Passive Aeroelastic Tailored Wing
Ground Vibration Test Using Fixed Base Correction Method

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PAT Wing GVT - Outline

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PAT Wing GVT - Goal, Objective & Success Criteria

• Passive Aeroelastic Tailored (PAT) Wing Ground Vibration Test (GVT) was tested July 10-12th, 2018 in NASA Armstrong’s Flight Loads Laboratory (FLL)

• Goal: Obtain PAT Wing modal characteristics from the GVT to compare test results with analytical models

• Objective: Measure the primary frequencies, mode shapes & damping (frequencies up to wing torsion mode, \( \approx 55 \) Hz) using traditional accelerometers with the PAT Wing installed on the Wing Loads Test Fixture (WLTF) table

• Success Criteria: Accurately obtaining the primary frequencies and shape modes of the PAT Wing (de-coupled from the WLTF table & attachment hardware modes) using the Fixed Base Correction (FBC) method
PAT Wing – Test Article Description

- Graphite-epoxy wingbox
  - Wingbox of 27% scale of uCRM
  - Right wing w/ high aspect ratio (13.5)
  - Root LE to tip TE: ≈ 39ft
  - Wing sweep 36.8°
  - Design & manufactured by Aurora

- 2 Spars, composite with 58 ribs
  - Outboard LE spar replaced with Aluminum (≈12 ft)

- 2 Skins
  - Tow-steered technology in wingskins

- 2 Reaction plates
  - 4 Reaction pins

- 14 Load lugs
  - 7 load lugs spanwise on LE & TE
  - Permanent fixtures
Test Setup – GVT Test Setup, Original Plan

- Original plan: Perform GVT using Fixed Base Correction on the Wing Loads Test Fixture (WLTF) to save cost and schedule rather than different boundary conditions from the loads testing
  - Reaction plates mounted with attachment hardware to WLTF table
  - WLTF table rotated 30°
  - Overhead loading structure installed
Actual Testing: Performed GVT with WLTF table on FLL floor supported by four retractable feet and with the fixture table secured with a strap to floor tracks

- Simplified GVT shaker setup since the wingtip is ≈ 50” off the floor, rather than the wingtip being 124” high
Test Setup – GVT Boundary Conditions with Table on Floor

- Boundary conditions: WLTF table on FLL floor with four retractable feet & one location on the table that was secured to the FLL floor with a strap
Test Setup – FEM with GVT Boundary Conditions

- Prior to GVT, Aurora updated NASA’s FEM to incorporate differences of the as-built wing that may impact structural response
  - FEM includes the WLTF table & attachment hardware
  - LaRC updated FEM to include boundary conditions with the table of the FLL floor
    - Fixed (1,2,3,4,5,6 DOFs) on all 5 grids
    - *BC not ideal for modal testing*

As-Built PAT Wing FEM

FEM Boundary Conditions
5 Locations on Feet & FLL Floor
Fixed Base Correction Method - Motivation

- Modal testing & finite element model (FEM) correlation desire free-free or rigid boundary conditions (BC) for comparisons
  - Expensive in cost & schedule to build & test with BC that replicate free-free or rigid
- Static test fixtures are large, heavy & unyielding, but do not provide adequate BC for modal tests
  - Dynamically too flexible & frequencies within test article frequency range of interest
  - Dynamic coupling between test article & test fixture causes significant FEM effort
- If modal test results could be corrected for fixture coupling, then other structural testing setups may be adequate for modal testing
  - Would allow significant cost & schedule savings by eliminating a unique setup for only modal testing

- Fixed base correction (FBC) method
  - CReW modal test was a pathfinder test to investigate FBC method - Attend Natalie’s presentation on Wed, June 12th at 8am in the Ground Vibration Testing II session
  - To simplify PAT Wing GVT, the FBC method was implemented with wing cantilevered from a static test fixture on the lab floor
Fixed Base Correction Method - Theory

