Passive Aeroelastic Tailored Wing Modal Test Using the Fixed Base Correction Method

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PAT Wing Ground Vibration Test (GVT) - Outline

- Fixed Based Correction (FBC) Method
  - Motivation
  - Theory
- Goal, Objective & Success Criteria
- Test Article Description
- PAT Wing GVT
  - Test Setup
  - Test Configurations
  - GVT Instrumentation
  - Accelerometer Layout
  - Shaker Layout for FBC
- Results
- Summary

Passive Aeroelastic Tailored (PAT) Wing
GVT using Fixed Base Correction Method – July 2018

Fixed Base Correction (FBC) 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 modal testing

- NASA Armstrong evaluated the Fixed base correction (FBC) method with two recent tests
  - CReW modal test was a pathfinder test to investigate FBC method prior to PAT Wing GVT where wing was cantilevered from a static test fixture with the wingtip ≈10ft off the ground
  - 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 can be 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

$$a_1 = \begin{bmatrix} \dfrac{-\omega^2(-\omega^2 m_2 + 2k)}{(-\omega^2 m_2 + 2k)(-\omega^2 m_1 + k) - k^2} & \dfrac{-\omega^2 k}{(-\omega^2 m_2 + 2k)(-\omega^2 m_1 + k) - k^2} \end{bmatrix} \begin{Bmatrix} f_1 \\ f_2 \end{Bmatrix}$$

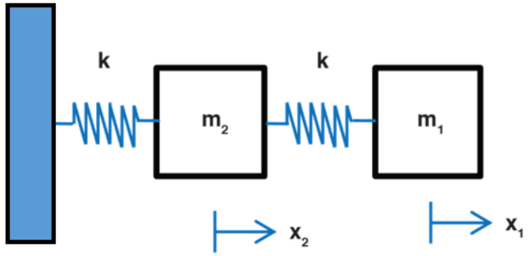
- FBC method uses DOF 1 force & DOF 2 acceleration as references, then resulting FRFs are associated with a structural system with dynamics associated with DOF 2 fixed

$$a_1 = \begin{bmatrix} \dfrac{-\omega^2}{-\omega^2 m_1 + k} & \dfrac{k}{-\omega^2 m_1 + k} \end{bmatrix} \begin{Bmatrix} f_1 \\ a_2 \end{Bmatrix}$$

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

- 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 or test fixture shakers with harder forces)
  - Use shaker accelerations as references rather than traditional shaker forces when calculating FRFs
    - Make sure drive point FRF are as co-located as practicable & as clean as practicable
    - Use seismic accelerometers as drive points on the base

Spring-Mass Two DOF System



Where:
m = mass
ω = frequency
k = structural stiffness
x = displacement
f = external force
a = acceleration
Subscripts 1 & 2 refer to blocks 1 & 2

PAT Wing GVT - Goal, Objective & Success Criteria

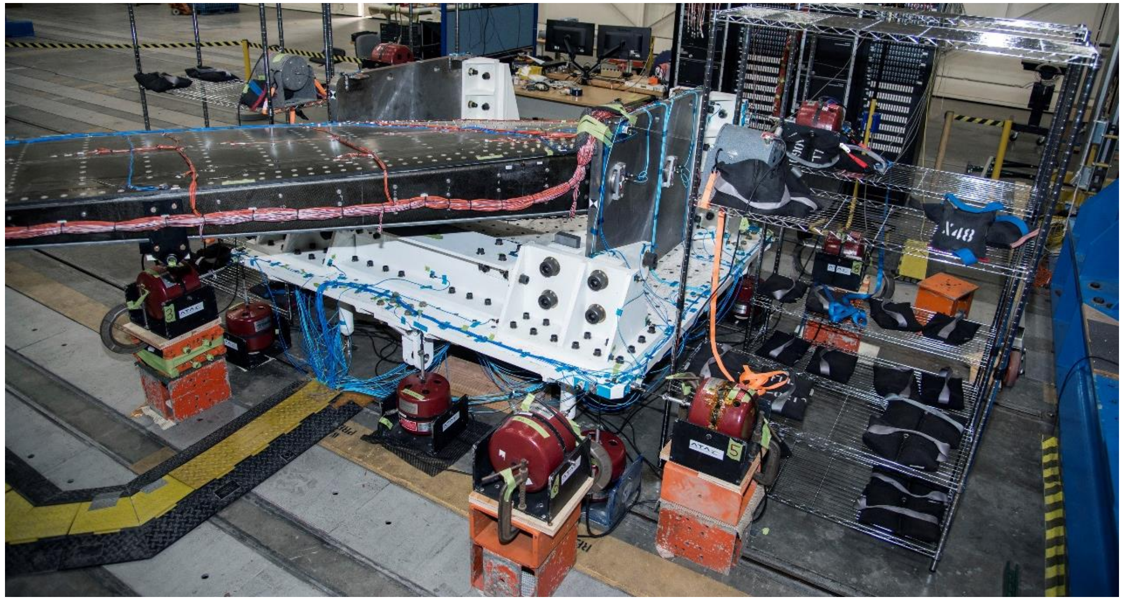
- Passive Aeroelastic Tailored (PAT) Wing Ground Vibration Test (GVT) was tested July 10-12th, 2018 in NASA Armstrong's Flight Loads Laboratory (FLL)

- 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, ≈ 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 GVT - July 2018

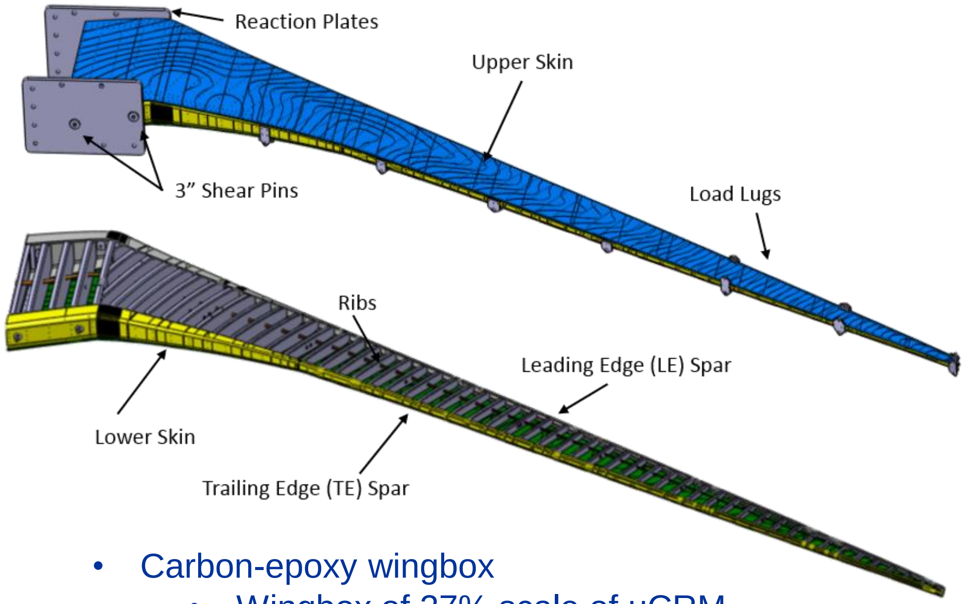


Passive Aeroelastic Tailored (PAT) Wing

- 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
  - Passive aeroelastic tailored structural design has been evaluating 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
      - **Ground Vibration Test - validate wing's frequencies & mode shapes**
      - Flexural Axis Test - validate wing's bend twist coupling response
      - Static Load Test - validate wing's response including stiffness, strains & deformations

