Rapid State Space Modeling Tool for Rectangular Wing Aeroservoelastic Studies

Dr. Peter M. Suh
Aerospace Engineer
Flight Controls and Dynamics
NASA Armstrong Flight Research Center

Dr. Howard J. Conyers
Aerospace Technologist
Engineering and Test Directorate
NASA Stennis Space Center

Dr. Dimitri N. Mavris
Aerospace Systems Design Laboratory Director
Georgia Institute of Technology

AIAA Modeling and Simulation Technologies Conference, Jan 5-9, 2015
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\(^2\)
  – 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
  - Compare to GVT

- Beam
  - Compare to Theory

- Generalized Aero Forces
  - Compare to Wind Tunnel Test
  - Direct Comparison
  - Rational Function Approximation

- Structure
  - Flutter Prediction

- Aero
  - Generalized Aero Forces

Finite Element Model
Beam Model Verification

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

\[ M = -100N - m \]
\[ F = -100N \]

Cantilever Theory versus FEM Beam Model: Deflection and Twist

\[ l = 1m \]
\[ w = 0.5m \]
\[ th = 6.35mm \]
Graphical Path of Verification and Validation of Tool

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

AIAA Modeling and Simulation Technologies Conference, Jan 5-9, 2015
Plate FEM Validation

- Ground Vibration Test (GVT) on a 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

<table>
<thead>
<tr>
<th></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

- Plates
  - Compare to GVT

- Beam
  - Compare to Theory

- Finite Element Model
  - Compare to GVT

- Structure
  - Flutter Prediction

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

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

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

Rational Function Approximation of GAF

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

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

V-f Analysis on Computational Plate Article
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

4. Compare to State Space Models

AIAA Modeling and Simulation Technologies Conference, Jan 5-9, 2015
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

- Plates
- Beam
- Finite Element Model
- Generalized Aero Forces
- Compare to Theory
- Compare to GVT
- Compare to State Space Models
- Compare to Wind Tunnel Test
- V-g
- V-f
- Flutter Prediction
- Structural Aero
- Aero
- Generalized Aero Forces
- Direct Comparison
- Rational Function Approximation
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

\[
\dot{x} = \begin{bmatrix}
\dot{x}_1 \\
\dot{x}_2 \\
\vdots \\
\dot{x}_6
\end{bmatrix} =
\begin{bmatrix}
0 & I & 0 & \cdots & 0 \\
-M^{-1}(\hat{R} & \hat{C} & \hat{q}I & \cdots & \hat{q}I) \\
0 & A_3 & -\beta_1\left(\frac{2V_\infty}{c}\right) & 0 & 0 \\
\vdots & \vdots & 0 & \ddots & 0 \\
0 & A_6 & 0 & 0 & -\beta_4\left(\frac{2V_\infty}{c}\right)
\end{bmatrix}
\begin{bmatrix}
x_1 \\
x_2 \\
\vdots \\
x_6
\end{bmatrix}
\]

- Modal displacement
- Modal velocity
- Aero lag states
- Control states
- Gust states
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 3\textsuperscript{rd} order transfer functions
  – 1\textsuperscript{st} order command lag
  – 2\textsuperscript{nd} order actuator dynamics

\begin{align*}
\frac{u_c}{u_{com}} &= \frac{1}{Ts + 1} \left( \frac{\omega^2}{s^2 + 2\omega\xi s + \omega^2} \right)
\end{align*}

Actuator Model with and without command lag
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.
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.
V-f Analysis

• Frequency analysis shows the flutter frequency at 28 rad/s

V-f Analysis of Analytical Wing Model
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

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

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

Bode Plot of Surface to Leading Edge Accelerometer

- [Accelerometer plot diagram showing response at 77 m/s and 40 m/s]
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