
</tr>
<tr>
<td>4</td>
<td>Low</td>
<td>High</td>
<td>Roll</td>
</tr>
</tbody>
</table>
Flight Data Comparison: Pitch response, low fuel, low speed

**Pitch Rate**

- Magnitude, dB
  - Flight test (blue)
  - Model (red)
- Phase, deg
- Coherence

**Wing Tip Accelerometer**

- Magnitude, dB
  - Flight test (blue)
  - Model (red)
- Phase, deg
- Coherence

Frequency, Hz

Short-period
First wing bending
Flight Data Comparison: Pitch response, low fuel, high speed

Pitch Rate

Magnitude, dB

Phase, deg

Coherence

Frequency, Hz

Wing Tip Accelerometer

Magnitude, dB

Phase, deg

Coherence

Frequency, Hz

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Flight Data Comparison: Roll Response, low fuel, high speed

Roll Rate

Wing Tip Accelerometer

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Conclusions

• Model generation for body freedom flutter

• Addressing issues in:
  • State Consistency
  • Low frequency dynamics
  • Unsteady aerodynamics

• Applied approach to X-56A MUTT
  • Comparing to flight test data