Ground Vibration Testing at NASA Armstrong, Emphasising on Passive Aeroelastic Tailored Wing Ground Vibration Test Using Fixed Base Correction Method

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Outline

• NASA Armstrong Overview
• Flight Loads Lab (FLL) Overview
• Ground Vibration Testing (GVT) at Armstrong
• Passive Aeroelastic Tailored (PAT) Wing
  • Test Article Description
  • Statics Load Testing
  • GVT: Goal, Objective & Success Criteria
    • Test Setup
      • Test Setup
      • Finite Element Model
      • Fixed Based Correction Method
      • GVT Equipment
      • Accelerometer Layout
      • Test Display Model
      • Shaker Layout for FBC
  • Results
  • Summary
NASA Centers

- National Aeronautics & Space Administration (NASA) Centers
  - NASA Headquarters (HQ)
  - Ames Research Center (ARC)
  - **Armstrong Flight Research Center (AFRC)**
  - Glenn Research Center (GRC)
  - Goddard Space Flight Center (GSFC)
  - Jet Propulsion Laboratory (JPL)
  - Johnson Space Center (JSC)
  - Kennedy Space Center (KSC)
  - Langley Research Center (LaRC)
  - Marshall Space Flight Center (MSFC)
  - Stennis Space Center (SSC)
NASA Armstrong, Edwards Air Force Base, CA

- Year-round flying weather
- Remote location
- Varied topography
- Extensive range airspace
- 29,000 ft of concrete runways
- 68 miles of lakebed runways
- 301,000 acres
- Supersonic corridor
- US Air Force Alliance
What Does NASA Armstrong Do?

- Advancing technology & science through flight
  - Aviation: Perform flight research & technology integration to revolutionize aviation and pioneer aerospace technology
  - Spaceflight: Validate space exploration concepts
  - Earth Science: Conduct airborne remote sensing and science observations

https://www.youtube.com/watch?v=aKZgHPTBcVI
Armstrong’s Capabilities

• Core Competencies
  • Flight operations & engineering staff
    • Back shops
  • Atmospheric flight research & test
    • Flight safety & risk management
    • Flight project & mission management
    • Flight research technology
    • Flight test operations
    • Experimental aircraft (piloted & unmanned)

• Facility Capability
  • Experimental & testbed aircraft
    • Self-certification process
  • Unmanned aircraft systems
    • Certificates of authorization
    • Ground control stations
    • Full range of UAS sizes & capabilities
  • Airborne science platforms
  • Range & aircraft test facilities
    • Dryden Aeronautical Test Range: Control Rooms
    • Research Aircraft Integration Facility: Simulations
    • Flight Loads Laboratory: Structural Testing
    • Building 703: Science Aircraft Facility
Armstrong’s Organization
Flight Loads Lab (FLL) Overview
What is the Flight Loads Laboratory?

- Where structures, dynamics & thermal component & airframe qualification/airworthiness & research happens
- High-bay test area with flight line access for large-scale structural & thermal testing of aerospace structures
  - Floor tie-down tracks, Strongbacks, Test fixture development
  - Structural Instrumentation & Data Acquisition
- Test Capabilities
  - **Loads:** Proof loading, load calibrations, deflection tests, control surface proof of operations, loads flight test
  - **Dynamics:** Modal test, flutter test, ASE test, freeplay test, mass property test
  - **Thermal:** Thermal and thermal-mechanical test, TPS development and test, pyrometry, SMAs, elastomer aerospace applications, frangible joint evaluations
  - **Sensors:** Conventional, high temperature & advanced instrumentation
Loads Calibration & Structural Loads Testing

- Loads testing of large aircraft and structures
- Application of realistic loads
- Derive equations for real-time determination of in-flight loads
- Component testing of unique structures with unique requirements
Thermal & Advanced Structural Testing

- Heating & loading of flight vehicles & structures to flight temperatures & loads
  - Temperature Range: -320°F to >3000°F
- Chamber for Large-Scale Testing
  - Test area: 10’x10’x10’
  - Quartz lamp & graphite heating
  - Water & gas cooling systems
  - Strongback
  - Nitrogen purged
  - Hydraulic systems
  - Video system
Mass Properties Testing

- Weight & balance of flight vehicles & structures
- Flight vehicles & structures moments of inertia (MOI) testing
  - Compound pendulum method & bifilar pendulum method

Orion Crew Module Weight & Balance

GIII UAVSAR Pod MOI

Phoenix MOI

Dream Chaser MOI
Ground Vibration Testing (GVT)

- Ground vibration testing of flight vehicles & structures
  - Measurement of structural mode shapes, natural frequencies & damping
- Supports validation of finite element models
- Soft-support system capable of testing structures up 60k lbs
How Does Structural Dynamics Fit into Flight Testing?

