PAT Wing Fixed Base Correction Modal Testing Debrief

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Presentation Outline

Note: All results shown here are preliminary

The objective of this presentation is to describe the PAT Wing modal testing conducted and results using Fixed Base Correction (FBC) method.

- FBC Theory – Drive point accelerations as references
- Description of Modal Test Setup
- FBC Signal Processing Techniques
  - FRF calculation
  - Partial FRF matrix inversion technique (SMURF)
- Decisions on where to add shakers (if needed)
- FBC Results
Fixed Base Correction - Theory

- Original fixed base correction theory used constraint shapes as references, but the method is more easily deployed using drive point accelerations as references.

\[
\begin{bmatrix}
 s^2m + k & -k \\
 -k & s^2m + k
\end{bmatrix}
\begin{bmatrix}
 X_1 \\
 X_2
\end{bmatrix} =
\begin{bmatrix}
 F_1 \\
 F_2
\end{bmatrix}
\]

- Using a drive point accelerometer as reference results in system modes with that DOF fixed.

- Make sure drive point FRF are as co-located as practicable.
- Make sure drive point FRF are as clean as practicable.
  - Use seismic accelerometers as drive points
  - Drive base shakers harder than wingtip shakers

- \( F_1 \) and \( F_2 \) as References: \( \omega_n^2 = 0.2k/m \)

\[
\begin{align*}
 X_1 &= \frac{s^2m_2 + k}{(s^2m + k)(s^2m + k) - k^2} F_1 + \frac{k}{(s^2m + k)(s^2m + k) - k^2} F_2 \\
 X_2 &= \frac{k}{(s^2m + k)(s^2m + k) - k^2} F_1 + \frac{s^2m_2 + k}{(s^2m + k)(s^2m + k) - k^2} F_2
\end{align*}
\]

- \( F_1 \) and \( X_2 \) as References: \( \omega_n^2 = k/m \)

\[
\begin{align*}
 X_1 &= \frac{1}{(s^2m + k)} F_1 + \frac{k}{(s^2m + k)} X_2 \\
 X_2 &= 0F_1 + 1X_2
\end{align*}
\]
PAT Wing Test Article

- Passive Aeroelastic Tailored (PAT) Wing is a tow-steered graphite epoxy, high aspect ratio, semi-span (~39ft) right wing box
- Designed and built for NASA by Aurora Flight Sciences
- Project funded by NASA ARMD Advanced Air Transport Technology (AATT) Project
PAT Wing Test Setup

Test Goal: Extract all fixed base modes to first torsion mode (near 55 Hz)
Modal Test Physical Boundary Conditions

Using these boundary conditions would lead to a very challenging model updating effort without Fixed Base Correction

- Test physical boundary conditions: White static test fixture on the lab floor with four retractable feet and one location on the fixture that is secured to the lab floor with a strap
  - Dynamically active boundary condition

Static Test Fixture Boundary Condition on Lab Floor
Initial Modal Test Setup

- ≈ 270 Accelerometers
- 10 Shakers/load cells
  - 10 Seismic accels (drive points)
- True Random Input
  - Flexibility in signal processing

Config. 1: 9 Base Shakers

Wingtip Shaker
Three Shaker Configurations

- Config. 1 (Initial Pass): 10 shakers – 9 on white static test fixture, 1 on wingtip
- Config. 2 (Second Pass): 12 shakers – Added 2 to aft white triangular brackets (lateral)
- Config. 3 (Final Pass): 14 shakers – Added 2 more to fwd wing root metallic plates (lateral)
Fixed Base Correction - Signal Processing is Iterative

- Forces usually have the highest S/N ratio and are therefore usually the best choice as basis vectors
  - Step 1. Calculate A/F FRF
  - Step 2. Use IMAT **SMURF** function to perform partial inversion of FRF matrix
    - Example: \( g = \text{smurf}(f, \text{ref}(2:\text{end}), \text{ref}(2:\text{end})) \), where
      - \( F \) is the FRFs in all positive DOF (\( f = \text{fn2pos}(f) \))
      - Not strictly necessary, but easier to manage
    - REF is the reference dof (\( [\text{ref}, \text{res}] = \text{ref_res}(f) \))
  - Step 3. Review FRF, and try new signal processing parameters if needed
  - Step 4. Fit modes using FRF associated with wingtip shaker FRF
Config 2: 12 Shakers