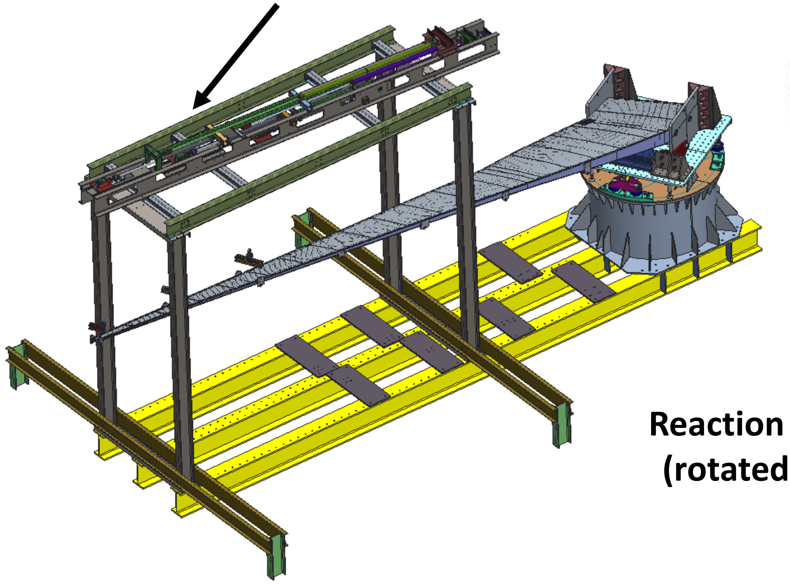
Passive Aeroelastic Tailored (PAT) Wing



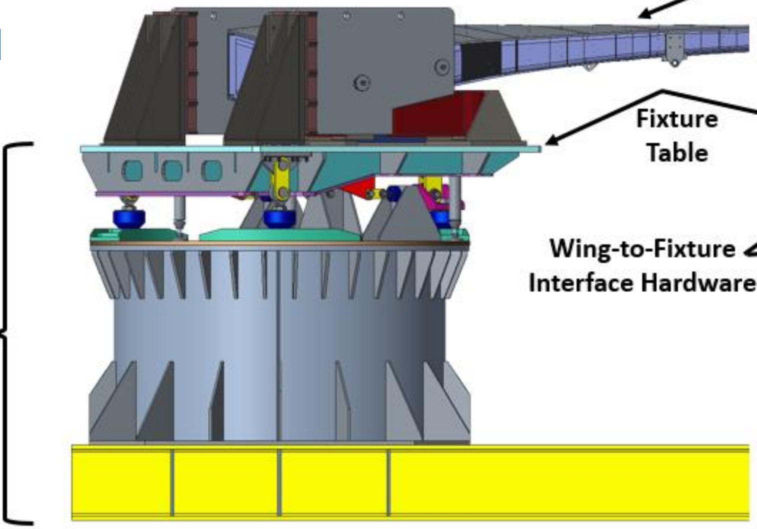
- Carbon-epoxy wingbox
  - Wingbox of 27% scale of uCRM
  - Right wing w/ high aspect ratio (13.5)
  - Root LE to tip TE: ≈ 39 ft
  - Wing sweep 36.8°
  - Design & manufactured by Aurora
- 2 Spars, composite with 58 ribs
- 2 Wingskins with Tow-steered technology
- 2 Reaction plates & 4 Reaction pins
- 14 Load lugs (7 load lugs spanwise on LE & TE)
- Total weight ≈ 2,600 lbs

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
    - Wingtip ≈ 124” off ground
    - Overhead loading structure installed



Overhead Loading Structure

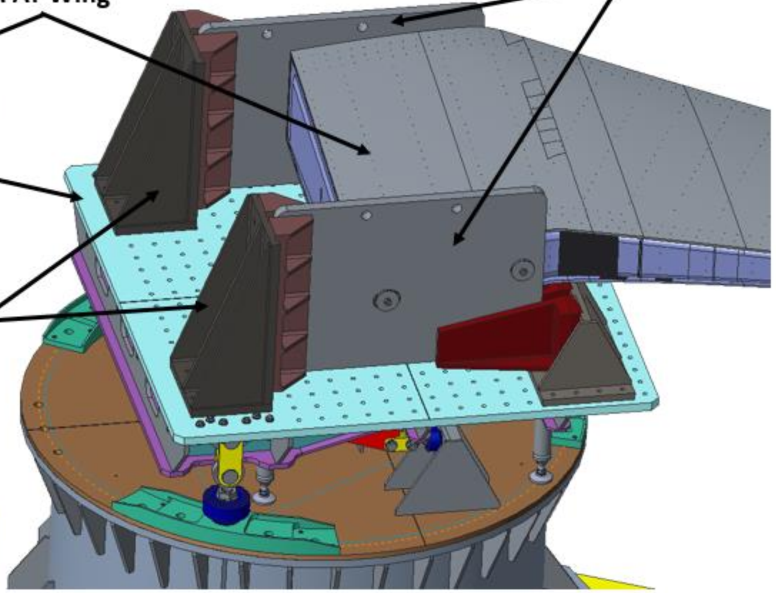


Wing Loads Test Fixture (WLTF)

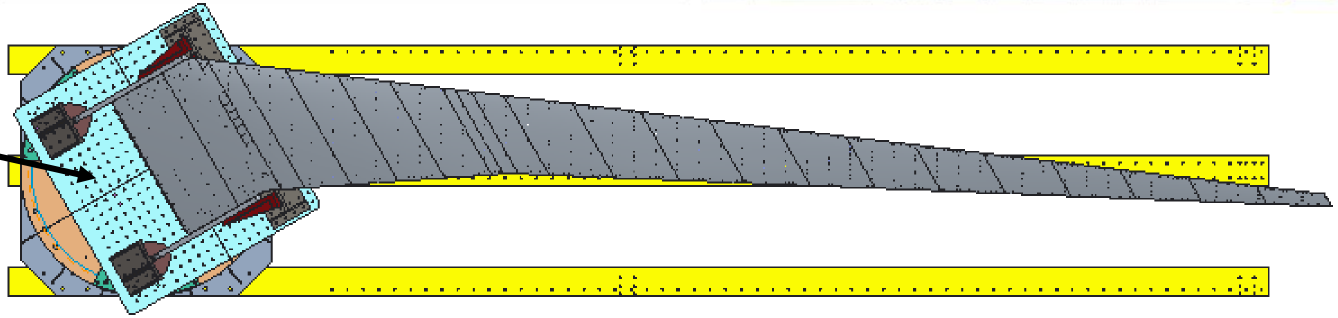
PAT Wing

Fixture Table

Wing-to-Fixture Interface Hardware



PAT Wing Reaction Plates



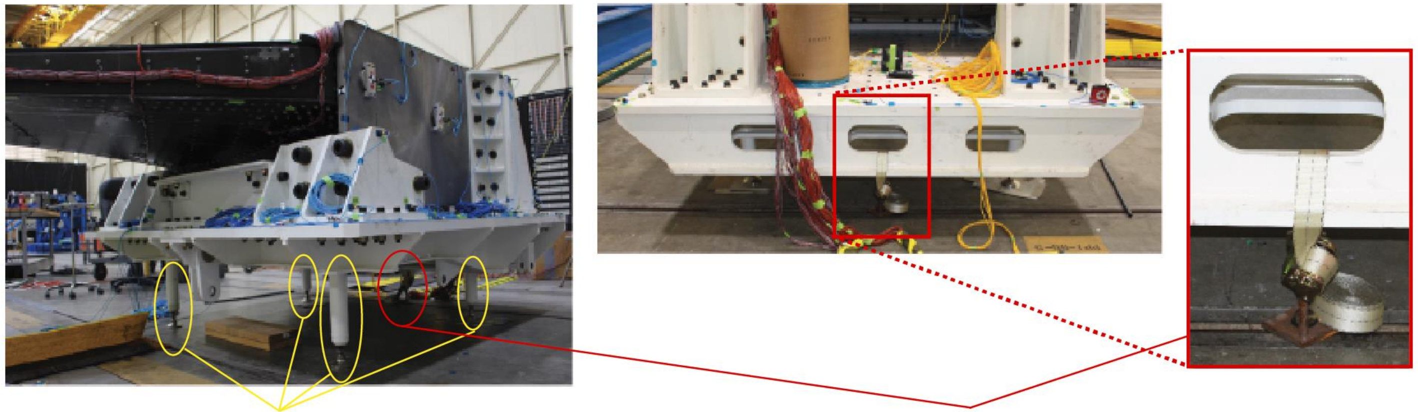
Reaction Table (rotated 30°)

Test Setup – GVT Test Setup, Simplified Actual Testing

- Simplified actual testing setup: Performed GVT with WLTF table on FLL floor
  - Simplified GVT shaker setup since the wingtip is ≈ 50” off the floor, rather than the wingtip being 124” high
- Boundary conditions: WLTF table on FLL floor supported by four retractable feet & one location on the table that was secured to the FLL floor tracks with a strap

WLTF Table Boundary Condition on FLL Floor

(NOT ideal for traditional modal testing)



Four retractable feet boundary condition

Table secured with strap to FLL floor boundary condition

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
  - 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)

