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

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PAT Wing GVT - Outline

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- Test Article Description
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  - Test Setup
  - Finite Element Model
  - Fixed Based Correction Method
  - GVT Equipment
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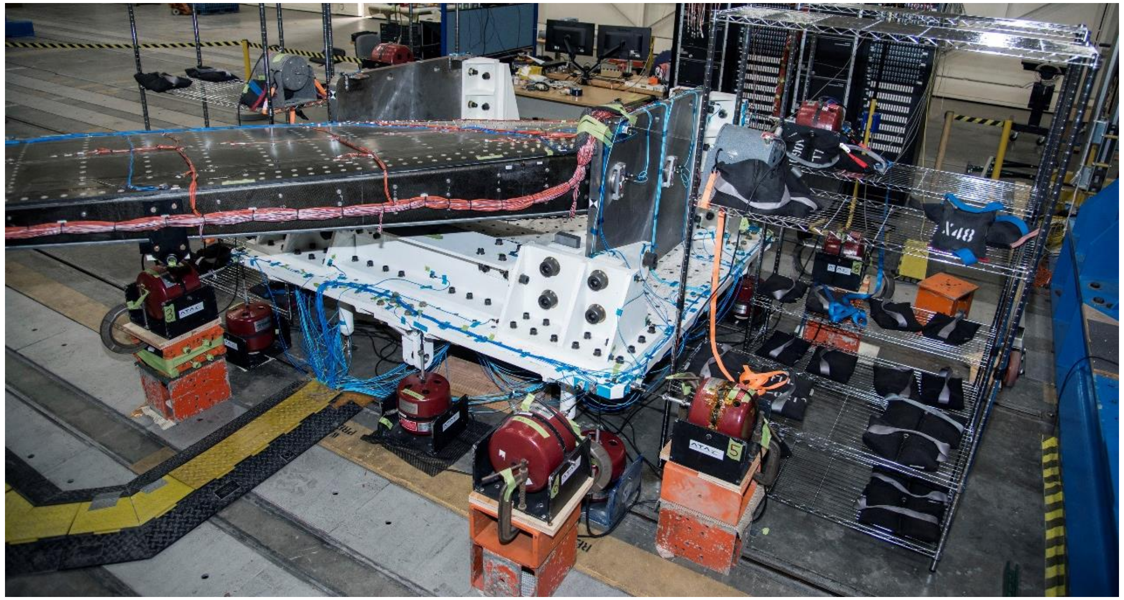
PAT Wing GVT - Goal, Objective & Success Criteria

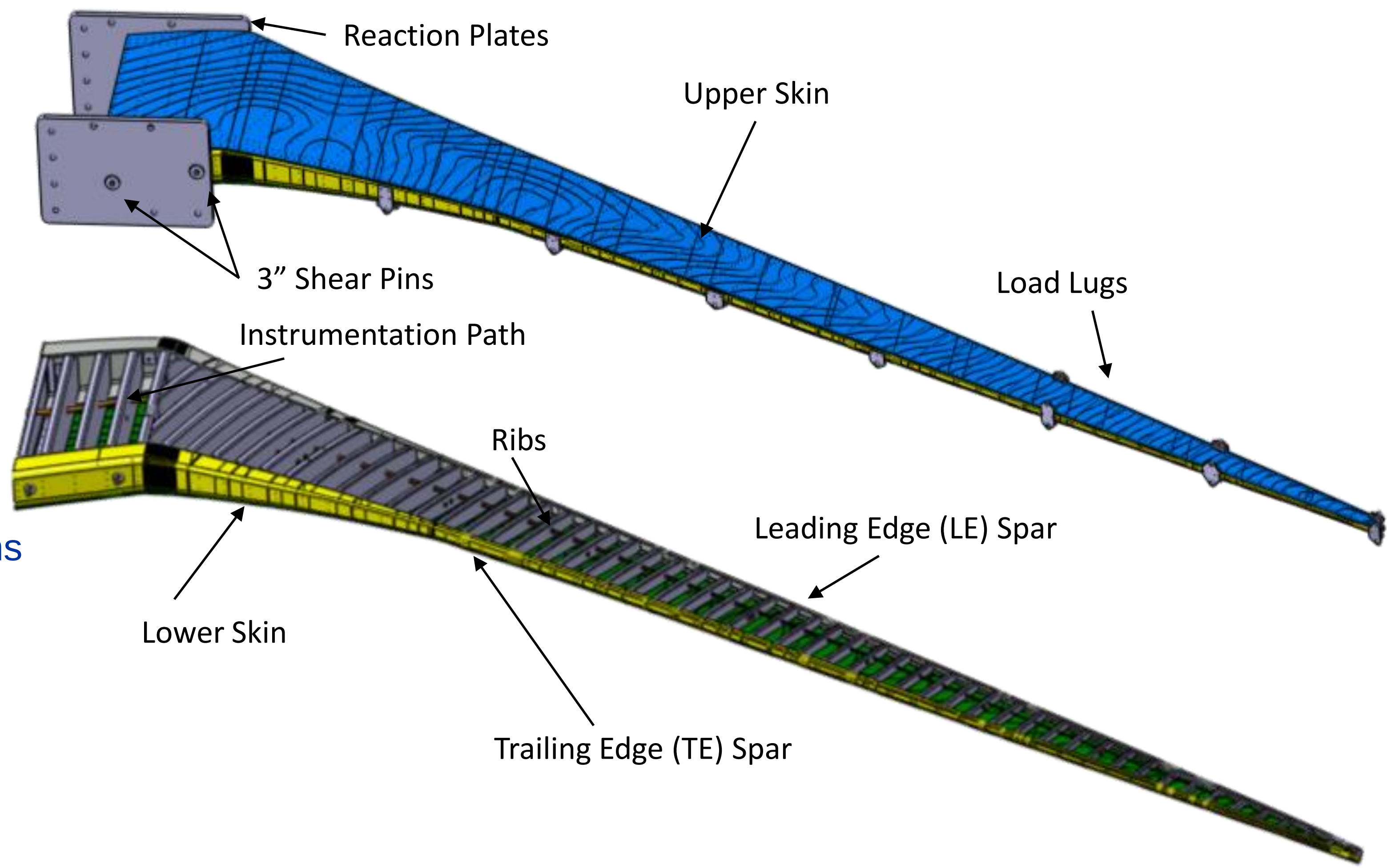
- Passive Aeroelastic Tailored (PAT) Wing Ground Vibration Test (GVT) was tested July 10-12th, 2018 in NASA Armstrong's Flight Loads Laboratory (FLL)
- Goal: Obtain PAT Wing modal characteristics from the GVT to compare test results with analytical models
- Objective: Measure the primary frequencies, mode shapes & damping (frequencies up to wing torsion mode, ≈ 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)



PAT Wing – Test Article Description

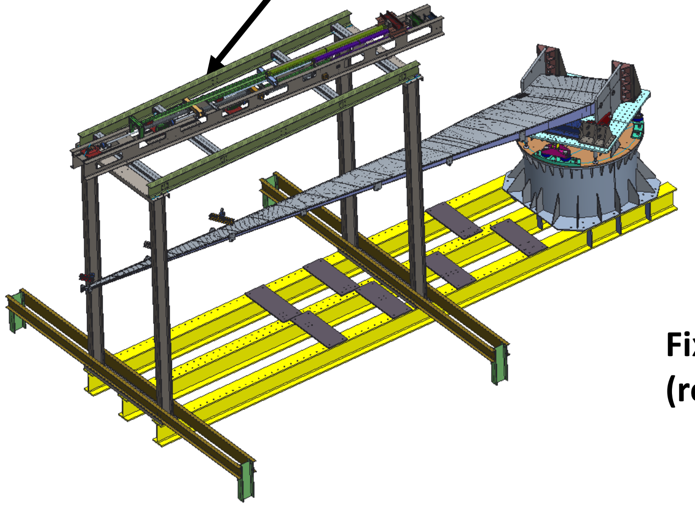
- Graphite-epoxy wingbox
  - Wingbox of 27% scale of uCRM
  - Right wing w/ high aspect ratio (13.5)
  - Root LE to tip TE: ≈ 39ft
  - Wing sweep 36.8°
  - Design & manufactured by Aurora
- 2 Spars, composite with 58 ribs
  - Outboard LE spar replaced with Aluminum (≈12 ft)
- 2 Skins
  - Tow-steered technology in wingskins
- 2 Reaction plates
  - 4 Reaction pins
- 14 Load lugs
  - 7 load lugs spanwise on LE & TE
  - Permanent fixtures