Filename: T10_A3_CR_12shakers_LowForce.ati

- Step 1: Calculate A/F FRF (using ALL shaker load cells)
Config 2: Use SMURF on Fixture Drive Points

\[ g = \text{smurf}(f, \text{ref}(2:end), \text{ref}(2:end)) \]

- Step 2: Partially invert FRF matrix so base drive point accelerometers and wingtip shaker forces are references using SMURF technique. (Use MATLAB IMAT function)
Config 2: Increasing $\Delta f$ can help clean up FRF

- Step 3: Try different signal processing parameters when needed
- Optimal signal processing parameters may vary with frequency
- Takeaway: Signal processing is iterative
Config 2: A/A FRF are Usually Noisy

Use A/F FRF to fit modes

- Base structure A/A can be cleaned up by using constraint shapes as references, but doing so takes effort and most often the structure A/F FRF are sufficient to extract modes
Config 2: Use FRFs associated with Wingtip Shaker Force to Fit Modes

➢ Step 4: Fit modes using standard modal analysis software
Config 2: 12 Shakers Results

Baseline / Nominal Method

Frequency: 3.46 Hz

Frequency: 5.13 Hz

Frequency: 9.21 Hz

Fixed Base Correction Method

Frequency: 3.48 Hz

Frequency: 10.88 Hz

Frequency: 10.12 Hz
Config 3: 14 Shakers Results

Helps remove flexible motion in wing root metallic plates

Fixed Base Correction Method
Config 2: 12 Shakers

58.2 Hz

Fixed Base Correction Method
Config 3: 14 Shakers

59.1 Hz
Two additional shakers removes lateral motion, but opens up new concerns

“Infinite Loop” of removing compliance by adding more shakers is limited by time, number of available shakers, or test objective requirements.

12 Shakers: 81.5 Hz

81 Hz mode with 12 shakers is eliminated with 14 shakers

14 Shakers: 77.4 Hz

Some vertical pedestal motion at 74 Hz with 14 shakers
Could mount vertical shakers to remove this mode, however:
1. This mode is higher in frequency than last target mode
2. We ran out of source signal generators
Config 1: 10 Shakers

FEM assumes white static test fixture is fixed

Test Shapes

<table>
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<th>Test Shapes</th>
<th>1</th>
<th>2</th>
<th>3</th>
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Test Self MAC Table

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<tr>
<th>Test Shapes</th>
<th>3.48</th>
<th>10.09</th>
<th>10.77</th>
<th>21.21</th>
<th>29.40</th>
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FEM/Test Cross MAC Table

| FEM Shapes | 3.38 | 10.33 | 10.95 | 22.36 | 29.32 | 36.61 | 39.64 | 51.67 | 54.89 | 61.19 | 62.18 | 73.43 | 76.05 | 92.77 | 95.87 | 99.65 | 104.86 |
|------------|------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| No.        | 1    | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9     | 10    | 11    | 12    | 13    | 14    | 15    | 16    | 17    |

Test: 88.99 Hz

White Triangular Stiffbacks Bending

FEM: 61.19 Hz

Triangular Bracket
Test Self MAC Table

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Test FEM Cross MAC Table

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Test Shapes 3.48 10.12 10.90 21.23 29.59 35.17 52.25 58.20 77.22 81.50 99.42

FEM: 51.42 Hz

Lateral wing root
metallic plate mode
### FEM/Test Cross MAC Table

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### Config 3: 14 Shakers

FEM assumes everything but wing is fixed

#### Test: 59.08 Hz
Fore-Aft mode, Pin joint slip
Examples of Mode Shapes

- View Animations of Fixed Base Modes
- Baseline A/F FRF had significant base motion
- Initial shaker set resulted in bending mode of base at 80+ Hz
- Second shaker set removed base bending motion
- Sliding motion of wing root pinned connection amplified when 14 shaker set used
Model Updating Strategy

- Use full finite element model (FEM), but constrain DOF associated with shaker/drive point accelerometers to best match the testing results
  - May have to spread load to avoid stress concentrations & local deformation of “point load” due to single DOF constraint

PAT Wing FEM

Constrain DOF (node & direction) in FEM associated with shaker/drive point FRFs
Test Summary

- Fixed Base Correction method was successfully used to extract fixed base modal results for the PAT wing that was mounted to a dynamically active static test fixture resting unsecured on a test facility floor.

- There are many potential scenarios where this FBC method can be used on future tests of structures mounted on other dynamically active static test fixtures.