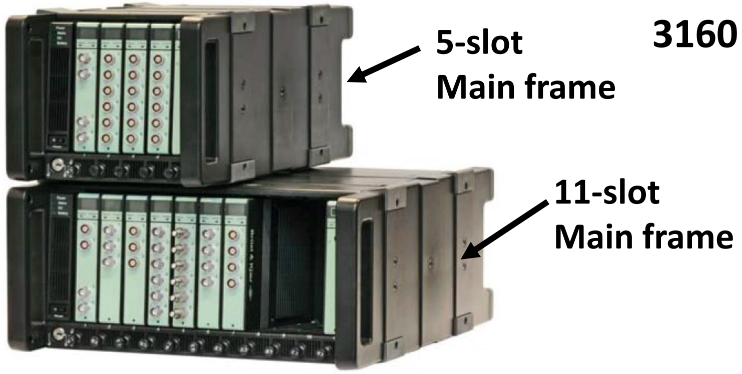
PCB T333B32
Uniaxial Accel

PCB T356A16
Triaxial Accel

PCB 393B04
Seismic Uniaxial Accel

MB Modal 110
Shaker

Brüel & Kjær LAN-XI DAQ



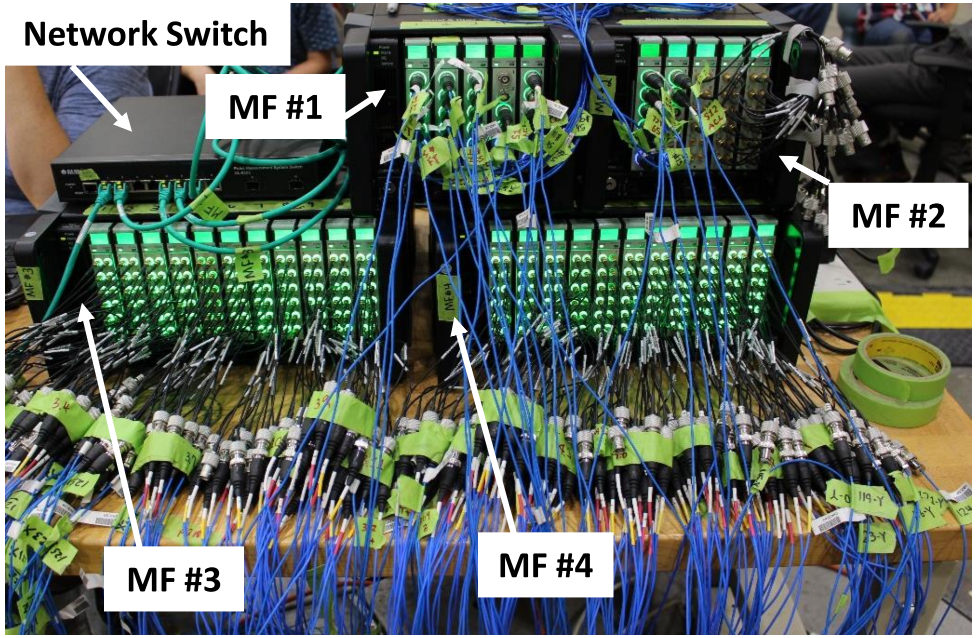
LAN-XI
3160 & 3053 Modules

Note: Some GVT hardware was provided by Contractor

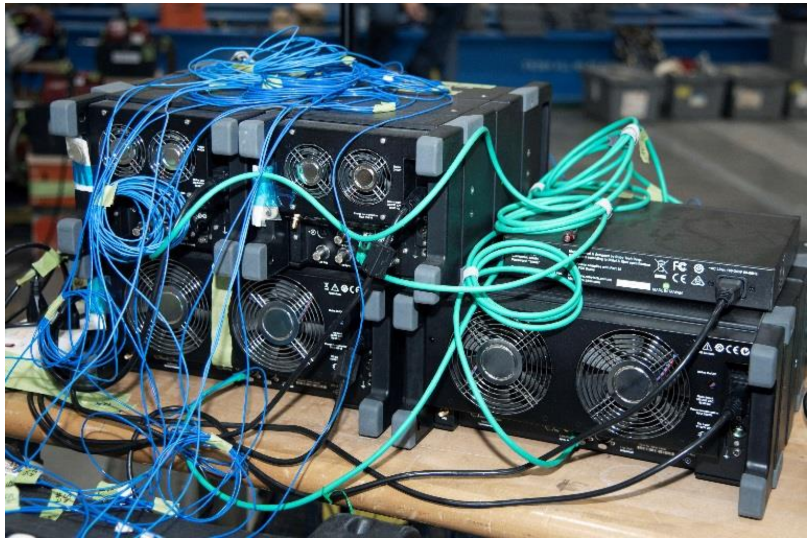
Test Setup – LAN-XI DAQ

- 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)