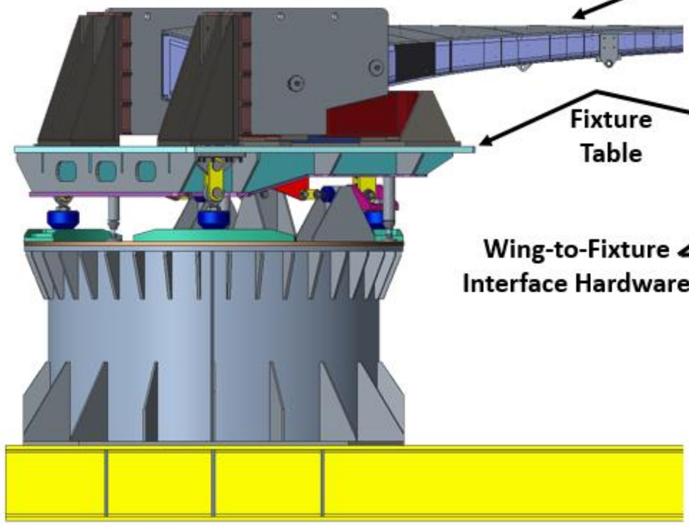
Test Setup – GVT Test Setup, Original Plan

- 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

Overhead Loading Structure



Wing Loads Test Fixture (WLTF)

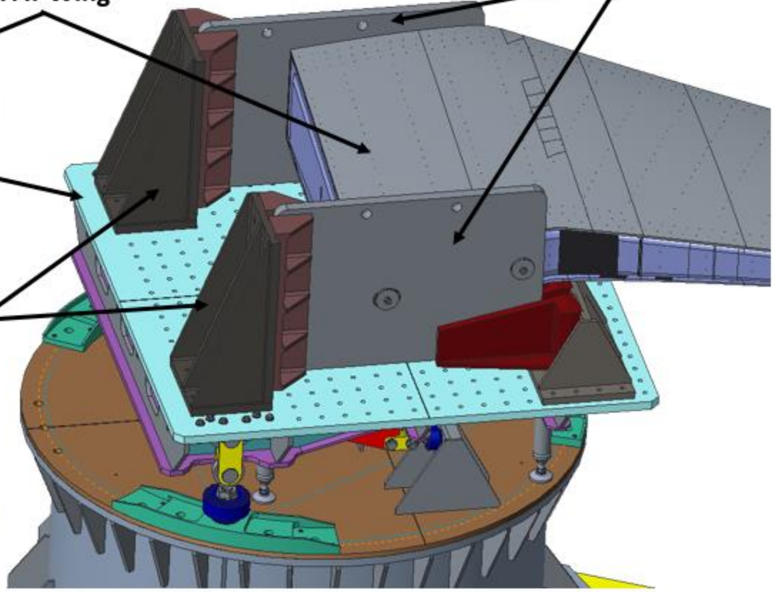


PAT Wing

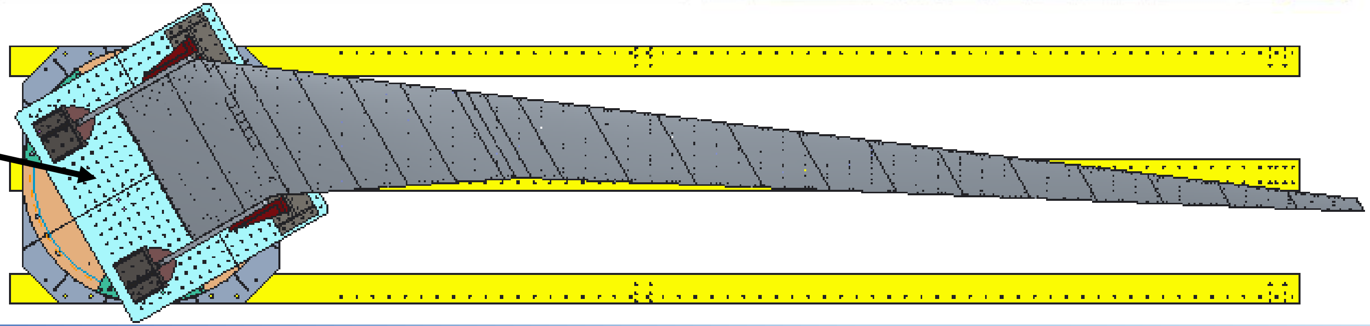
Fixture Table

Wing-to-Fixture Interface Hardware

PAT Wing Reaction Plates

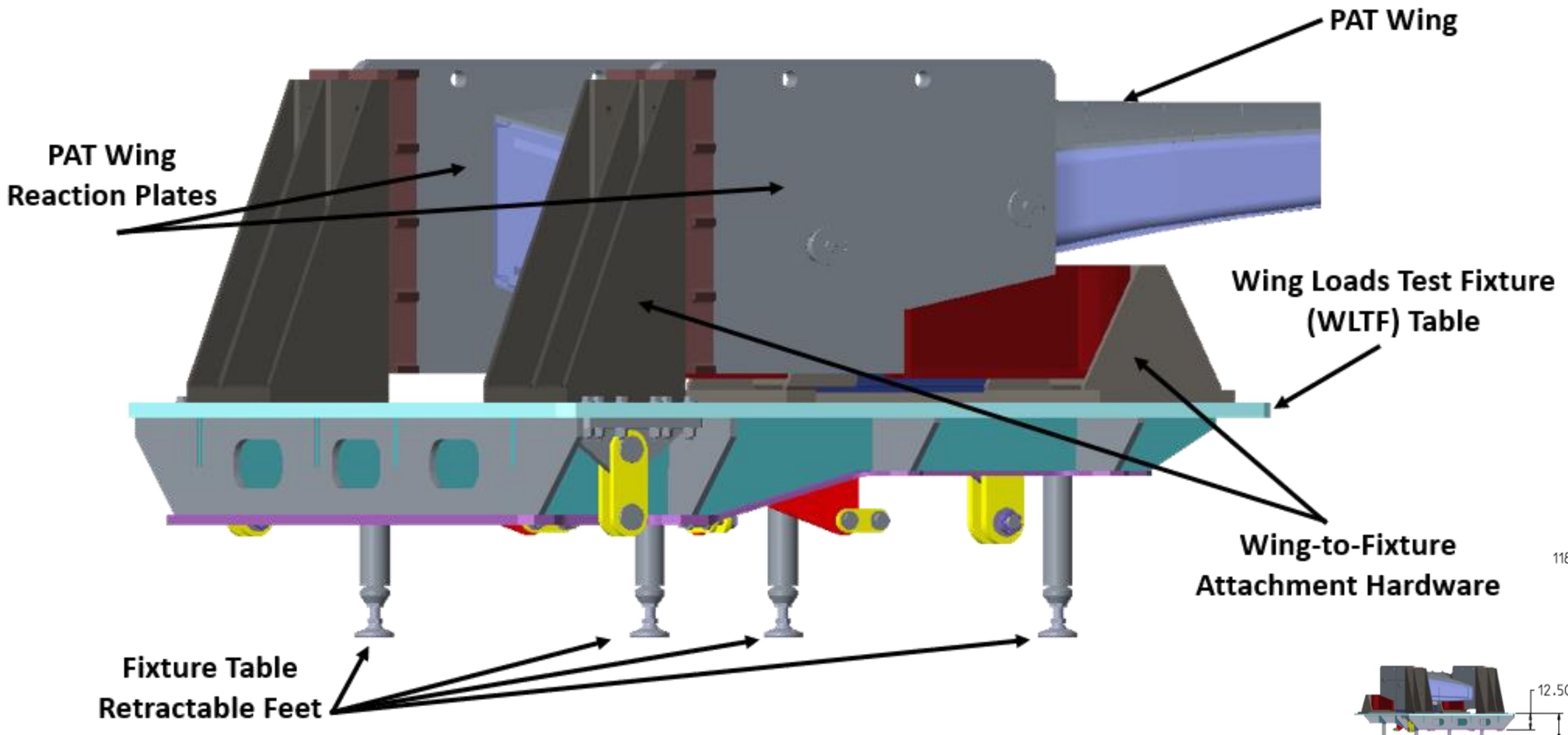


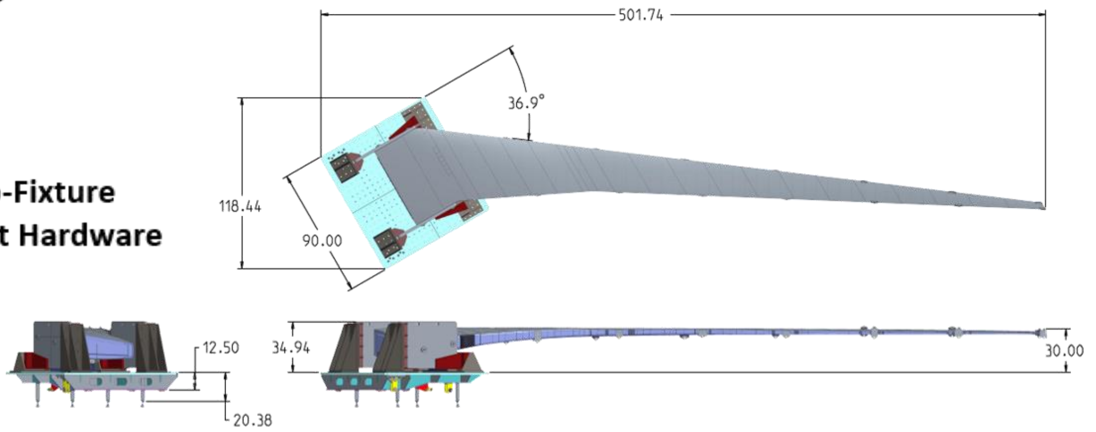
Fixture Table (rotated 30°)