- Structural dynamics #1 purpose in terms of safety of flight is to prevent FLUTTER.
- Flutter is a destructive oscillation caused by interaction of aerodynamic forces, structural elasticity & inertial effects.
- GVTs help validate models to analyze & prevent flutter from occurring.

**FLUTTER IS BAD!**
Ground Vibration Testing (GVT) at NASA Armstrong
Ground Vibration Test

Input
Force Transducer
Time History

System

Output
Accelerometer
Time History
Many outputs over entire structure

System Under Test
Impact Hammer
Sensor to Measure Input Force

GVT Results
Frequency Response Function (FRF) characterize the system
System = \frac{System Response or Output}{System Input}
FRFs are obtained for points all over the test system and a curve fitting algorithm is used to define the mode shapes

System Output
Accelerometers to Measure Vibration Output

What boundary conditions will the system have for GVT? ⇒ Greatly affects results
GVT’s Goals, Objectives & Challenges

- **GVT Goal**: Gather modal data to validate and/or correlate the finite element model (FEM) which will later be used in the flutter analysis to grant airworthiness.

- **GVT Objective**: Measure & characterize the structural frequencies, mode shapes & damping.

- **GVT Challenge**: Obtaining test boundary conditions (BCs) which are comparable to FEM BCs:
  - Frequencies & mode shapes heavily depend on the BCs.
  - FEM modal analysis often use rigid or free-free BCs.
  - Rigid BCs ⇒ Very difficult to obtain in ground test… Nothing is completely rigid.
  - Free-free BCs ⇒ Challenging, but obtainable in ground test.
    - Need to simulate the aircraft flying (landing gear up, no constraints).
    - Soft Support System (SSS) minimize structural coupling by isolating rigid-body modes from aircraft’s elastic modes, thus simulating as close as possible the free-flight conditions the aircraft will experience.
      - SSS typically have a natural frequency below the first natural frequency of the test article & allows for a “floating” type effect.
      - If designed efficiently, SSS should have no effect on the test article mass, stiffness or damping.
      - SSS examples: Bungee cords or air bag systems.
GVT Boundary Condition: Self-Jack Soft Support System

• 60k lbs Self-Jacking Soft Support System
  • 3 canisters interface at aircraft jacking locations
    • Canisters filled with Nitrogen
  • Each soft support is rated for 20,000 lbs
  • SSS has ≈ 1 Hz natural frequency
    • Allows for a “floating” type effect
  • Self-Jacking allows landing gear to be retracted

Self-Jack Soft Support Canister
GVT Boundary Condition: Overhead Soft Support System

- Overhead Soft Support Systems
  - MIL spec bungees or custom build bungees
  - SSS can be custom designed based on aircraft pick-up locations and desired SSS frequency (typical ≈ 1 Hz)
  - As wings are becoming more flexible, SSS designs are becoming more difficult

Phantom Eye GVT with Custom Build Overhead SSS

Ikhana GVT using Overhead Bungees

MIL-C-5651B, Type II Bungees
GVT Boundary Condition: Soft Tires

- Sometime soft (partially deflated) tires are used as a soft support system
  - Used for ease of use
  - GVT data will have landing gear affects
  - Can be acceptable BCs for small test article on larger aircraft (i.e. F-15 centerline experiments)

F-15 on Soft Tires
for Centerline Experiment GVTs

Swept Wing Laminar Flow (SWLF)

Supersonic Boundary Layer Transition (SBLT) II

C-20 on Soft Tires
with Generation Orbit’s Inert Test Article GVT
GVT Boundary Condition: Strongback (Rigid)

- FLL Strongback is used to mount test articles to for some GVTs
  - Weighs 7,000 lbs
  - Fixed with 8-bolted ground points to FLL floor tracks
  - Laterally flexible
  - Strongback can couple with test article's modes of interest

X-56 Wing GVT Mounted on Strongback

FLL Strongback & FEM

Strongback Mode Shape – Laterally Flexible
GVT Boundary Condition: Other Test Fixture (*Semi-Rigid*)

- Different test fixtures have been used to mount test articles on for some GVTs
  - Test fixture attaches to FLL floor tracks
  - Test fixture are usually build for load testing
  - Test fixture vertical stiffness is usually acceptable, but flexible in the other two directions
  - Test fixture will eventually couple with test article’s modes of interest

Multiple test fixtures are shown with their corresponding FEM mode shapes:

- **Anti-Symmetric Wing 1st Bending FEM Mode Shape**
  - NOT Coupled with Test Fixture

