Rapid State Space Modeling Tool for Rectangular Wing Aeroservoelastic Studies

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Outline

• Overview & Motivation
• Aeroservoelastic tool
• Verification and Validation studies
• State Space Model Development and Results
• Conclusions
Overview & Motivation

• Overview
  – Presentation of computational and experimental results from a recently developed rectangular wing aeroservoelastic modeling tool

• Motivation
  – Compare tool to independently published work\textsuperscript{2}
  – To support rapid investigation of aeroservoelastic phenomena in a medium-fidelity tool
    • Also novel sensors such as fiber optics
  – Provide a rapid aeroservoelastic design platform which can serve students of aeroservoelasticity

Background

- In previous work\(^1\), tool used to model a clamped wing structure with two control surfaces and fiber optic sensor feedback used for flutter suppression

\(^1\)Suh, P. M., and Mavris, D. N., Modal Filtering for Control of Flexible Aircraft, AIAA 2013-1741
Aeroservoelastic Tool Overview

- Tool allows the user to quickly move from inputs like aspect ratio, control surface count, and half span to a linear time invariant state space model which can be used for control
  - A few seconds of real time computation
  - Most important structural and aerodynamic properties are parametric
Graphical Path of Verification and Validation of Tool

- Plates
- Beam
- Finite Element Model
- Compare to GVT
- Compare to Theory
- Structure
- Flutter Prediction
- Aero
- Generalized Aero Forces
- Direct Comparison
- Rational Function Approximation
- Compare to Wind Tunnel Test

Compare to State Space Models
Beam Model Verification

- Beams used to model wing structure
  - FEM with 30 elements compared to theory
    show good matches in bending and torsion

\[ F = -100N \]
\[ M = -100N \cdot m \]
\[ l = 1m \]
\[ w = 0.5m \]
\[ th = 6.35mm \]
Graphical Path of Verification and Validation of Tool

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- Compare to Wind Tunnel Test
- Compare to State Space Models
  - V-g
  - V-f
Plate FEM Validation

- Ground Vibration Test (GVT) on an article used for validation of plate FEM
- Plate FEM Discretized with 16x16 12 DOF isotropic plate elements
- Experiment shows good correlation with ANSYS and tool

![GVT on Article (with a hole for a different test)](image)

### Experimental Data

<table>
<thead>
<tr>
<th>Mode</th>
<th>ANSYS Frequencies, Hz</th>
<th>Tool FEM Frequencies, Hz</th>
<th>Conyers et al. GVT, Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode # 1</td>
<td>3.99</td>
<td>3.99</td>
<td>4.13</td>
</tr>
<tr>
<td>Mode # 2</td>
<td>16.96</td>
<td>16.97</td>
<td>17.24</td>
</tr>
<tr>
<td>Mode # 3</td>
<td>24.86</td>
<td>24.89</td>
<td>24.38</td>
</tr>
<tr>
<td>Mode # 4</td>
<td>55.33</td>
<td>55.40</td>
<td>54.25</td>
</tr>
<tr>
<td>Mode # 5</td>
<td>69.84</td>
<td>69.92</td>
<td>69.00</td>
</tr>
</tbody>
</table>

\[ l = 304.8\text{mm} \]
\[ w = 152.4\text{mm} \]
\[ th = 1.588\text{m} \]
Graphical Path of Verification and Validation of Tool

- Finite Element Model
  - Plates
    - Compare to GVT
  - Beam
    - Compare to Theory

Structure
- Flutter Prediction
  - V-g
    - V-f
  - Compare to State Space Models
  - Compare to Wind Tunnel Test

Aero
- Generalized Aero Forces
  - Direct Comparison
  - Rational Function Approximation
RFA Verification

- Generalized aerodynamic forces (GAF) computed for plate
- Roger’s rational function approximation (RFA) used to fit GAF coefficients
  - 4 lag states
- Least squares error for bending and twist coefficients

Generalized Aerodynamic Force

\[ Q(ik) = Z_f^T D(ik)^{-1} A_p W_{c.p}. \]

Rational Function Approximation of GAF

\[ \hat{Q}(\tilde{s}) = A_0 + \tilde{s} A_1 + \tilde{s}^2 A_2 + \sum_{l=1}^{L} \frac{\tilde{s}}{\tilde{s} + \beta_l} A_{2+l} \]

Comparison of GAF and RFA Curve Fits
V-g Analysis using RFA

- The test plate article flutter speed was predicted to be 19.9 m/s
  - traditional bending/torsion flutter mode

V-g Analysis on Computational Plate Article
V-f Analysis using RFA

- The test plate article flutter frequency was predicted to be 10.9 rad/s
  - Torsional mode shifts closer to bending mode
  - Characteristic of a one side clamped plate flutter mode
Graphical Path of Verification and Validation of Tool

- Plates
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- Rational Function Approximation
- V-g V-f
- Compare to State Space Models
- V-g V-f
- Compare to Theory
Flutter Validation Experimental Study

- A wind tunnel investigation was completed at Duke University in previous work
  - Tool flutter speed shows good correlation with Conyers et al.’s flutter code
    - Differences may be due to use of more aero panels in the tool
  - Wind tunnel results were comparably close

<table>
<thead>
<tr>
<th></th>
<th>Conyers et al. Flutter Code</th>
<th>Tool Flutter Code</th>
<th>Conyers et al. Wind Tunnel Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flutter speed, m/s</td>
<td>20.8</td>
<td>19.9</td>
<td>20.05</td>
</tr>
<tr>
<td>Flutter frequency, Hz</td>
<td>10.3</td>
<td>10.9</td>
<td>11.50</td>
</tr>
</tbody>
</table>