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

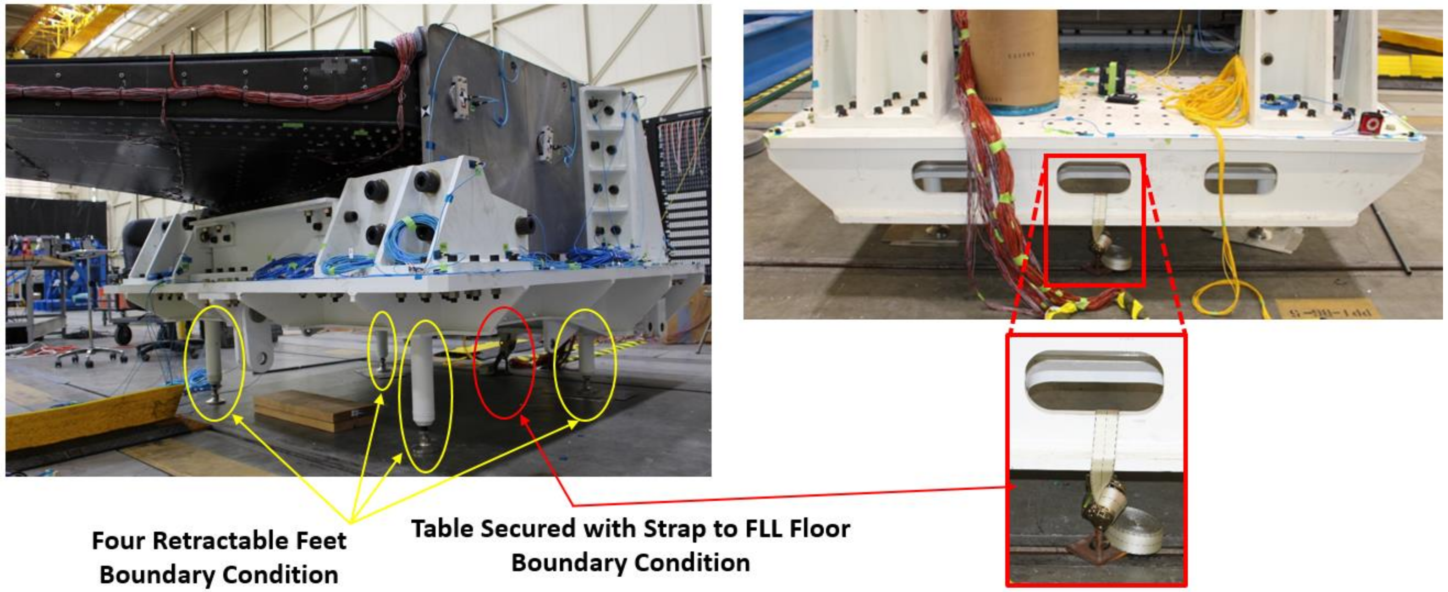




Test Setup – GVT Boundary Conditions with Table on Floor

- 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)



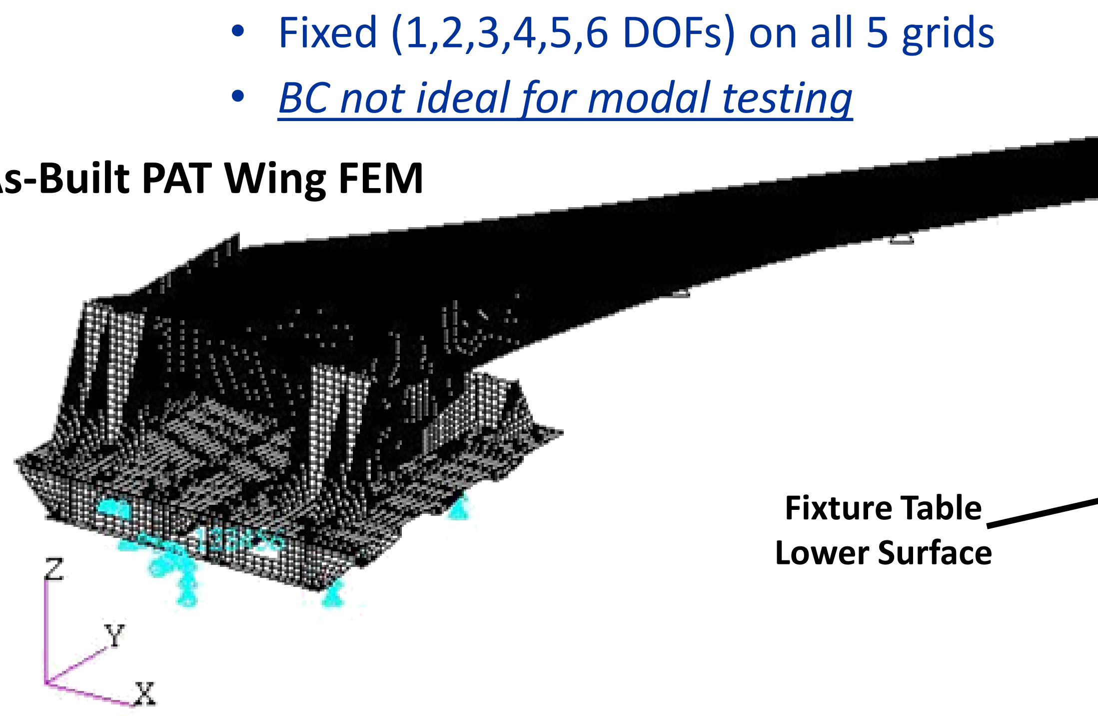
Four Retractable Feet Boundary Condition

Table Secured with Strap to FLL Floor Boundary Condition

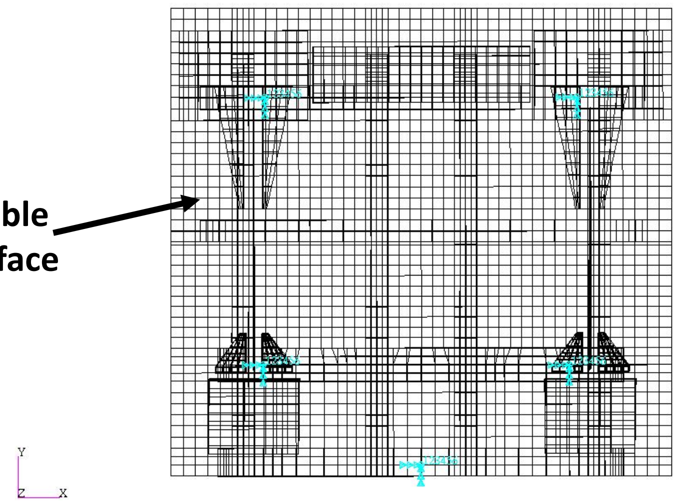
Test Setup – FEM with GVT Boundary Conditions

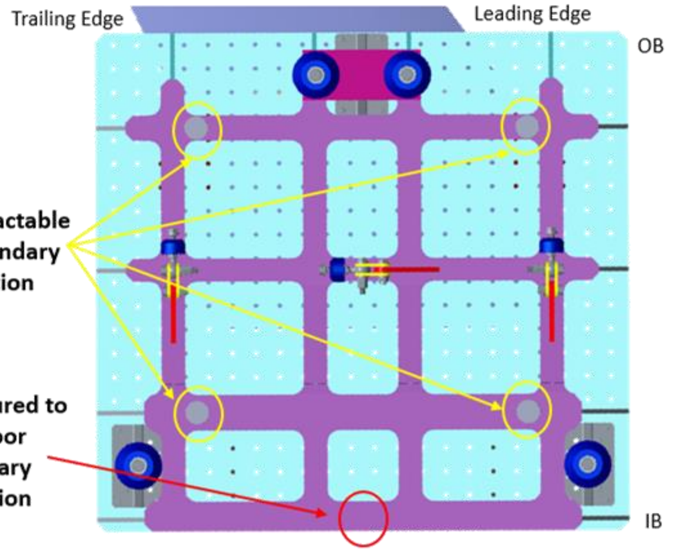
- Prior to GVT, Aurora updated NASA's FEM to incorporate differences of the as-built wing that may impact structural response
  - FEM includes the WLTF table & attachment hardware
  - LaRC updated FEM to include boundary conditions with the table of the FLL floor
    - Fixed (1,2,3,4,5,6 DOFs) on all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