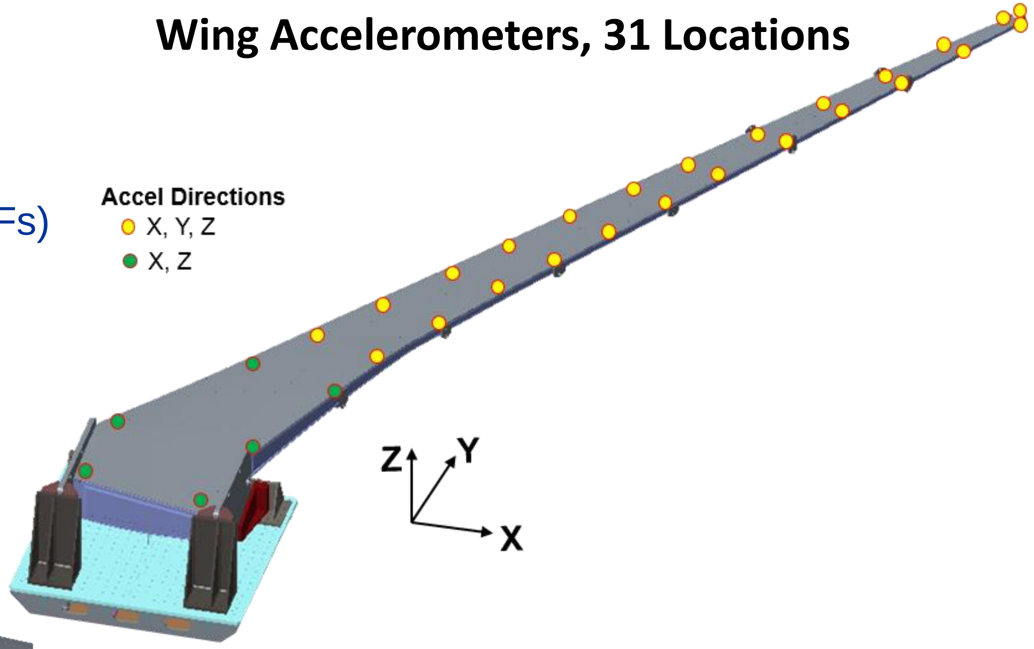


Note: Some LAN-XI source modules were provided by Contractor

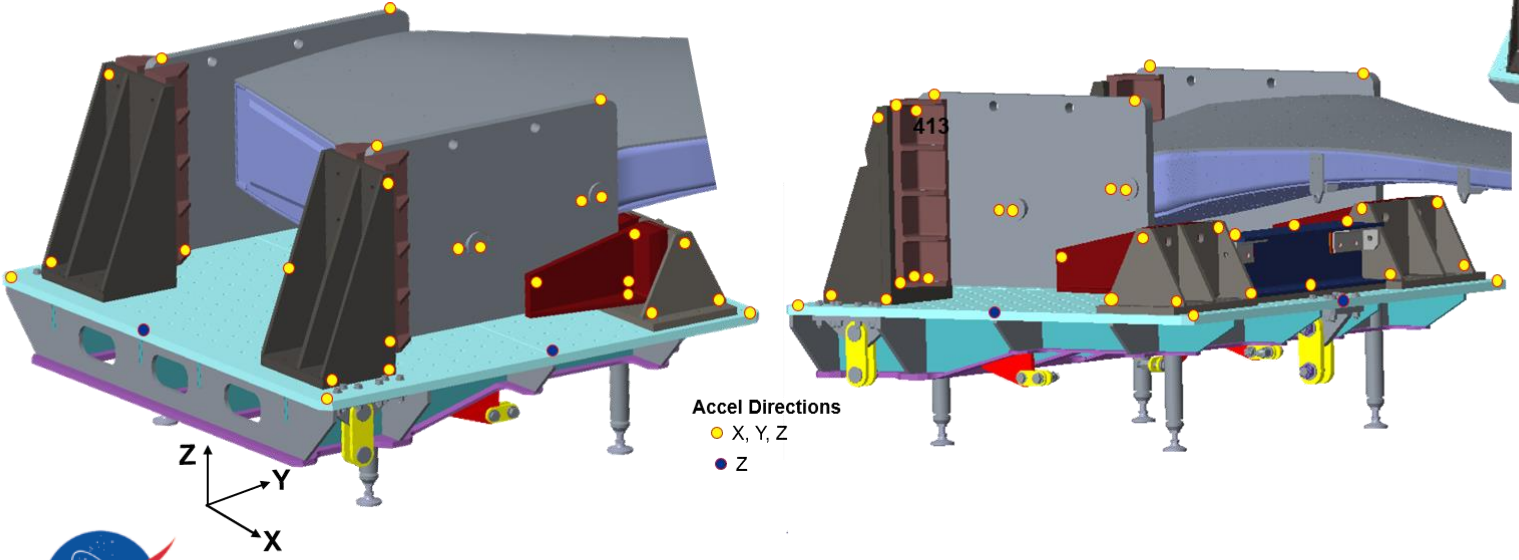
Test Setup – Accelerometer Layout for FBC

- Accelerometers, Total: 106 Accel Locations (274 Accel DOFs)
    - Reference Accels at Shakers – 14 locations (14 DOFs)
    - Wing – 31 locations (87 DOFs)
    - Hardware being fixed was majority of accels, 61 locations (173 DOFs)
        - Wing Reaction Plates & Pins – 16 locations (48 DOFs)
        - Reaction Table – 9 locations (17 DOFs)
        - Attachment Hardware (TE) – 18 locations (54 DOFs)
        - Attachment Hardware (LE) – 18 locations (54 DOFs)

Wing Accelerometers, 31 Locations

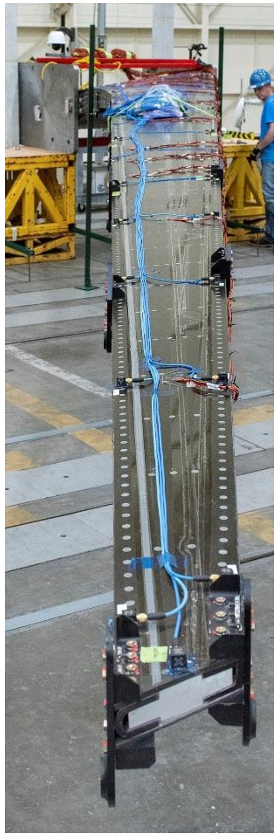


Accelerometers of Hardware being Fixed with FBC, 61 Locations

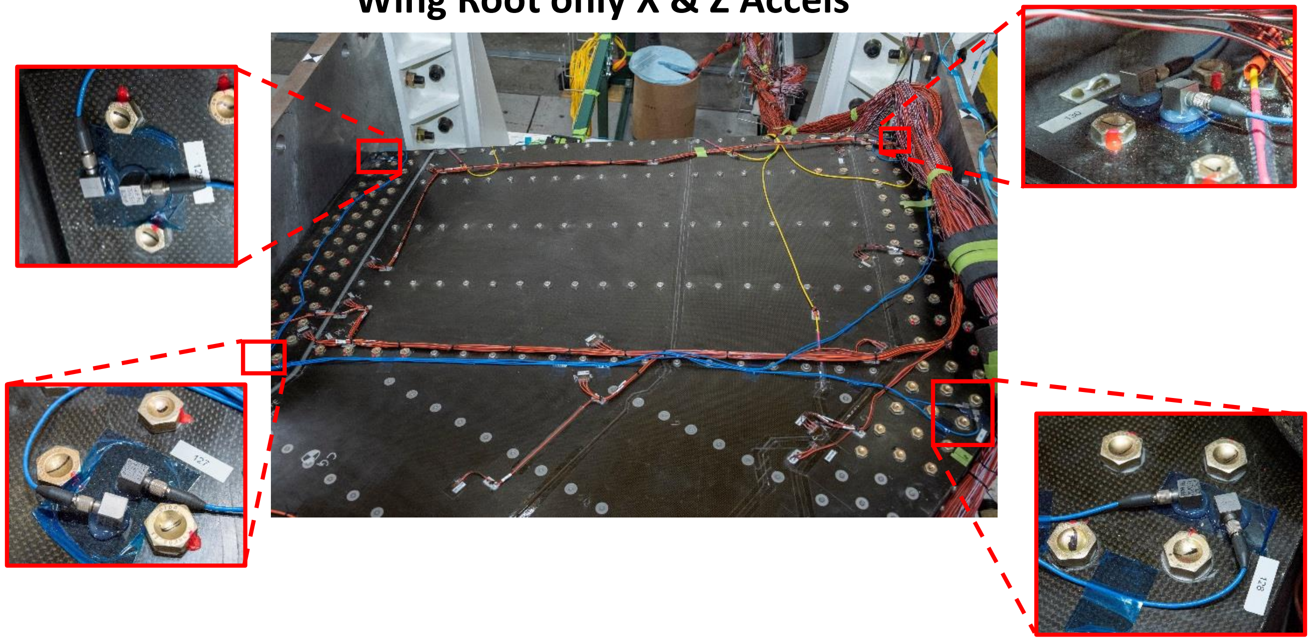


Test Setup – Accel Wing Photos

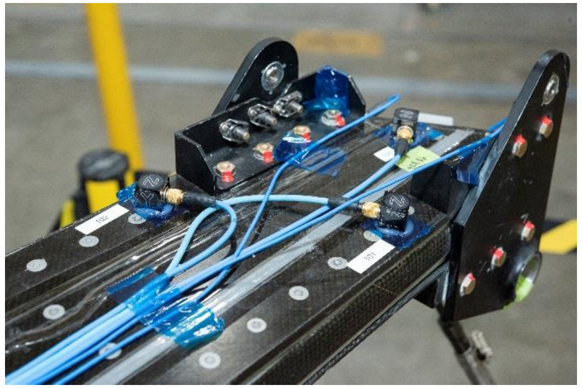
- Accel coordinates obtained from FEM
  - All nodes in global coordinate system wrt WLTF
    - X+ (out Trailing Edge), Y+ (out Outboard), Z+ (up)
    - Used 30° template to install wing accels with correct angle orientation