- **Anti-Symmetric Aileron Rotation FEM Mode Shape**
  - Coupled with Test Fixture

The images depict:
- Static Loads Test Fixture FEM
- First Two Lateral Structural Mode Shapes

X-57 Mod III Wing GVT Mounted on Static Loads Test Fixture
Passive Aeroelastic Tailored (PAT) Wing
Passive Aeroelastic Tailored (PAT) Wing

- NASA’s Advanced Air Transport Technology (AATT) Project desires to develop technologies to design, build & test higher aspect ratio wings for lower induced drag and thus lower fuel burn
  - Future vehicles will be lightweight, highly-flexible tailored composite wings
  - Structural engineering & test facilities need to enhance their abilities to accurately model, instrument & test future wing concepts
- Passive aeroelastic tailored structural design has been exploring the design space to enable aeroelastically tailored wing structures to increase wing aspect ratio (from 9 to 14) and reduce weight by 20-25% without impacting aeroelastic performance

- PAT Wing project
  - Project team: Aurora Flight Sciences Corporation, NASA Langley Research Center & NASA Armstrong Flight Research Center
  - Goals
    - Design & fabricate a passive aeroelastic tailored structural wingbox using the towed-steering technology
    - Create finite element models with the towed-steering technology & conduct structural analyses
    - Conduct structural ground tests to validate analytical models & assumptions
  - Three main structural tests were performed at Armstrong’s FLL
    - Ground Vibration Test - validate the wing’s frequencies & mode shapes
    - Flexural Axis Test - validate the wing’s bend twist coupling response
    - Static Load Test - validate the wing’s response including stiffness, strains & deformations
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
Automated Fiber Placement (AFP)
Tow-Steering for Aeroelastic Tailoring
uCRM-13.5 27% Scaled Test Article Wing Skins

October 2016

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Video of Aurora’s Automated Fiber Placement (AFP) fabrication with tow-steering of PAT Wing upper skin

Video credit: Aurora
PAT Wing Static Load Testing

- PAT Wing Static Load Testing performed late 2019 on the self-reacting Wing Loads Test Fixture
  - -1g static download test ⇒ hydraulics actuators
  - +1g and +2.5g static upload tests ⇒ hydraulics actuators & overhead pulley system
- Test instrumentation: Conventional foil strain gages, fiber optic sensing system (FOSS), deflection potentiometers, inclinometers & digital image correlation (DIC) targets

Upload Test
String Pot Displacements vs. Percent Load
Wingtip deflection ≈ 80.8 in (6.7 ft) at 90% Load

PAT Wing Static Load Testing

Wingtip deflection ≈ 80.8 in (6.7 ft) at 90% Load
PAT Wing Static Load Testing, -1g Test Configuration

- For -1g static download test, all 14 actuators attached from underneath wing
- Distributed loads simulated in-flight load predictions
- Test was incrementally loaded and unloaded in 4 increments ramping up to maximum test load

Negative Loads – Actuator is in Compression
Positive Loads – Actuator is in Tension
PAT Wing Static Load Testing, +1g, +2.5g Test Configuration

- For +1g and +2.5g static upload tests, inboard 8 actuators attached from underneath wing, outboard 6 actuators attached to cables with moving pulleys to accommodate high deflections
- Distributed loads simulated in-flight load predictions
- Test was incrementally loaded and unloaded in 4 increments ramping up to maximum test load
PAT Wing, Front View of 50% Static Load Test, +2.5g Config.

- Wingtip deflection ≈ 47 in (3.9 ft) during 50% static load test during the +2.5g test configuration
PAT Wing, End View of 50% Static Load Test, +2.5g Config.
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 (up to wing 1st torsion mode, ≈ 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
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
Test Setup – GVT Test Setup, Actual Testing

- 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

WLTF Table Boundary Condition on FLL Floor (NOT ideal for modal testing)
Fixed Base Correction Method - Motivation

- Modal testing & 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
  - Calibration Research Wing (CReW) modal test was a pathfinder test to investigate FBC method
    - 1st aircraft FBC application
    - 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:

\[
a_1 = \frac{-\omega^2 (-\omega^2 m_2 + 2k)}{(-\omega^2 m_2 + 2k)(-\omega^2 m_1 + k) - k^2} \begin{bmatrix}
f_1 \\
f_2
\end{bmatrix}
\]

- 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:

\[
a_1 = \frac{-\omega^2}{-\omega^2 m_1 + k} \begin{bmatrix}
f_1 \\
\end{bmatrix}
\]

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

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
CReW GVT using Fixed Base Correction Method