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

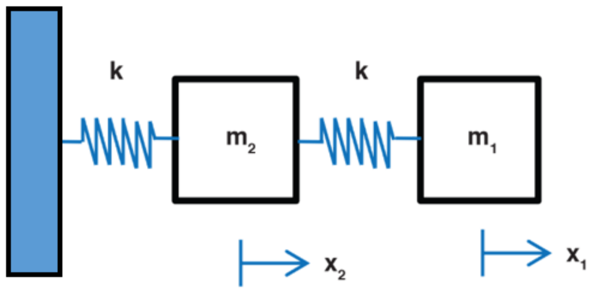
$$a_1 = \begin{bmatrix} \dfrac{-\omega^2(-\omega^2 m_2 + 2k)}{(-\omega^2 m_2 + 2k)(-\omega^2 m_1 + k) - k^2} & \dfrac{-\omega^2 k}{(-\omega^2 m_2 + 2k)(-\omega^2 m_1 + k) - k^2} \end{bmatrix} \begin{Bmatrix} f_1 \\ f_2 \end{Bmatrix}$$

- 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

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

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)

PCB T333B32 Uniaxial Accel

PCB T356A16 Triaxial Accel

PCB 393B04 Seismic Uniaxial Accel

Dytran Impact Hammer

MB Modal 110 Shaker

Brüel & Kjær LAN-XI DAQ

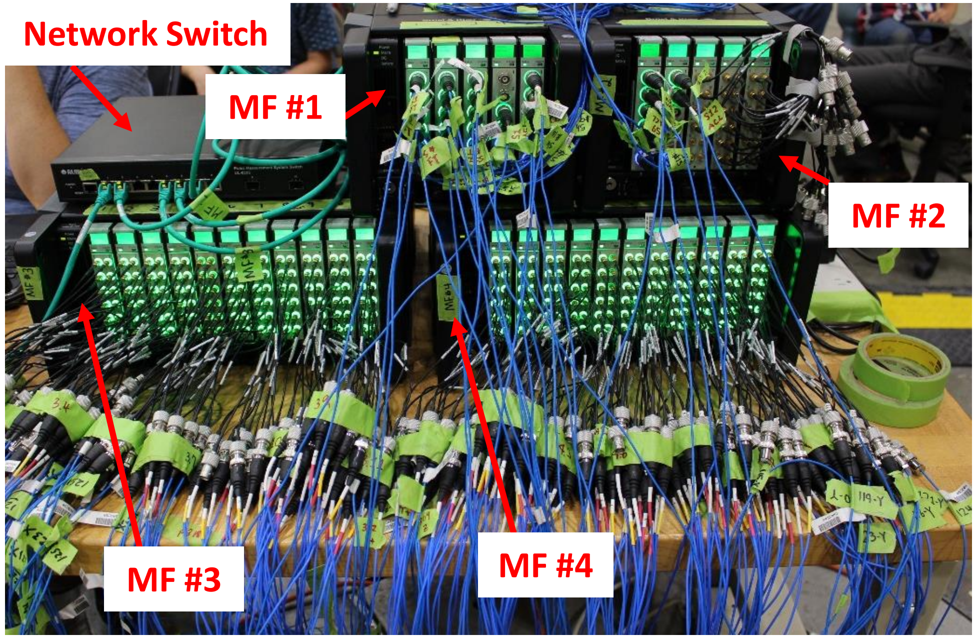
LAN-XI 3160 & 3053 Modules

Note: Some GVT hardware was provided by Contractor

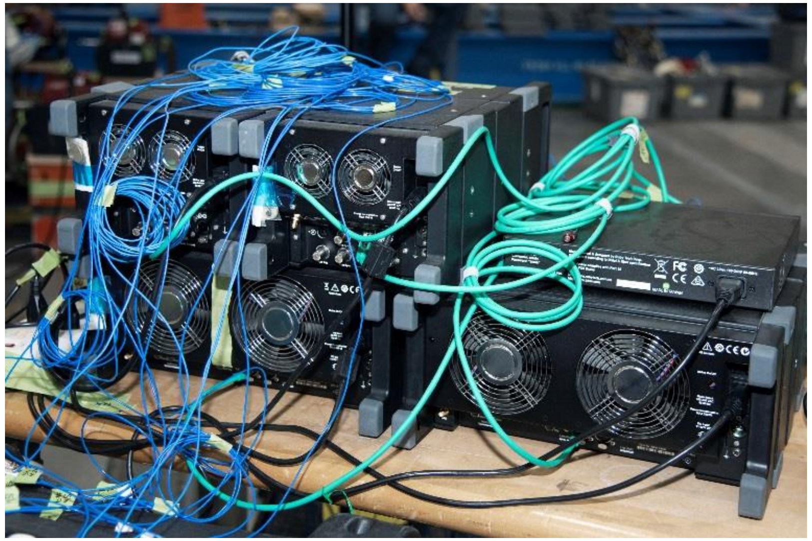
Test Setup – LAN-XI DAQ

- 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)



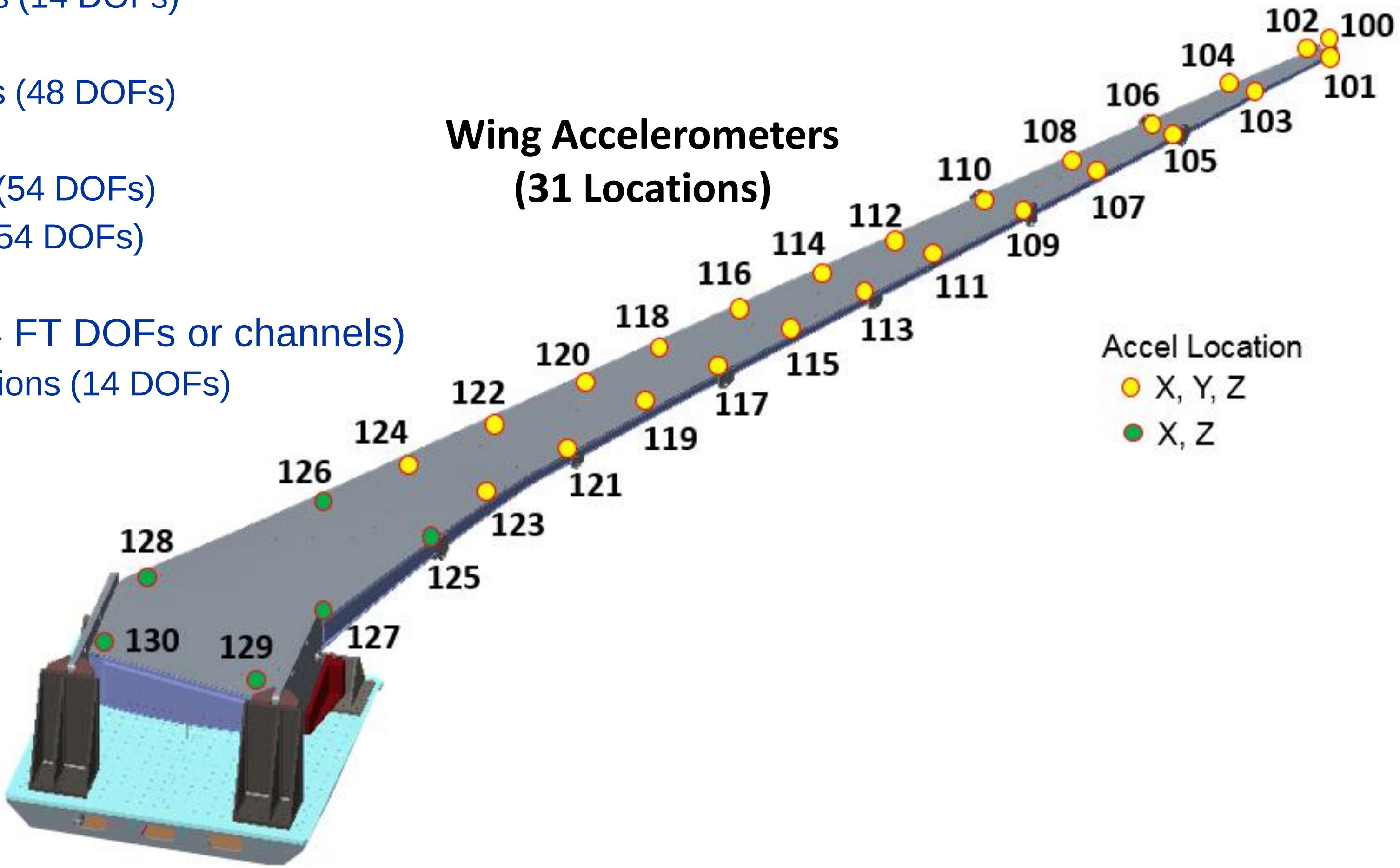
Note: Some LAN-XI source modules were provided by Contractor