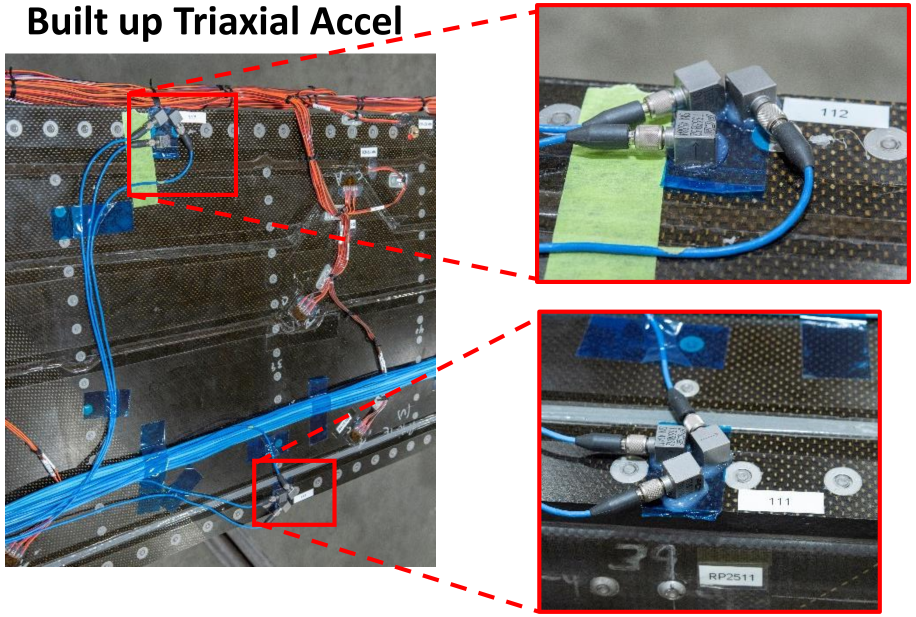
Wing Root only X & Z Accels



Wingtip Triaxial Accels



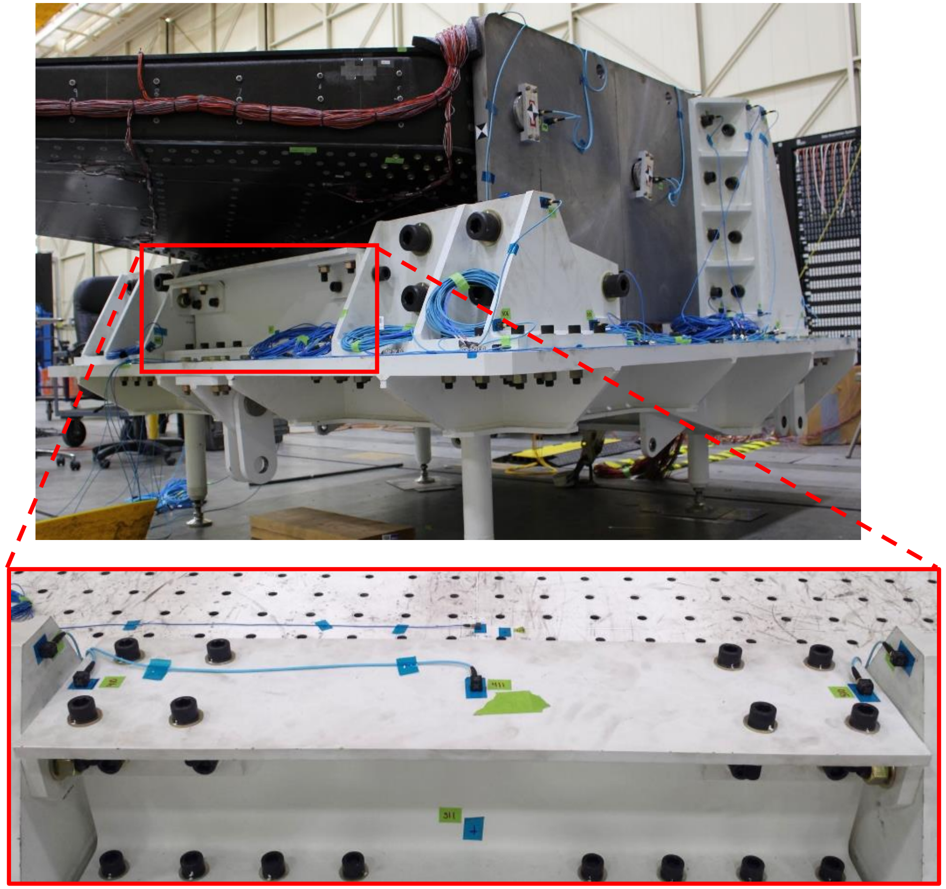
Built up Triaxial Accel



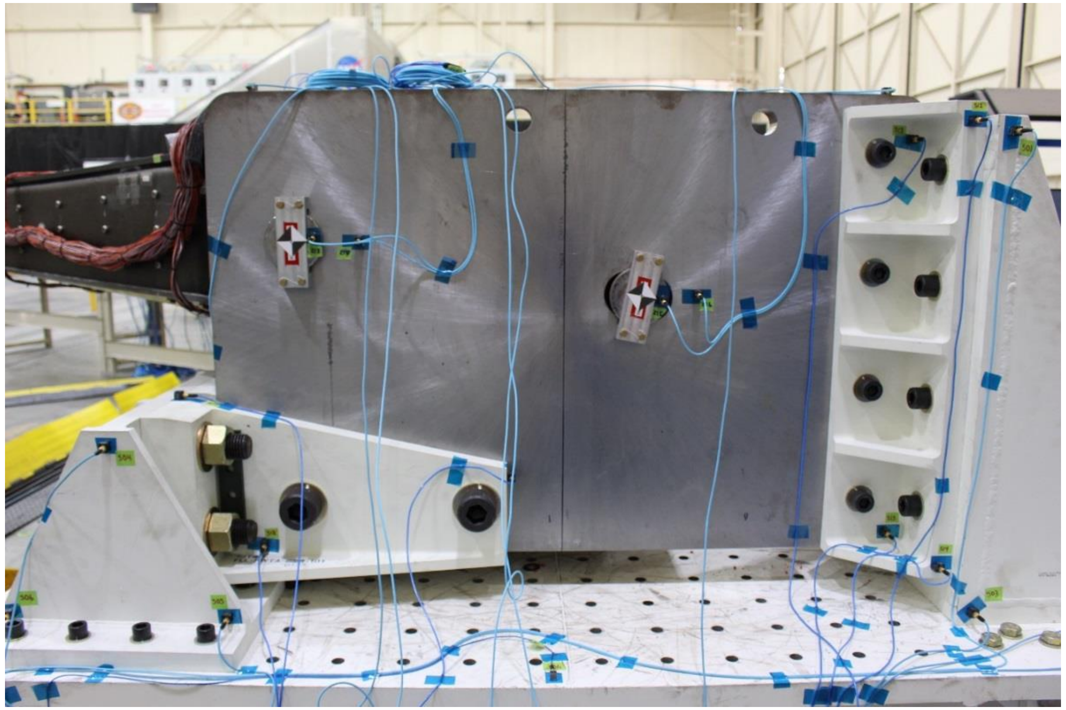
Test Setup – Accel Attachment Hardware Photos

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

Triaxial Accels Mainly on Attachment Hardware



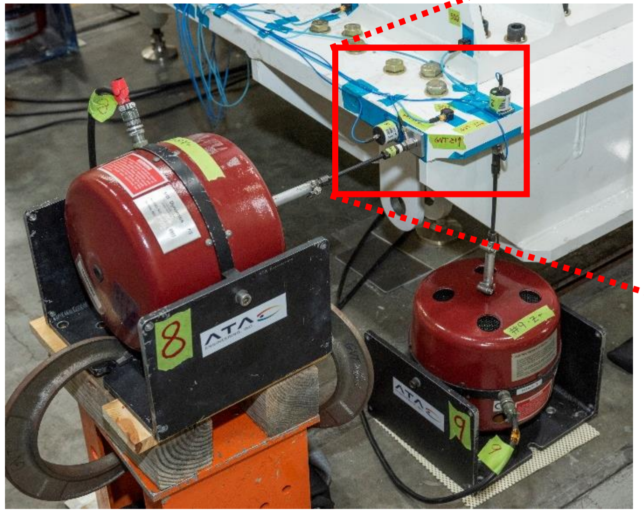
Attachment Hardware Accels – Leading Edge side



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)