• Two approaches for extracting fixed base modes from structures mounted on flexible tables
  1. Constraint equation to measure mass-normalized mode shapes to generate fixed base modes
     • Method requires well-excited modes so that modal mass can be accurately calculated
     • Advantage - Large number of shakers do not necessarily need to be mounted on the base
     • Disadvantage - Accuracy is reduced if the fixed base modes are not a linear combination of the measured mode shapes
  2. FBC method uses base accelerations as references to calculate frequency response functions (FRFs) associated with a fixed base, then FRFs are analyzed to extract fixed based modes of the test article

• Fixed Base Correction GVT methodology developed by ATA Engineering, Inc. & implemented in ATA’s IMAT (Interface between MATLAB, Analysis and Test) software
  • Requires multiple shakers on both the test article & mounting fixture
  • Method excites static test fixture base directly & uses drive point accelerations as references when calculating FRFs instead of traditional shaker forces as references
  • Essentially removes the fixture response from the wing response
Fixed Base Correction Method - Theory

• FBC method is illustrated with a simple spring-mass two degree-of-freedom (DOF) system
• Applying Newton’s second law, the equation of motion for an undamped system in the frequency domain

\[
\begin{bmatrix}
-\omega^2 m_1 + k & -k \\
-k & -\omega^2 m_2 + 2k
\end{bmatrix}
\begin{bmatrix}
x_1 \\
x_2
\end{bmatrix} =
\begin{bmatrix}
f_1 \\
f_2
\end{bmatrix}
\]

• Traditional modal testing calculates FRFs using DOFs 1 & 2 forces applied as references for the full system response

\[
a_1 = \frac{-\omega^2(-\omega^2 m_2 + 2k)}{(-\omega^2 m_2 + 2k)(-\omega^2 m_1 + k) - k^2}
\]

• FBC method uses DOF 1 force & DOF 2 acceleration as references, then resulting FRFs are associated with a structural system with dynamics associated with DOF 2 fixed

\[
a_1 = \frac{-\omega^2}{-\omega^2 m_1 + k}
\]

• FRF associated with DOF 1 applied force is equivalent to the FRF of a fixed base system

![Spring-Mass Two DOF System](image)

Where:
- \( m \) = mass
- \( \omega \) = frequency
- \( k \) = structural stiffness
- \( x \) = displacement
- \( f \) = external force
- \( a \) = acceleration

Subscripts 1 & 2 refer to blocks 1 & 2
Fixed Base Correction Method – Best Practice

- Best practice for implementing FBC method
  - Need at least one independent excitation source (i.e. shakers) for each DOF that is desired to be fixed
  - Requires multiple shakers used on both test article & test fixture
    - Drive the base (test fixture) shakers with harder forces than wingtip shaker
  - Use shaker accelerations as references rather than traditional shaker forces when calculating FRFs
    - 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 on the base
Test Setup – GVT Equipment

- **GVT Equipment**
  - **Accelerometers**
    - PCB T333B32 uniaxial accels
    - PCB T356A16 triaxial accels
    - PCB 393B04 seismic uniaxial accels
  - **Excitation Systems**
    - Shakers: MB Dynamics Electromagnetic Modal 110 shaker
    - Impact Hammer: Dytran 5800B4 impact hammer
  - **Data Acquisition (DAQ) system**: Brüel & Kjær LAN-XI DAQ
    - DAQ capable of recording 328 channels
      - Mainframes
        - LAN-XI 5-slot Main frame, 2 qty
        - LAN-XI 11-slot Main frame, 2 qty
      - Modules
        - LAN-XI 4ch input + 2ch output 3160 source modules, 7 qty
          - Capable of running 14 shakers
          - Capable of recording 28 channels
        - LAN-XI 12-channel 3053 modules, 25 qty
          - Capable of recording 300 channels
  - **GVT Software**:
    - Ideas Test (acquired time histories)
    - IMAT (all test related analysis & FBC analysis)

Note: Some GVT hardware was provided by Contractor
Test Setup – LAN-XI DAQ

- LAN-XI DAQ frontend setup: Four mainframes (two 5-slot & two 11-slot) capable of driving 14 shakers & recording 328 channels with network switch daisy chaining modules
  - MF#1: five source module (3160)
  - MF#2: two source modules (3160) & three 12-channel input module (3053)
  - MF#2: eleven 12-channel input modules (3053)
  - MF#2: eleven 12-channel input modules (3053)