Test Setup – Accelerometer Layout

- 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)

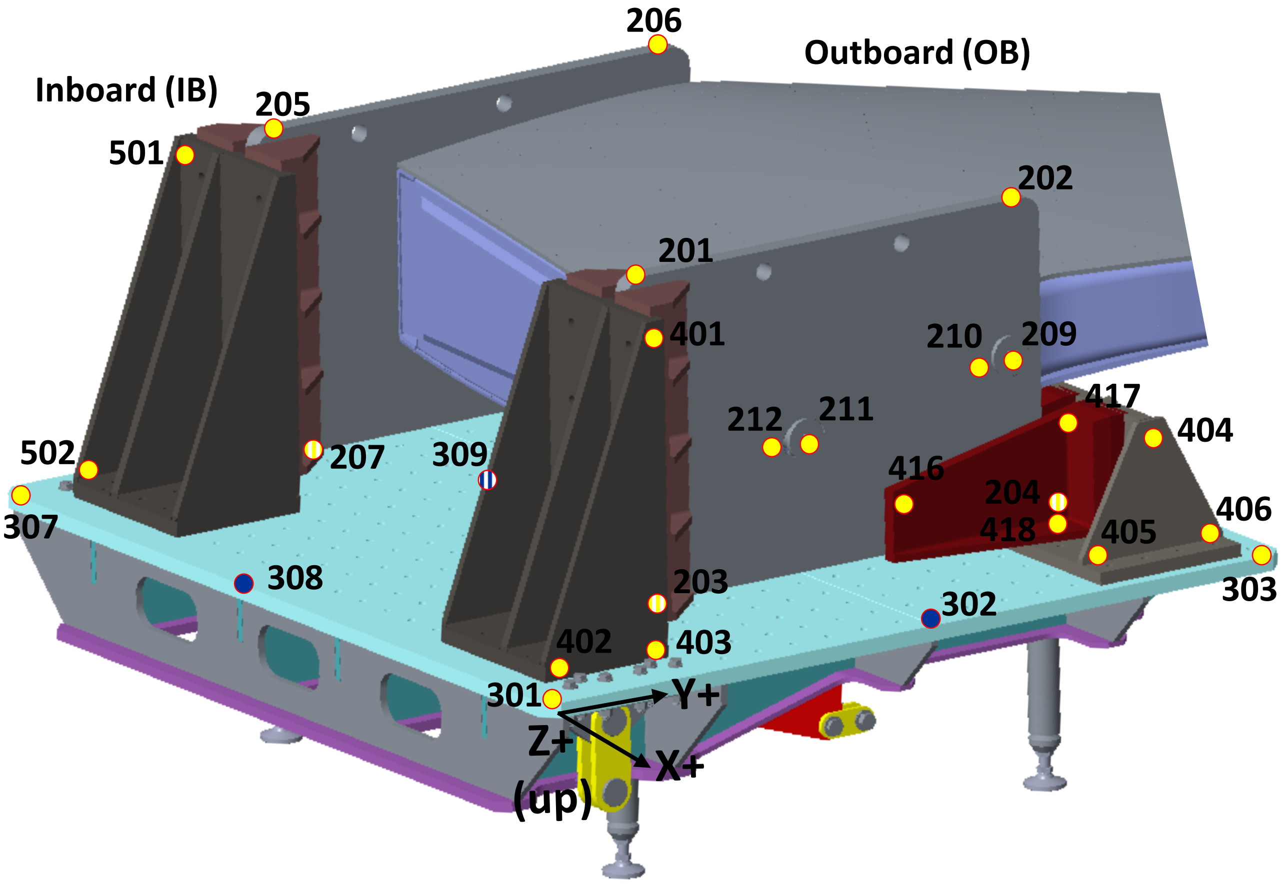
- Node Numbering
  - Reference Accels & Shakers – 00 series
  - Wing – 100 series
  - Wing Reaction Plates & Pins – 200 series
  - Fixture Table – 300 series
  - Attachment Hardware (TE) – 400 series
  - Attachment Hardware (LE) – 500 series