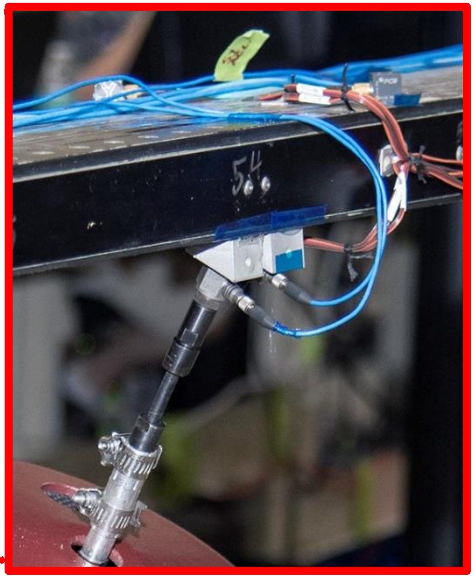
“Fixed” Shaker Locations



Seismic Accels

Wingtip Shaker

Traditional Modal Accel

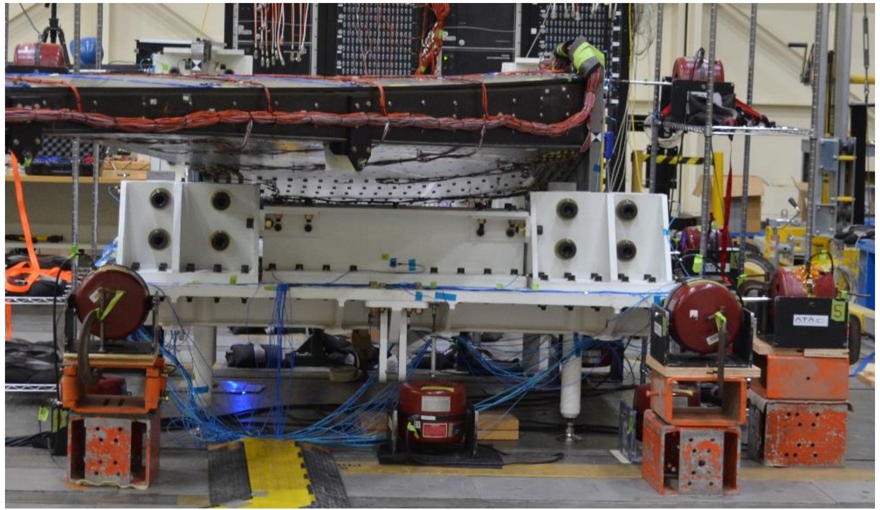


GVT Shaker Layout - Fixed Base Correction Method

- 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

Wingtip Shaker

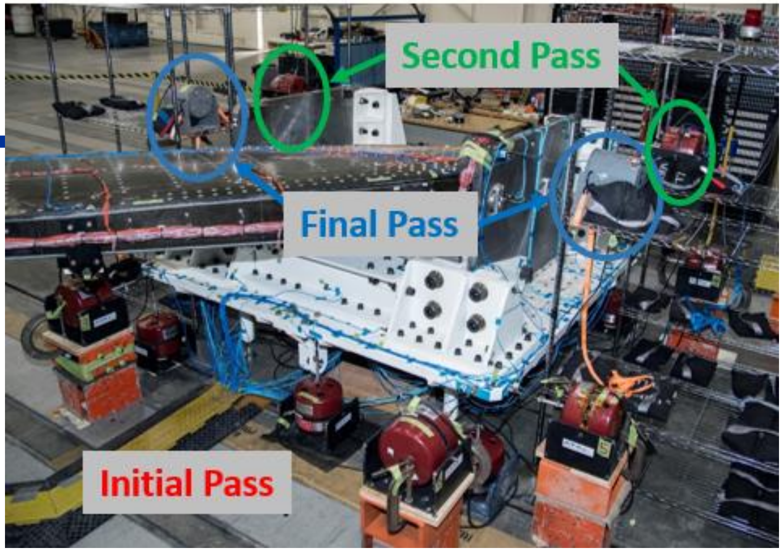
“Fixed” WLTF Shaker Locations



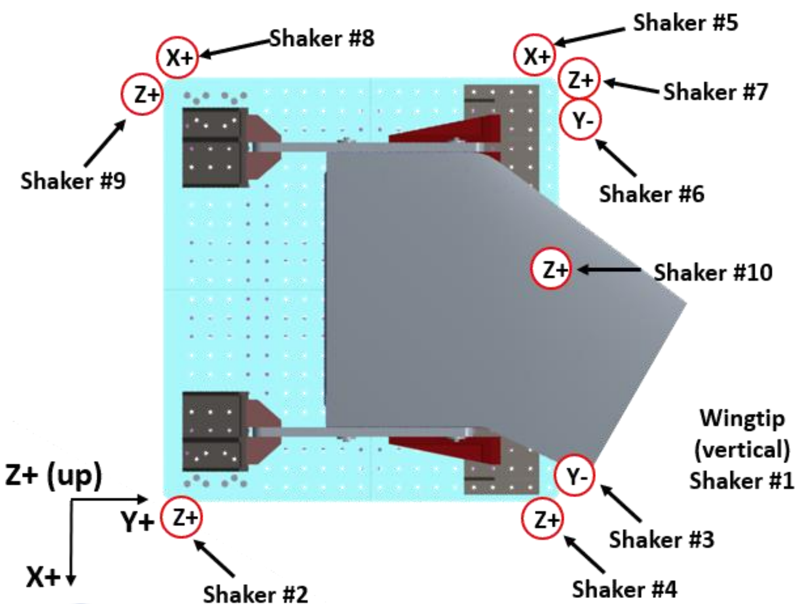
PAT Wing GVT Shaker Layouts for FBC

- Shaker configurations for FBC method
  - 10 Shakers, Initial Pass – 9 on reaction table, 1 on wingtip
  - 12 Shakers, Second Pass – Added 2 on aft triangular brackets (fore/aft)
  - 14 Shakers, Final Pass – Added 2 on wing root reaction plates (fore/aft)