LAN-XI DAQ Setup for PAT Wing GVT

Total: 288 Channels Enabled (Accels & Force Transducers)

Note: Some LAN-XI source modules were provided by Contractor
Test Setup – Accelerometer Layout

- Accelerometers, Total: 106 Accel Locations (274 Accel DOFs or channels)
  - Reference Accels at Shakers – 14 locations (14 DOFs)
  - Wing – 31 locations (87 DOFs)
  - Wing Reaction Plates & Pins – 16 locations (48 DOFs)
  - Fixture Table – 9 locations (17 DOFs)
  - Attachment Hardware (TE) – 18 locations (54 DOFs)
  - Attachment Hardware (LE) – 18 locations (54 DOFs)

- Force Transducers, Total: 14 Locations (14 FT DOFs or channels)
  - Shakers with Force Transducers – 14 locations (14 DOFs)

- Node Numbering
  - Reference Accels & Shakers – 00 series
  - Wing – 100 series
  - Wing Reaction Plates & Pins – 200 series
  - Fixture Table – 300 series
  - Attachment Hardware (TE) – 400 series
  - Attachment Hardware (LE) – 500 series
Test Setup – Accelerometer Layout

Reaction Plates, Table & Attachment Hardware  Accelerometers (61 locations)

Accel Directions
- X, Y, Z
- X, Z
- Z

Inboard (IB)
Outboard (OB)

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Test Setup – Accel Wing Photos

- Accel coordinates obtained from FEM
  - All nodes in global coordinate system wrt WLTF
    - X+ (out Trailing Edge), Y+ (out Outboard), Z+ (up)
    - Used 30° template to install wing accels with correct angle orientation
Test Setup – Accel Attachment Hardware Photos

• Some attachment hardware accels were installed before wing was installed on WLTF table

Triaxial Accels Mainly on Attachment Hardware

Attachment Hardware Accels – Leading Edge side
Test Setup – Shaker Force Transducer & Accel Photos

- Wingtip shaker - Force Transducers & Accels (100 mV/g)
- “Fixed” shakers on Table & Attachment Hardware - Force Transducers & Seismic Accels (1000 mV/g)
Test Setup – Test Display Model (TDM)

PAT Wing GVT Test Display Model (TDM)

- Top View
- Iso View
- Side View
- Outboard
- Inboard
GVT Shaker Layout - Fixed Base Correction Method

- FBC method requires multiple independent drive points (shakers) mounted to test fixture & test article
  - Shaker layout depends on where FBC technique is trying to fix the BC
    - Needs at least as many independent sources as there are independent boundary deformations of the desired fixed hardware in the test article frequency range of interest
- Shaker placement around the WLTF was adjusted to excite primary base modes & maximize the capability of the FBC to decouple the base modes from the wing modes
  - Higher shaker forces were required on the base
  - A few different shaker configurations were attempted to find optimal shaker configuration which fixed the reaction table
- Shaker direction on reaction table is important & eliminates the effect of the reaction table from moving in the shaker direction
GVT Shaker Layout - Fixed Base Correction Method

- Shaker configurations for FBC method – kept adding additional shakers to improve the fixed base modes
  - Config. 1 (Initial Pass): 10 shakers – 9 on fixture table, 1 on wingtip
  - Config. 2 (Second Pass): 12 shakers – Added 2 on aft triangular brackets (lateral)
  - Config. 3 (Final Pass): 14 shakers – Added 2 on wing root reaction plates (lateral)
PAT Wing GVT Shaker Layouts

- Shaker configurations for FBC method
  - Config. 1 (Initial Pass): 10 shakers – 9 on fixture table, 1 on wingtip
  - Config. 2 (Second Pass): 12 shakers – Added 2 on aft triangular brackets (lateral)
  - Config. 3 (Final Pass): 14 shakers – Added 2 on wing root reaction plates (lateral)
PAT Wing GVT Shaker Layouts & FEM Boundary Conditions