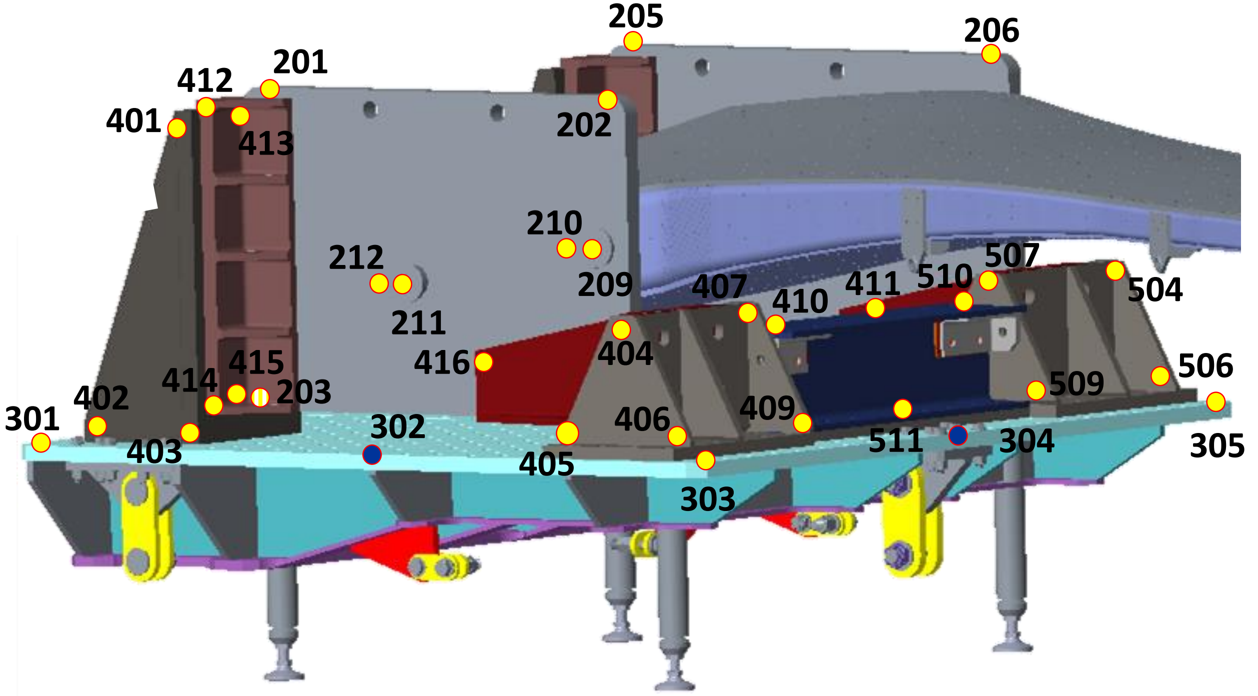


Test Setup – Accelerometer Layout

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

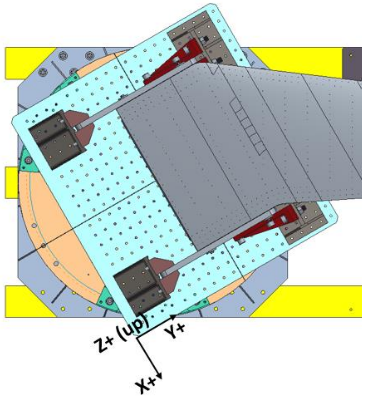
Accel Directions
- X, Y, Z
- X, Z
- Z



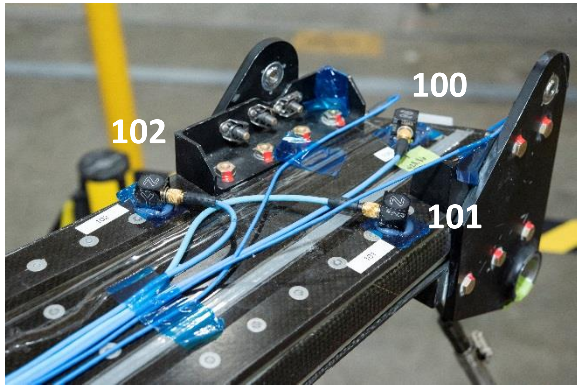


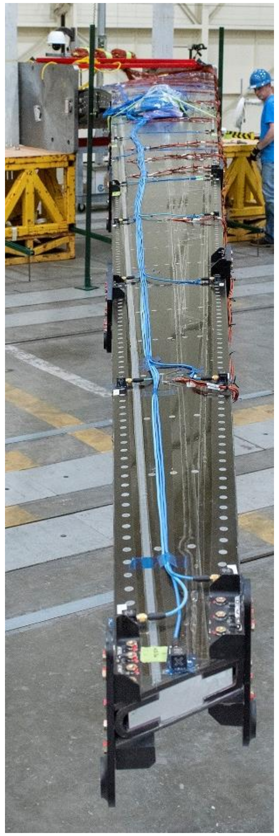
Test Setup – Accel Wing Photos

- 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

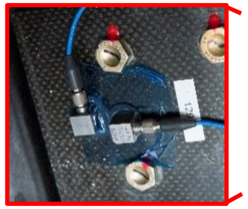


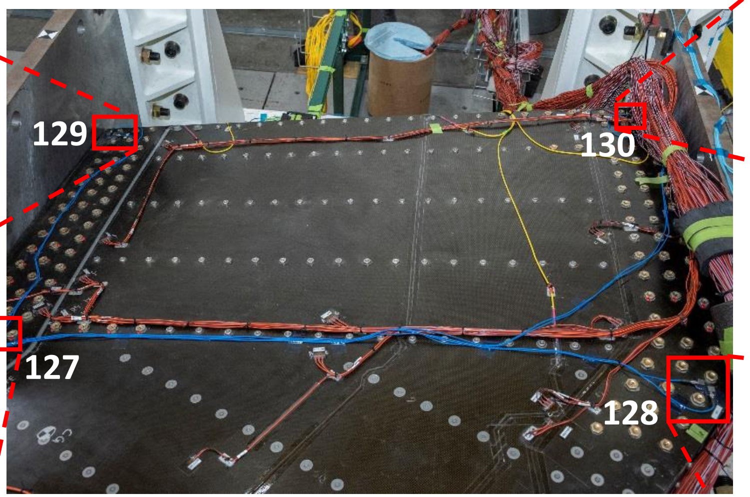
Wingtip Triaxial Accels



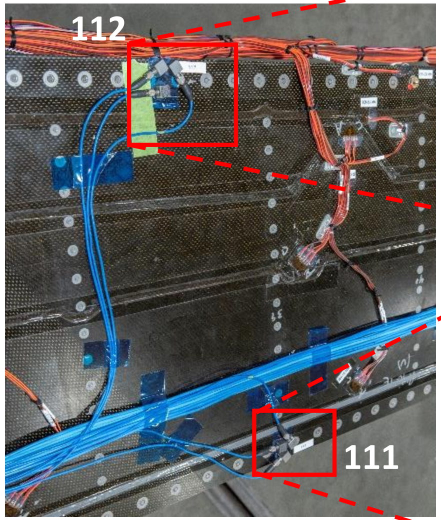


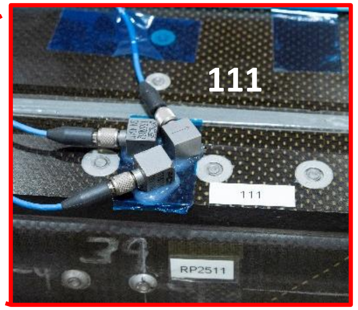
Wing Root only X & Z Accels





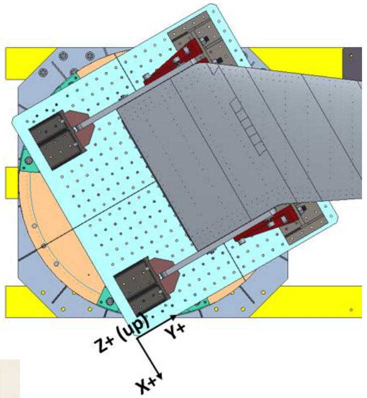
Built up Triaxial Accel



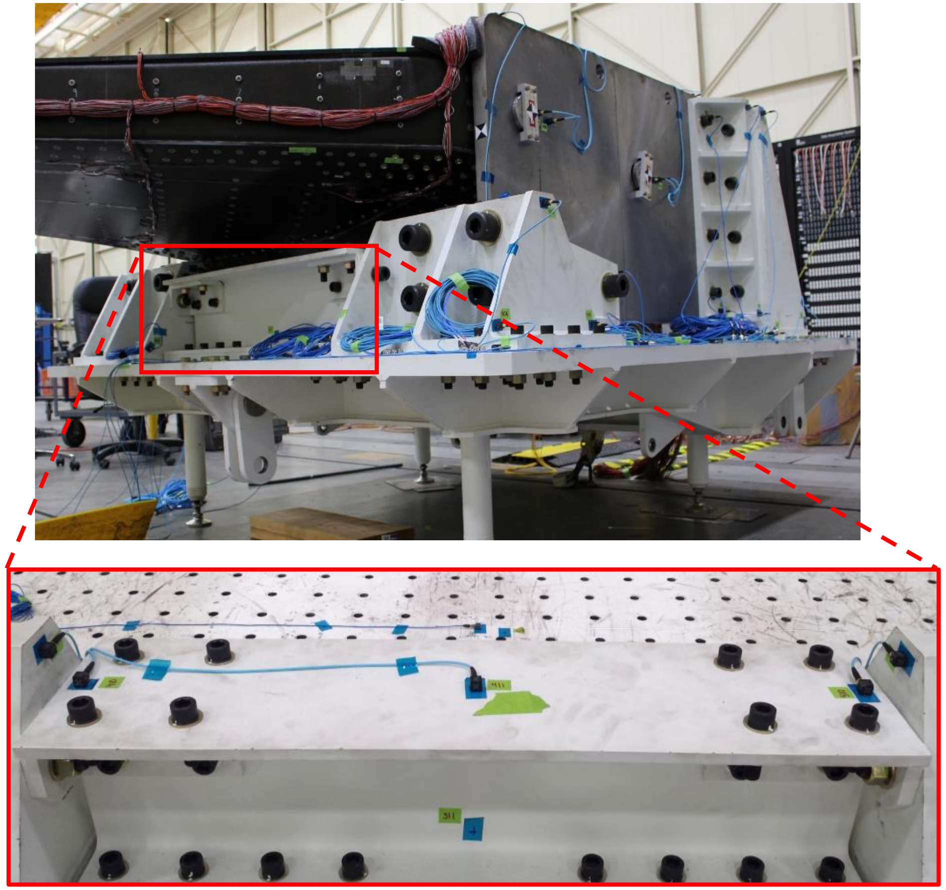


Test Setup – Accel Attachment Hardware Photos

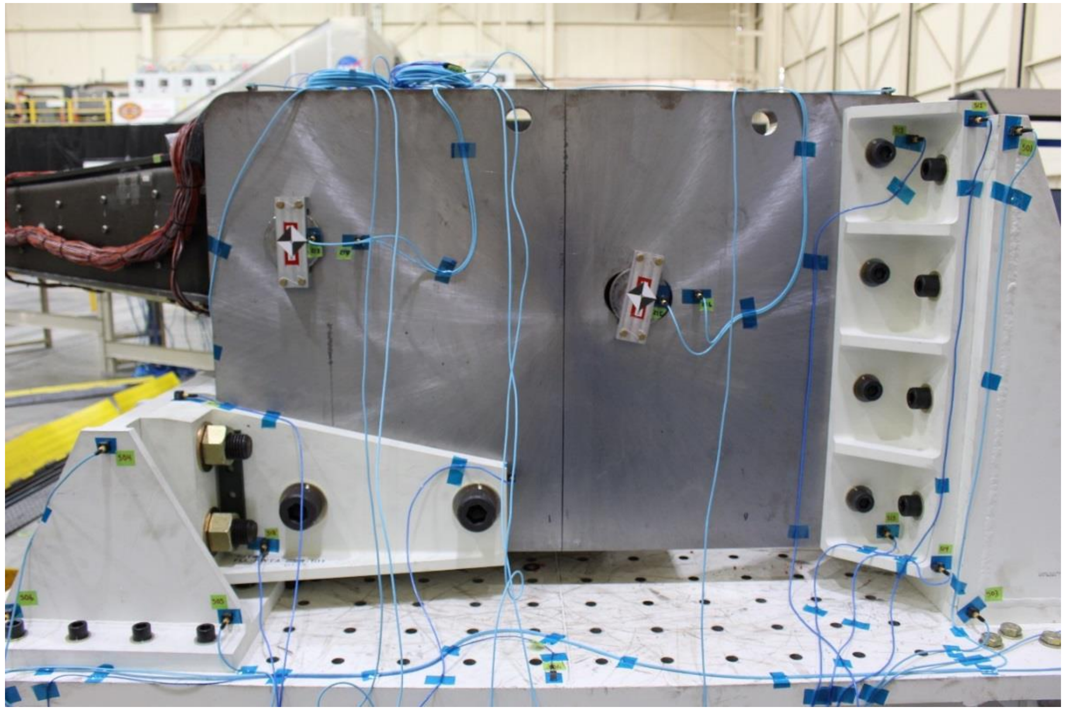
- Some attachment hardware accels were installed before wing was installed on WLTF table