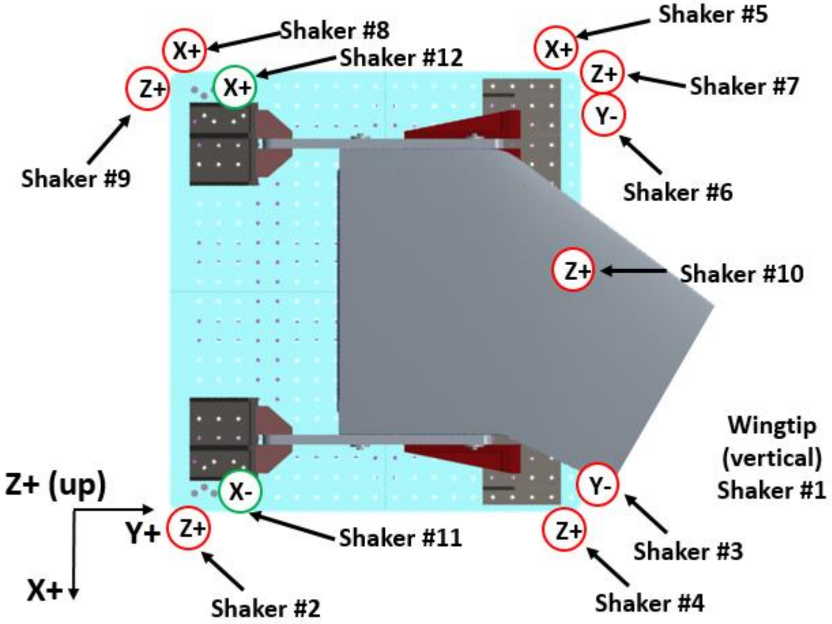
PAT Wing GVT - Shaker Configurations



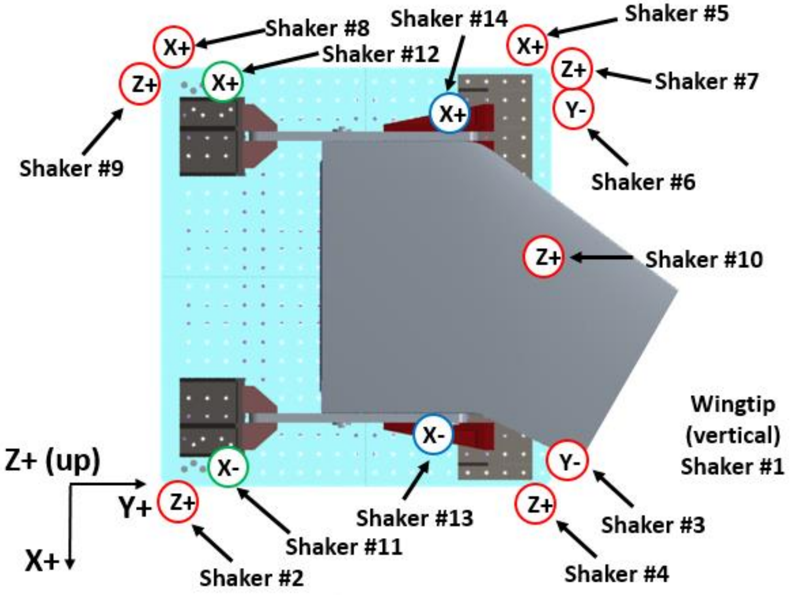
10 Shakers, Initial Pass



12 Shakers, Second Pass



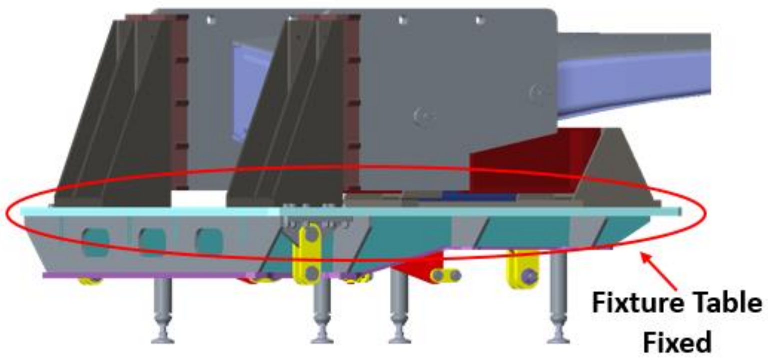
14 Shakers, Final Pass



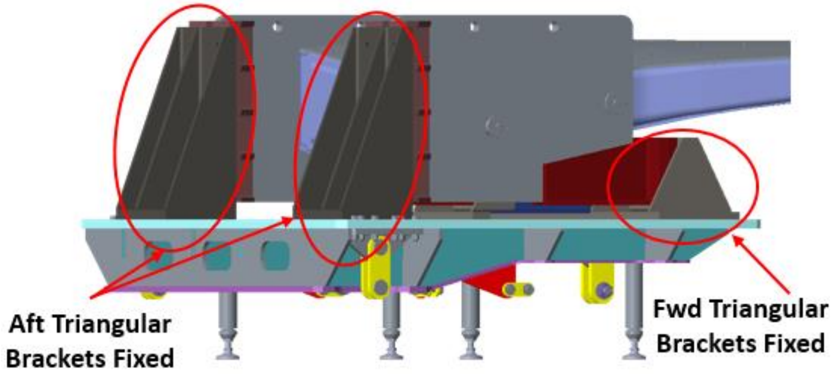
PAT Wing GVT Shaker Layouts & FEM Boundary Conditions

- FEM “Fixed” boundary conditions were applied to all nodes on related hardware
  - 10 Shakers, Initial Pass – 9 on reaction table, 1 on wingtip
  - 12 Shakers, Second Pass – Added 2 on aft triangular brackets (fore/aft)
  - 14 Shakers, Final Pass – Added 2 on wing root reaction plates (fore/aft)

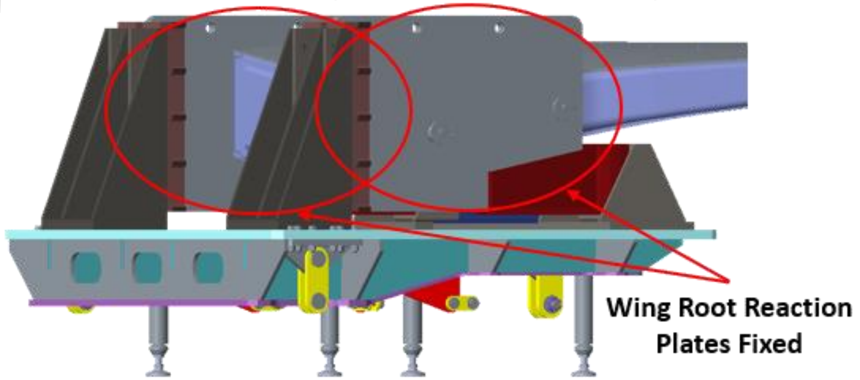
10 Shakers, Initial Pass
Reaction Table “Fixed”



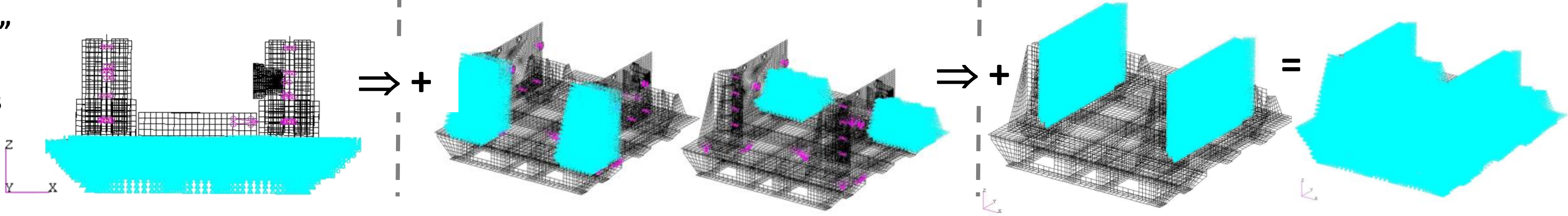
12 Shakers, Second Pass
Triangular Brackets “Fixed”



14 Shakers, Final Pass
Everything “Fixed”, but Wing



FEM “Fixed” Boundary Conditions



Results – 14 Shakers, Uncorrected vs. FBC

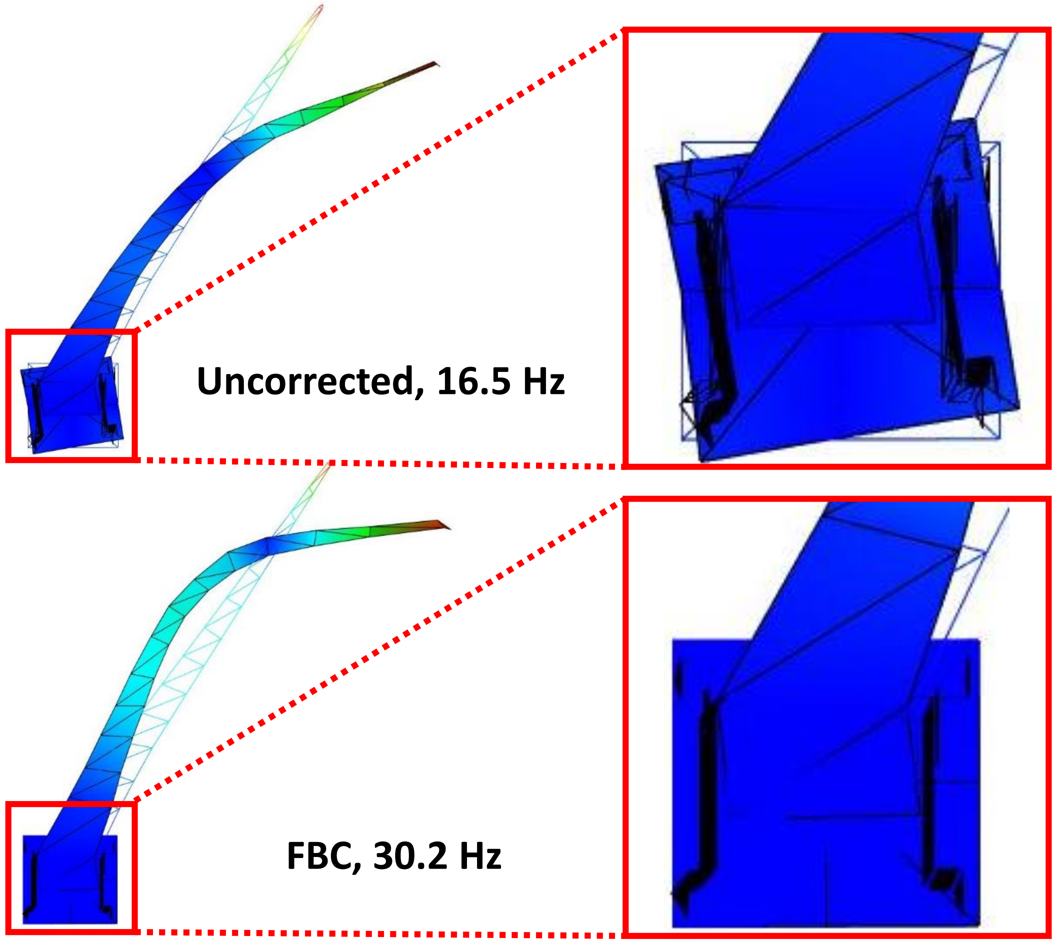
- FBC mode shapes show very little base deflection
- Uncorrected mode shapes show significant base rotation
  - Wing bending modes coupled the least with WLTF (setup is stiffer vertically than in other directions)
  - Wing fore/aft modes coupled the most with WLTF & required significant correction
- 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
  - Promising sign of the effectiveness of the FBC method

Frequency % Difference to FEM

14 Shakers GVT: Uncorrected vs. Fixed Base Correction

Mode #	Mode Description	Frequency (Hz)			% Difference to FEM Frequency	
		FEM	14-Shaker Uncorrected	14-Shaker FBC	14-Shaker Uncorrected	14-Shaker FBC
1	W1B	3.4	3.5	3.6	3%	5%
2	W2B	10.4	10.1	10.0	-3%	-4%
3	W1F/A	11.3	5.1	11.0	-55%	-3%
4	W3B	22.5	22.0	21.2	-2%	-6%
5	W2F/A	31.7	16.5	30.2	-48%	-5%
6	W4B	37.2	35.4	35.2	-5%	-5%
7	W5B (W1T)	51.8	50.4	52.2	-3%	1%
8	W1T	55.2	56.5	56.4	2%	2%