Graphical Path of Verification and Validation of Tool

1. Finite Element Model
   - Plates
   - Beam
   - Compare to GVT
   - Compare to Theory

2. Structure
   - Flutter Prediction
   - V-g
   - V-f
   - Compare to Wind Tunnel Test

3. Aero
   - Generalized Aero Forces
     - Direct Comparison
     - Rational Function Approximation
   - Compare to State Space Models

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State Space Model Verification

• We verify that the state space models correlate with what was predicted from the V-g and V-f analyses.
State Space Model Architecture

- Components of state space models
  - FEM mass, stiffness, damping and modal matrices
  - Rational function approximation coefficients
  - Actuator dynamic models
  - Flight condition

\[
\dot{x} = \begin{bmatrix}
\dot{x}_1 \\
\dot{x}_2 \\
\vdots \\
\dot{x}_6
\end{bmatrix} = \begin{bmatrix}
0 & I & 0 & \cdots & 0 \\
-\hat{M}^{-1}(\hat{R} \hat{C} \bar{q}I & \cdots & \bar{q}I) & 0 & \cdots & 0 \\
0 & A_3 & -\beta_1 \left(\frac{2V_{\infty}}{c}\right) & 0 & 0 \\
\vdots & \vdots & 0 & \ddots & 0 \\
0 & A_6 & 0 & 0 & -\beta_4 \left(\frac{2V_{\infty}}{c}\right)
\end{bmatrix}
\begin{bmatrix}
x_1 \\
x_2 \\
x_3 \\
\vdots \\
x_6
\end{bmatrix}
\begin{bmatrix}
u_c \\
\dot{u}_c \\
\ddots \\
\dot{u}_c
\end{bmatrix} + \begin{bmatrix}
0 & 0 & 0 & \cdots & 0 \\
-\hat{M}^{-1}(\hat{R}_g \hat{C}_g \bar{M}) & 0 & \cdots & 0 \\
0 & A_{g1} & \ddots & 0 \\
0 & A_{g4}
\end{bmatrix}
\begin{bmatrix}
w_g \\
\dot{w}_g
\end{bmatrix}
\]
Analytical Model with Control Surfaces

- Verification of state space models is completed for a wing model with
  - internal aluminum beam spar and rib structure
  - aluminum skin
  - a control surface and a leading edge accelerometer

Analytical Model with One Control Surface and a Leading Edge Accelerometer
Actuator Dynamics

- Actuators are modeled as 3rd order transfer functions
  - 1st order command lag
  - 2nd order actuator dynamics

\[ \frac{u_c}{u_{com}} = \frac{1}{Ts + 1} \left( \frac{\omega^2}{s^2 + 2\omega\xi s + \omega^2} \right) \]
Analytical Wing Mode Shapes

- Mass normalized mode shapes are computed with high torsional spring stiffness in connected control surfaces.
- Control modes are computed with low torsional spring stiffness and a prescribed 1 deg. rotation boundary condition.

Analytical Wing Modal Analysis

a) First bending, frequency = 16 rad/s
b) First torsion, frequency = 43.4 rad/s
c) Second bending, frequency = 85.6 rad/s
d) Second torsion, frequency = 184.6 rad/s
State Space Model Verification

• We verify that the state space models correlate with what was predicted from the V-g and V-f analyses

Bode

Poles

V-g
V-f

Gust Response

Time history

Compare to each other
V-g Analysis with RFA

- V-g analysis of wing shows a traditional bending/torsion flutter mode appearing at 76.5 m/s
Wing Model Pole Migration

- The bending mode becomes more stable
- The torsion mode becomes neutrally stable at 76.5 m/s
- Flutter speed is the same as predicted in the V-g analysis
State Space Model Verification

• We verify that the state space models correlate with what was predicted from the V-g and V-f analyses.

![Diagram showing Bode, Poles, V-g, V-f, Gust Response, Time history nodes connected by arrows with "Compare to each other" label.]
V-f Analysis

- Frequency analysis shows the flutter frequency at 28 rad/s
Bode Plot of State Space Model

- At speed below flutter speed, amplitudes of two distinct modes visible
- At flutter speed only flutter mode is visible
- Frequency is the same as predicted from the V-f analysis
State Space Model Verification

• We verify that the state space models correlate with what was predicted from the V-g and V-f analyses
Impulse to State Space Model

- Flutter is apparent in model designed past flutter speed
  - Divergent oscillatory
- Model at lower speed is damped after impulse
State Space Model Verification

• We verify that the state space models correlate with what was predicted from the V-g and V-f analyses
1-cos Gust Model

- Gust inputs to structure are designed with gust modes and 1-cos gust input structure

Gust mode approximation

$$g_{wash} = -\exp\left(i \frac{2k}{c} (x_{c.p.} - \bar{x}_{gust})\right)$$

Gust velocity

$$w_g(t) = \frac{w_{g,max}}{2} (1 - \cos(Gt))$$

Gust acceleration

$$\dot{w}_g(t) = \frac{w_{g,max}}{2} \sin(Gt) G$$

Gust frequency

$$G = 2 \frac{\dot{w}_{g,max}}{w_{g,max}}$$
Gust Input to State Space Model

• The response of wing to 1-cos gust is expected
  – Low frequency gust response and high frequency oscillations from flutter are seen to be superimposed
Conclusions

• Several first step verification and validation studies were presented for a new aeroservoelastic tool

• More verification and validation is needed to assess the state space models including
  – An experimental flutter test and active flutter suppression

• This work further supports independent flutter analysis conducted by Dr. Conyers in his dissertation
Future Work

• Improvements will be made to include rigid body modes in the tool
• Input structure will be made more user friendly
• Would like to look into transitioning to use as an open tool for students
Questions?