Triaxial Accels Mainly on Attachment Hardware



Attachment Hardware Accels – Leading Edge side



Test Setup – Shaker Force Transducer & Accel Photos

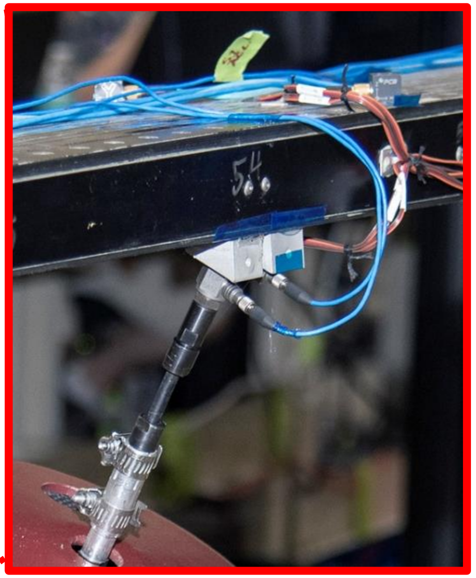
- Wingtip shaker - Force Transducers & Accels (100 mV/g)
- “Fixed” shakers on Table & Attachment Hardware - Force Transducers & Seismic Accels (1000 mV/g)

“Fixed” Shaker Locations

Seismic Accels

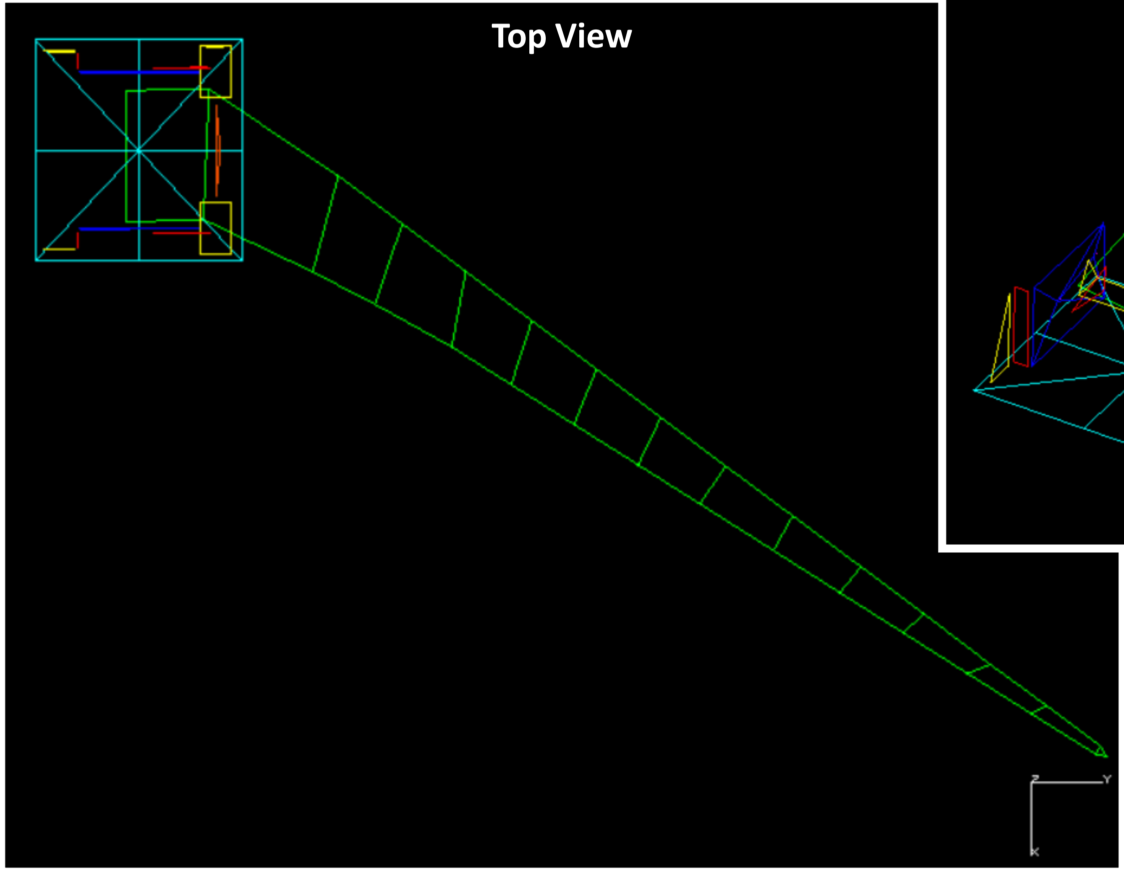
Wingtip Shaker

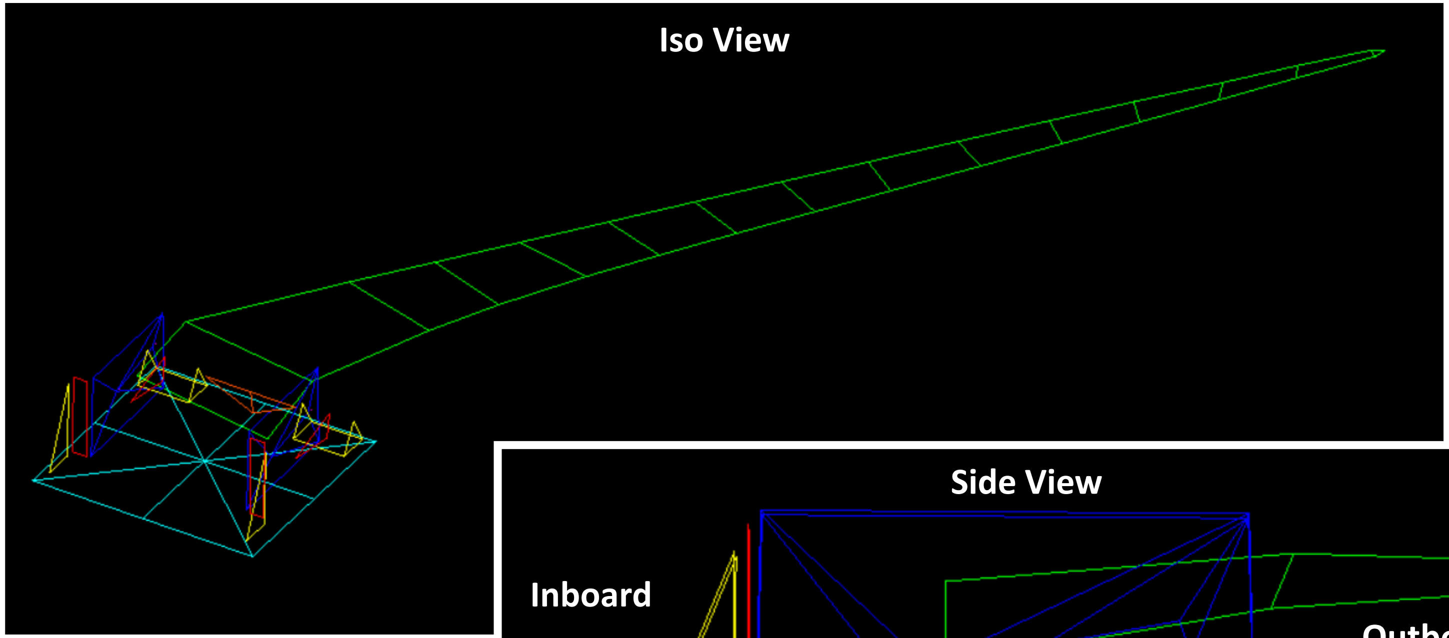
Normal Accel

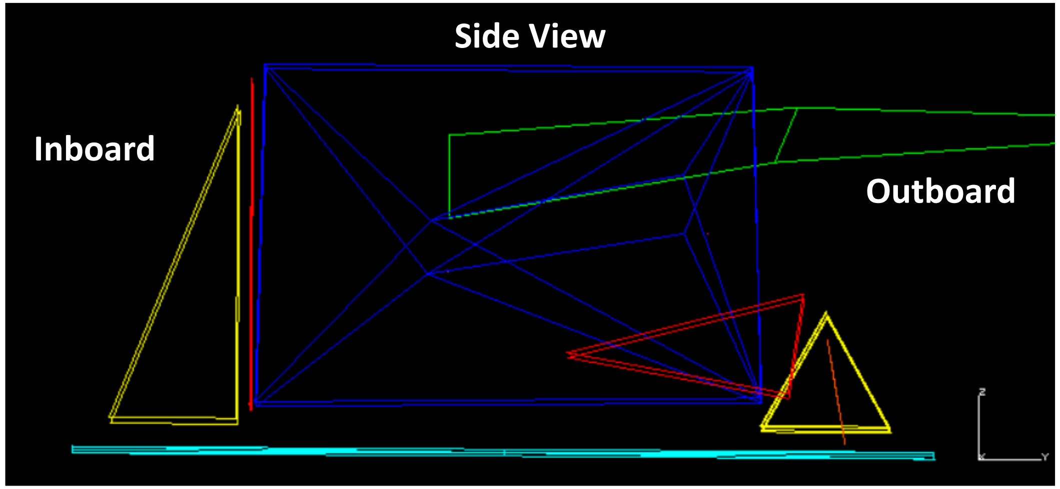


Test Setup – Test Display Model (TDM)