14 Shaker Test Results – Wing 2nd Fore/Aft GVT: Uncorrected vs. Fixed Base Correction



Uncorrected, 16.5 Hz

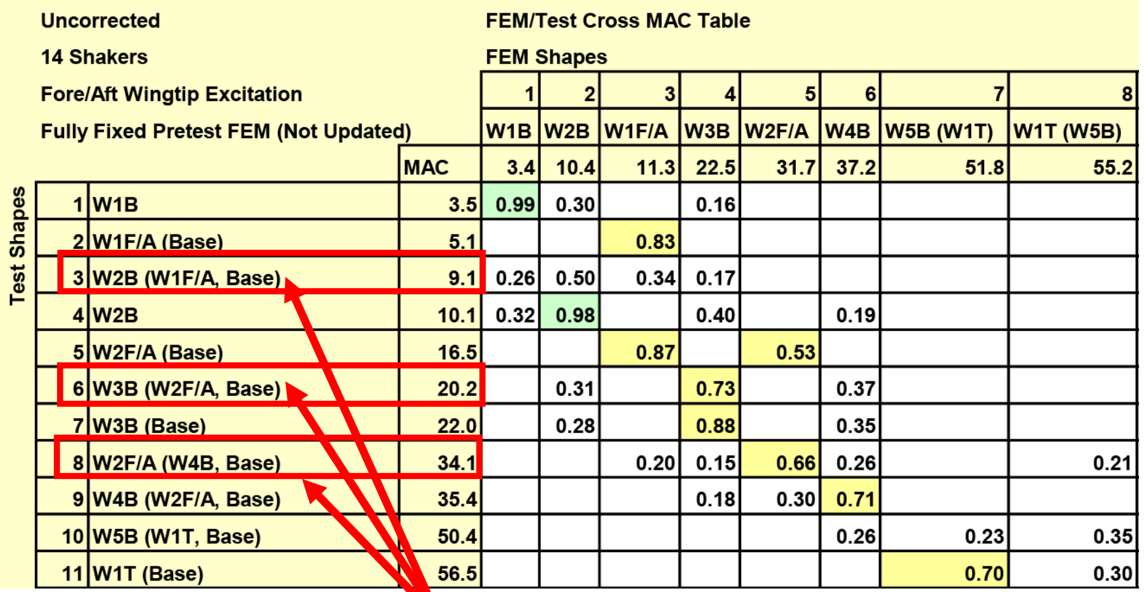
FBC, 30.2 Hz

Results – 14 Shakers, Uncorrected vs. FBC

- Modal Assurance Criteria (MAC) cleans up when applying FBC
- Uncorrected modes have substantial base rotation
- FBC eliminates some modes when fixing the base

Modal Assurance Criteria (MAC), 14 Shaker Tests

Uncorrected vs. FEM



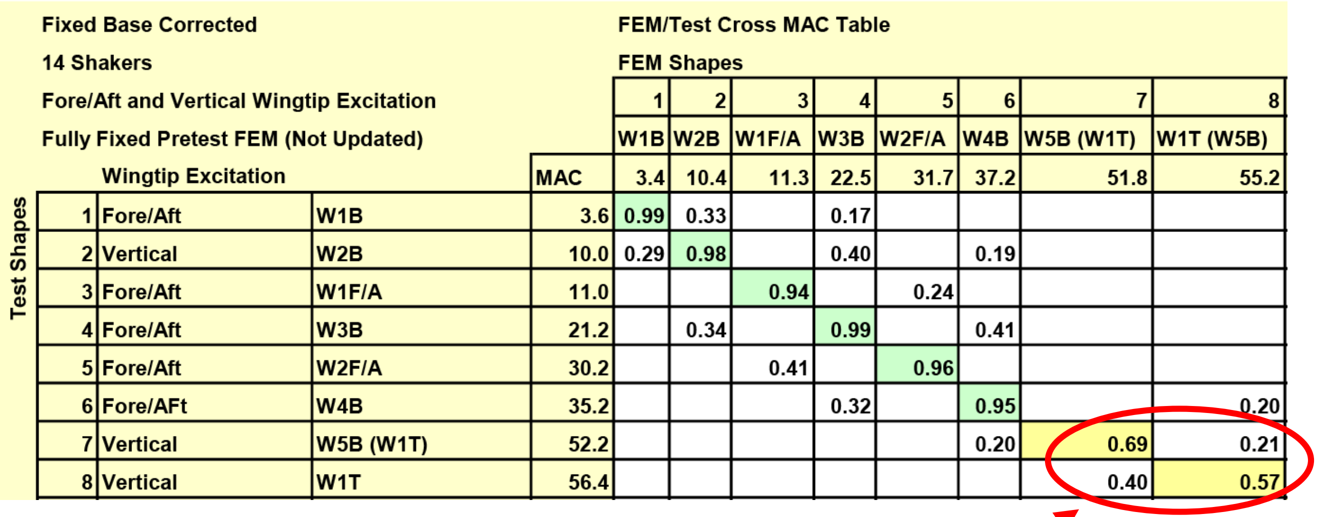
Uncorrected
14 Shakers
Fore/Aft Wingtip Excitation
Fully Fixed Pretest FEM (Not Updated)

FEM/Test Cross MAC Table
FEM Shapes

Test Shapes			1	2	3	4	5	6	7	8
			W1B	W2B	W1F/A	W3B	W2F/A	W4B	W5B (W1T)	W1T (W5B)
		MAC	3.4	10.4	11.3	22.5	31.7	37.2	51.8	55.2
1	W1B	3.5	0.99	0.30		0.16				
2	W1F/A (Base)	5.1			0.83					
3	W2B (W1F/A, Base)	9.1	0.26	0.50	0.34	0.17				
4	W2B	10.1	0.32	0.98		0.40		0.19		
5	W2F/A (Base)	16.5			0.87		0.53			
6	W3B (W2F/A, Base)	20.2		0.31		0.73		0.37		
7	W3B (Base)	22.0		0.28		0.88		0.35		
8	W2F/A (W4B, Base)	34.1			0.20	0.15	0.66	0.26		0.21
9	W4B (W2F/A, Base)	35.4				0.18	0.30	0.71		
10	W5B (W1T, Base)	50.4						0.26	0.23	0.35
11	W1T (Base)	56.5							0.70	0.30

Note: Duplicated modes with lots of base motion eliminated when applying FBC

Fixed Base Correction vs. FEM



Fixed Base Corrected
14 Shakers
Fore/Aft and Vertical Wingtip Excitation
Fully Fixed Pretest FEM (Not Updated)

FEM/Test Cross MAC Table
FEM Shapes

Test Shapes				1	2	3	4	5	6	7	8
				W1B	W2B	W1F/A	W3B	W2F/A	W4B	W5B (W1T)	W1T (W5B)
	Wingtip Excitation		MAC	3.4	10.4	11.3	22.5	31.7	37.2	51.8	55.2
1	Fore/Aft	W1B	3.6	0.99	0.33		0.17				
2	Vertical	W2B	10.0	0.29	0.98		0.40		0.19		
3	Fore/Aft	W1F/A	11.0			0.94		0.24			
4	Fore/Aft	W3B	21.2		0.34		0.99		0.41		
5	Fore/Aft	W2F/A	30.2			0.41		0.96			
6	Fore/AFt	W4B	35.2				0.32		0.95		0.20
7	Vertical	W5B (W1T)	52.2						0.20	0.69	0.21
8	Vertical	W1T	56.4							0.40	0.57

Note: FEM has W5B & W1T highly coupled where GVT showed wing is not as coupled

Summary

- PAT Wing GVT results show success and the feasibility of using the Fixed Base Correction (FBC) method to decouple the wing & test fixture modes for a flexible wing mounted to a dynamically active static test fixture

- Fixed Base Correction method
  - FBC results produce test results with reliable boundary conditions to replicate in analytical models
  - FBC has the potential to change how some modal testing is traditionally performed and can save money and schedule time by eliminating an independent setup for modal testing
  - Many potential scenarios where this technique can be used on future tests of structures mounted on other dynamically active test fixtures

Questions