- FEM “Fixed” boundary conditions were applied to all nodes on related hardware
  - Config. 1 (Initial Pass): 10 shakers – 9 on fixture table, 1 on wingtip
  - Config. 2 (Second Pass): 12 shakers – Added 2 on aft triangular brackets (lateral)
  - Config. 3 (Final Pass): 14 shakers – Added 2 on wing root reaction plates (lateral)
Preliminary Results – 14 Shakers, Uncorrected vs. FBC

- FBC mode shapes show very little base deflection
- Uncorrected mode shapes show significant base rotation
  - Wing bending modes coupled the least with WLTF (stiffer vertically than in other directions)
  - Wing fore/aft modes coupled the most with WLTF & required significant correction (≈14 Hz)
- FBC method was able to remove a majority of the dynamics of the static test fixture to acquire fixed base modes while still accurately measuring the shape of the wing
Preliminary Results – 14 Shakers, FBC vs. FEM

- **Preliminary results** combined from two tests (T15 & T16) with 14 shakers
  - T15, 13 shakers on base & 1 Wingtip shaker fore/aft with 30° vertical excitation, Filename: T15_C1_CR_14shakers_LowForce
  - T16, 13 shakers on base & 1 Wingtip shaker vertical with 30° fore/aft excitation, Filename: T16_C2_CR_14shakers_LowForce

### Modal Assurance Criteria (MAC)

<table>
<thead>
<tr>
<th>Test Shapes</th>
<th>FEM/Test Cross MAC Table</th>
<th>Test</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEM Shapes</td>
<td>CRSS CRSS</td>
<td>CRSS</td>
<td>CRSS</td>
</tr>
<tr>
<td>1</td>
<td>3.39</td>
<td>10.45</td>
<td>11.35</td>
</tr>
<tr>
<td>2</td>
<td>23.4</td>
<td>99</td>
<td>29</td>
</tr>
<tr>
<td>3</td>
<td>11.05</td>
<td>31</td>
<td>98</td>
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<td>4</td>
<td>21.22</td>
<td>35</td>
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<td>6</td>
<td>35.23</td>
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<td>96</td>
</tr>
<tr>
<td>7</td>
<td>52.20</td>
<td>20</td>
<td>62</td>
</tr>
<tr>
<td>8</td>
<td>56.67</td>
<td>20</td>
<td>62</td>
</tr>
<tr>
<td>CRSS</td>
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<tr>
<td>CRSS All</td>
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<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

### 14 Shaker Test Combined Results

<table>
<thead>
<tr>
<th>Test Mode No.</th>
<th>FEM Mode No.</th>
<th>Test Freq (Hz)</th>
<th>FEM Freq (Hz)</th>
<th>Freq % Diff</th>
<th>Test Mode Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>3.48</td>
<td>3.39</td>
<td>-0.4%</td>
<td>1st Wing Bending</td>
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<tr>
<td>2</td>
<td>2</td>
<td>10.05</td>
<td>10.45</td>
<td>4.0%</td>
<td>2nd Wing Bending</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>11.02</td>
<td>11.35</td>
<td>3.0%</td>
<td>1st Wing Fore/Aft</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>21.22</td>
<td>22.64</td>
<td>6.7%</td>
<td>3rd Wing Bending</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>30.15</td>
<td>31.98</td>
<td>6.1%</td>
<td>2nd Wing Fore/Aft</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>35.23</td>
<td>37.46</td>
<td>6.3%</td>
<td>4th Wing Bending</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>52.20</td>
<td>51.94</td>
<td>-0.5%</td>
<td>5th Wing Bending (FEM: 1st wing Torsion)</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>56.67</td>
<td>55.54</td>
<td>-2.0%</td>
<td>1st Wing Torsion (FEM: 5th Wing Bending)</td>
</tr>
</tbody>
</table>

Note: Modes switch order when corrected
Note: FEM assumes everything but wing is fixed
Summary

• Baseline A/F FRF had significant base motion
• Config. 1 (Initial Pass): 10 shakers – resulted in bending mode of base at 80+ Hz
• Config. 2 (Second Pass): 12 shakers – removed base bending motion
• Config. 3 (Final Pass): 14 shakers – sliding motion of wing root pinned connection was amplified

• 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

• FEM model updating strategy
  • Use full FEM, but constrain DOF associated only with shaker/drive point accelerometers to best match the testing results
Questions