- Calibration Research Wing (CReW) GVT was the pathfinder test for PAT Wing to investigate FBC method & the first aircraft FBC application

- CReW GVT had two different boundary conditions of the reaction table feet to investigate the FBC method
  1. Feet Up configuration
  2. Feet Down configuration

- FBC method attempted to “fix” the reaction table or make the reaction table rigid for both different boundary conditions and decouple the wing modes from the WLTF modes

- CReW GVT fixed WLTF at the reaction table boundary
  - 10 shakers: 1 shaker on wingtip & 9 shakers on fixture table
    - Wingtip shaker ⇒ excited wing modes
    - WLTF shakers ⇒ excited rigid body motion of the reaction table & C-channels in-plane bending
CReW GVT Results with Different Boundary Conditions

- Uncorrected results
  - Feet Up & Feet Down Uncorrected results shows wing fore/aft & torsion modes are very different due to their differences in boundary conditions

- FBC results
  - Feet Up & Feet Down FBC results line up on top of each other
    - FBC FRFs look very similar & have corresponding frequency peaks

- FBC approach was able to aid two different physical table boundary configurations (Feet Up vs. Feet Down) to produce equivalent wing modal results
**PAT Wing 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
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)

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

- FBC method requires numerous accelerometers on the base structure
PAT Wing GVT – 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)
  - Weighed wing with GVT sensors and cables attached to later smear cable weight across the FEM
PAT Wing GVT – 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
PAT Wing GVT – 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)
PAT Wing 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
PAT Wing GVT Shaker Layout - Fixed Base Correction Method

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

- Shaker configurations for FBC method
  - 10 shakers (Initial Pass): 9 shakers on fixture table, 1 shaker on wingtip
  - 12 shakers (Second Pass): Added 2 shakers on aft triangular brackets (fore/aft)
  - 14 shakers (Final Pass): Added 2 shakers on wing root reaction plates (fore/aft)
FEM "Fixed" boundary conditions were applied to all nodes on related hardware.

- 10 shakers (Initial Pass): 9 shakers on fixture table, 1 shaker on wingtip
- 12 shakers (Second Pass): Added 2 shakers on aft triangular brackets (fore/aft)
- 14 shakers (Final Pass): Added 2 shakers on wing root reaction plates (fore/aft)
PAT Wing GVT 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
PAT Wing GVT Results – 14 Shakers, FBC vs. FEM

- As the number of shakers increase on the base, the Cross-Modal Assurance Criteria (MAC) starts to clean up and the test modes line up with the FEM modes.

Percent Frequencies Difference w/ respect to FEM Uncorrected vs. FBC for 14 Shakers

<table>
<thead>
<tr>
<th>Mode #</th>
<th>Mode Description</th>
<th>% Difference to FEM Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>W1B</td>
<td>-3% 5%</td>
</tr>
<tr>
<td>2</td>
<td>W1F/A</td>
<td>51% -4%</td>
</tr>
<tr>
<td>3</td>
<td>W2B</td>
<td>10% -3%</td>
</tr>
<tr>
<td>4</td>
<td>W2F/A</td>
<td>27% -6%</td>
</tr>
<tr>
<td>5</td>
<td>W3B</td>
<td>31% -5%</td>
</tr>
<tr>
<td>6</td>
<td>W4B</td>
<td>5% -5%</td>
</tr>
<tr>
<td>7</td>
<td>W5B/W1T</td>
<td>3% 1%</td>
</tr>
<tr>
<td>8</td>
<td>W1T</td>
<td>-2% 2%</td>
</tr>
<tr>
<td>9</td>
<td>W3F/A</td>
<td>6% -8%</td>
</tr>
<tr>
<td>10</td>
<td>W6B</td>
<td>-6% 1%</td>
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<tr>
<td>11</td>
<td>W4F/A</td>
<td>6% -5%</td>
</tr>
<tr>
<td>12</td>
<td>W2T</td>
<td>-4% 4%</td>
</tr>
<tr>
<td>13</td>
<td>W7B</td>
<td>N/A 3%</td>
</tr>
</tbody>
</table>

Modal Assurance Criteria (MAC) with 14 Shakers
Cross-MAC Compares GVT vs. FEM
PAT Wing GVT Summary

- Uncorrected mode shapes had significant base motion
  - Particularly wing fore/aft modes & torsional modes

- Fixed Base Correction method
  - FBC method continued to remove more base motion as more shakers were added in the correct directions & locations on the base
  - FBC results produce test results with reliable and comparable boundary conditions to replicate in the analytical model
  - FBC 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
  - FBC technique demonstrates how experimental mechanics finds unique engineering solutions in the aeroelastic community
Questions