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
Aeroservoelasticity

Aeroelasticity

Elastic Forces

Aerodynamic Forces

Inertial Forces

Control Forces

Flight Mechanics
Aeroelasticity as a closed loop

- Control Surfaces
- Aerodynamics
- Flight/Structural Dynamics
- Stability & Performance
- Flutter Suppression
- Aeroelasticity
Active Flutter Suppression

Use flight controls to maintain stability
- Does not have a weight penalty

Past efforts have had mixed results
- B-52 successfully suppressed flutter 1973
- DAST was unsuccessful, circa 1980
- See AIAA 2017-1119, by Eli Livne

Body freedom flutter
- Structural dynamics destabilize flight dynamics
Multi-Utility Technology Testbed
X-56A MUTT

Designed for testing active flutter suppression
- Flexible wings have unstable flutter modes
- AFRL Funded
- Lockheed Martin Build

For developing technologies
Modeling Philosophy
How does MUTT translate to N+3?

Definition of model interfaces
- Discipline models will change
  - Origin of the parameters
  - Form of the equations
- The interfaces change less
  - Inputs and outputs are very common

Physics Based Modeling
- Predictive capability of the models
- How do the physics define the interface
- How do we model before flight test

Verifiable
- Keep complexity in check
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
Structural (Modal) States

Deformed shape is combination of mode shapes
- What shapes do we use?

Orthonormal Modes
- Standard in structural analysis
- Modes do not exchange energy
  - No inertial coupling
  - No elastic coupling
- Aerodynamics add

Mean Axis
- Used for integration of nonlinear flight dynamics
- No inertial coupling between rigid body and flexible modes
  - Orthonormal modes are sufficient, but not necessary
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
Assumed Modes: Other Benefits

Uncertainty
- There is no uncertainty in the mode shape
- Uncertainty is captured in other physical parameters

Structural Nonlinearities
- Can generate parameter varying model
- Only mass and stiffness matrices change

Constant Aerodynamic Coefficients
- Structural properties don’t effect the behavior of the airflow
- Aerodynamic coefficients do not change with structural properties
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
  \[ \frac{\partial}{\partial v} \bar{q} = 2 \frac{\bar{q}}{v} \]
- Applying 6DoF coefficients neglects change in force on the structure
- \( A_{1\text{aug}} = S \)

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

\[ \begin{bmatrix}
-2C_D_0 & C_{L0} & 0 & \cdots & 0 \\
-2C_L_0 & -C_{D0} & 0 & \cdots & 0 \\
2C_{\eta1} & 0 & 0 & \cdots & 0 \\
2C_{\eta1} & 0 & 0 & \cdots & 0 \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
2C_{\eta1} & 0 & 0 & \cdots & 0 \\
\end{bmatrix} \]
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

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

Flight dynamics
- Low frequency
- Aerodynamics are algebraic
  - Depend only on the current state

Structural Dynamics
- High frequency
  - On the order of the dynamics of the flow
  - Significant delays in the response

Need to model the flow dynamics
The Problem: Unsteady Aerodynamics

Time scales
- Wide range required
  - Very long for phugoid
  - Very short for structural dynamics
- Increases computational cost

Frequency domain aeroelasticity tools
- Considering harmonic motions simplifies the dynamics
- No closed form solution from frequency response to time history
- Time histories are required for evaluating closed loop performance
Previous method: Rational Function Approximation

Rogers Rational Function Approximation

\[ \{q\} \approx (A_0 + A_1 i k + A_2 k^2 + D (i k I - R)^{-1} E i k) \eta \]

- 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
  - $A_0 = A_0 T_{\tilde{\eta}2x} + A_1 T_{\tilde{\eta}2x}$
  - $A_1' = A_1 T_{\tilde{\eta}2u} + A_2 T_{\tilde{\eta}2x} T_{\tilde{\eta}2x} T_{\tilde{\eta}2u}$
  - $A_2' = A_2 T_{\tilde{\eta}2u}$
- Results in erroneous coefficients
  - Vehicle heading does not effect aerodynamic forces
  - Issues are emphasized in model reduction
  - Removing increases the error in the RFA

Steady Modal Axis

Steady Stability Axis

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The Solution:
Frequency domain Transformation

Apply transformation directly to frequency domain aerodynamics

\[
\begin{bmatrix}
T_{\eta 2u} & T_{\eta 2x} \\
0 & T_{\eta 2x}
\end{bmatrix}
\begin{bmatrix}
u \\ x
\end{bmatrix}
\]

Stability Axis RFA

\[
\{ q \} \approx A_0 x + (A_1 + A_2 ik + D(ikI - R)^{-1}E)u
\]

- 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
Stability Axis RFA: Other Benefits

Model Calibration/Tuning
- Quasi-Steady Model
  - $A_0 x + (A_1 - DR^{-1}E)u$
  - Form identical to classical flight mechanics

Integration with lookup tables
- Set quasi-steady to zero
  - $A_1 = DR^{-1}E$
- Allows non-linear aero tables
  - Unsteady model is increment to tables
  - Does not double count loads
  - Captures unsteadiness
  - Captures rigid-flexible coupling

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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
- Basic 6-DoF model

Matching the flight dynamics
- Short-period
- Phugoid

Does not capture structural modes

Higher roll-off and phase loss
- Sensors
- Unsteady aero

Structural control
- Requires higher bandwidth controller
Flight Data

INPUTS

Orthogonal Multisines
High Bandwidth
Reduced Surface Rates
Short Maneuvers
Statistical Reputability

TEST POINTS

<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>

Low fuel emphasize assumed modes
Low speed emphasizes aerodynamic lags
High speed emphasize aerodynamic coupling
Flight Data Comparison: Pitch response, low fuel, low speed

**PITCH RATE**

- **Magnitude, dB**
  - Flight test
  - Model
  - Short-period
  - First wing bending

- **Phase, deg**

- **Coherence**

**WING TIP ACCELEROMETER**

- **Magnitude, dB**
  - Flight test
  - Model

- **Phase, deg**

- **Coherence**

**Frequency, Hz**

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Flight Data Comparison: Pitch response, low fuel, high speed

PITCH RATE

- Magnitude, dB
  - Flight test
  - Model

- Phase, deg

- Coherence

WING TIP ACCELEROMETER

- Magnitude, dB
  - Flight test
  - Model

- 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

Details in paper AIAA 2017-0019