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

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• 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
- 29,000ft (8,840m) of concrete runways
- 68 miles (110km) of lakebed runways
- 301,000 acres (1,220km²)
- 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

Center Director

- EEO
- Chief Counsel
- Mission Info & Test Systems
- Flight Operations
- Research & Engineering
  - Safety & Mission Assurance
  - Mission Support
  - Programs

- Aerostructures
  - Systems Engineering & Integration
  - Vehicle Integration & Test
  - Operations

- Aerodynamics & Propulsion
- Dynamics & Controls
- Sensors & Systems Development
- Aero/Structural Loads
- Thermal & Advanced Structures
- Flight Loads Laboratory

Aerostructures

Structural Dynamics
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 (-195°C to >1650°C)
- Chamber for Large-Scale Testing
  - Test area: 10ftx10ftx10ft (3mx3mx3m)
  - 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

Dream Chaser MOI

GIII UAVSAR Pod 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 60,000lbs (27,215kg)
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

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 depends 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 20,000lbs (9,070kg)
  - 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

G-III GVT with Self-Jack Soft Support System

Self-Jack Soft Support Canister

F-15 Quiet Spike GVT on Soft Support System
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 7,000lbs (3,175kg)
  - 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
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 built 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

Static Loads Test Fixture FEM
First Two Lateral Structural 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

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 (≈ 12m)
  - Wing sweep 36.8°
  - Design & manufactured by Aurora
- 2 Spars, composite with 58 ribs
- 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
PAT Wing Tow-Steering Upper Skin Automated Fiber Placement Layup

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
PAT Wing Static Load Testing

- PAT Wing Static Load Testing performed late 2018 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 ≈ 80.8in (205cm) at 90% Load

PAT Wing Static Load Testing
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

PAT Wing Static Load Testing
-1g Test Configuration

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 Static Load Testing
+1g, +2.5g Test Configuration

Negative Loads – Actuator is in Compression
Positive Loads – Actuator is in Tension
PAT Wing, Front View of 50% Static Load Test, +2.5g Config.

- Wingtip deflection ≈ 47in (119cm) 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
  • FBC is an experimental mechanics technique for modal testing
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 to be lower to the ground
    - Wingtip ≈ 50in (127cm) off the floor, rather than original plan with wingtip ≈ 124in (315cm) high
Test Setup – GVT Boundary Conditions with Table on Floor

- Physical 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
  - Experimental mechanics technique for modal testing in the aeroelastic community
  - 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:

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

- 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:

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

- 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)
PAT Wing GVT 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**

- 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)

**Total: 288 Channels Enabled (Accels & Force Transducers)**
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 in order to later smear cable weight across the FEM
• 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)

“Fixed” Shaker Locations

Wingtip Shaker

Seismic Accels

Normal GVT Accel
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
Shaker configurations for FBC method – kept adding additional shakers to improve the fixed base modes

- **Initial Pass**: 9 shakers on fixture table, 1 shaker on wingtip
- **Second Pass**: Added 2 shakers on aft triangular brackets (fore/aft)
- **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)
PAT Wing GVT Shaker Layouts & FEM Boundary Conditions

- 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 (W2F/A ≈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

14 Shaker Test Results – Wing 2nd Fore/Aft
GVT: Uncorrected 16.5 Hz
GVT: FBC 30.2 Hz
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 14-Shaker Uncorrected</th>
<th>14-Shaker FBC</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>W1B</td>
<td>-3%</td>
<td>5%</td>
</tr>
<tr>
<td>2</td>
<td>W1F/A</td>
<td>51%</td>
<td>-3%</td>
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<tr>
<td>3</td>
<td>W2B</td>
<td>10%</td>
<td>-3%</td>
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<td>W2F/A</td>
<td>27%</td>
<td>-6%</td>
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<td>W3B</td>
<td>31%</td>
<td>-5%</td>
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<td>W4B</td>
<td>5%</td>
<td>-5%</td>
</tr>
<tr>
<td>7</td>
<td>W5B/W1T</td>
<td>3%</td>
<td>1%</td>
</tr>
<tr>
<td>8</td>
<td>W1T</td>
<td>-2%</td>
<td>2%</td>
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<tr>
<td>9</td>
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<td>4%</td>
</tr>
<tr>
<td>13</td>
<td>W7B</td>
<td>N/A</td>
<td>3%</td>
</tr>
</tbody>
</table>

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

Test Objective: Modes up to W1T
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