PAT Wing GVT Test Display Model (TDM)







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

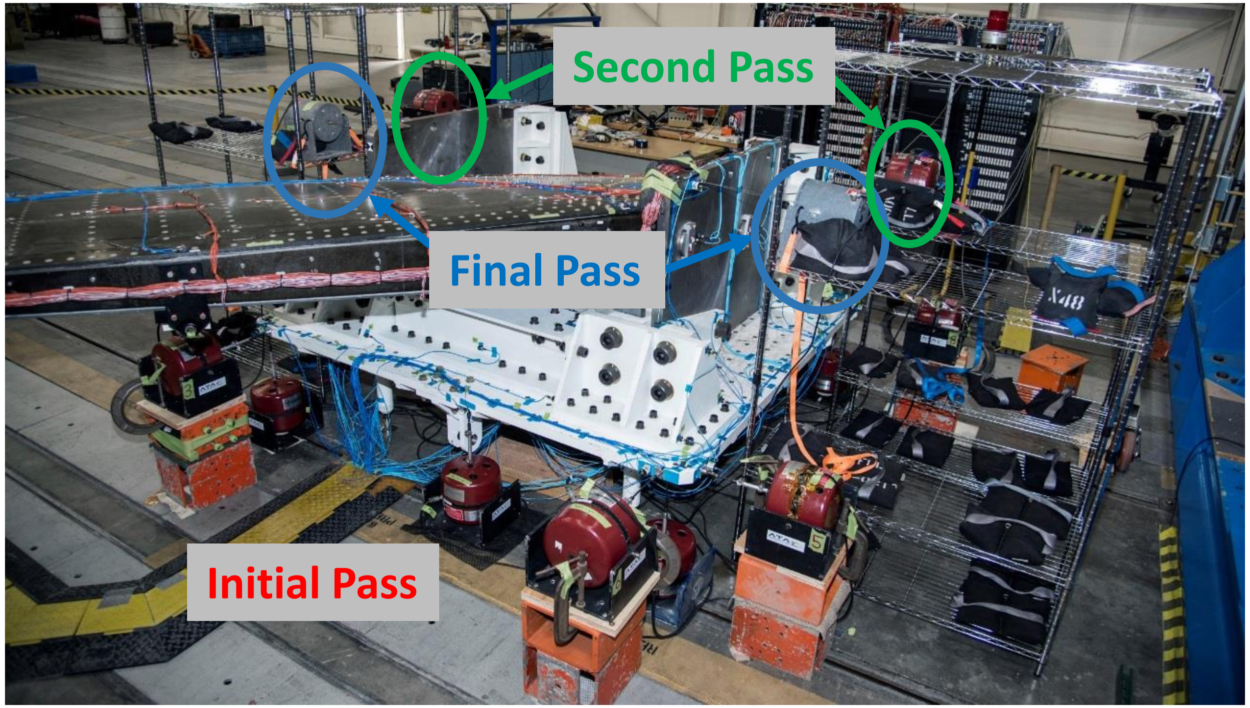
Wingtip Shaker

"Fixed" WLTF Shaker Locations

GVT Shaker Layout - Fixed Base Correction Method

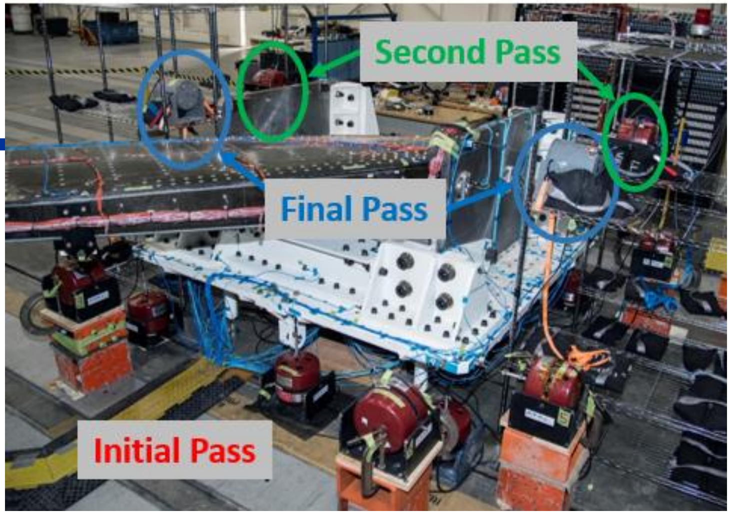
- Shaker configurations for FBC method – kept adding additional shakers to improve the fixed base modes
  - Config. 1 (Initial Pass): 10 shakers – 9 on fixture table, 1 on wingtip
  - Config. 2 (Second Pass): 12 shakers – Added 2 on aft triangular brackets (lateral)
  - Config. 3 (Final Pass): 14 shakers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

PAT Wing GVT - Shaker Configurations



PAT Wing GVT Shaker Layouts

PAT Wing GVT - Shaker Configurations



- Shaker configurations for FBC method
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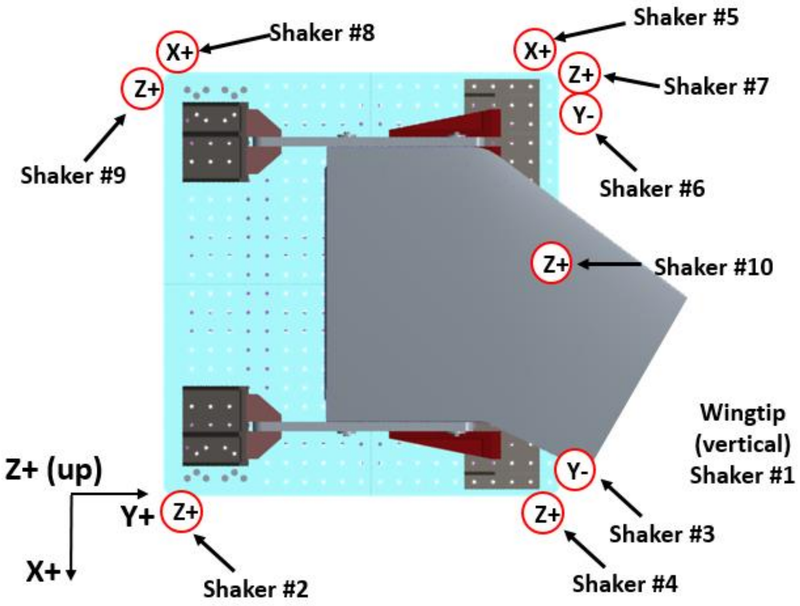
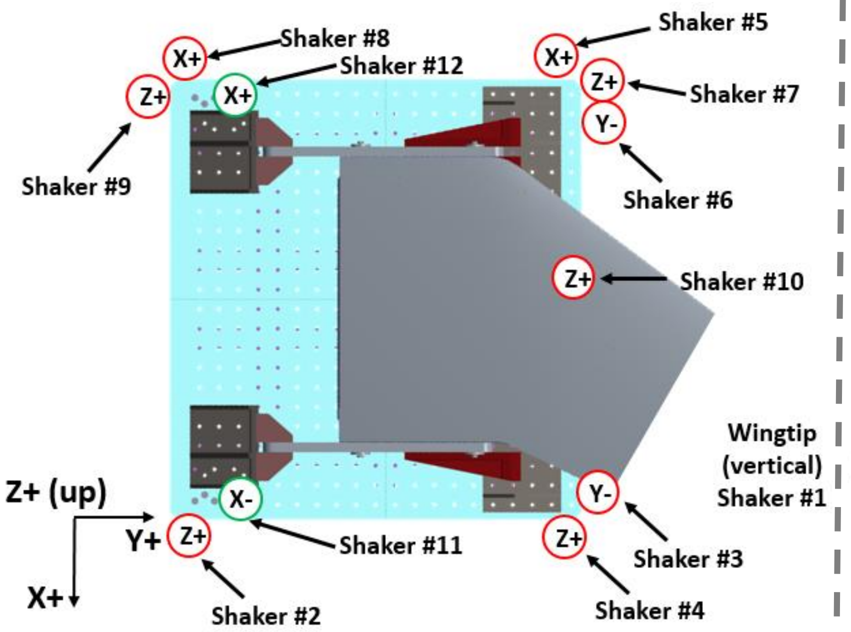
  - Config. 3 (Final Pass): 14 shakers – Added 2 on wing root reaction plates (lateral)

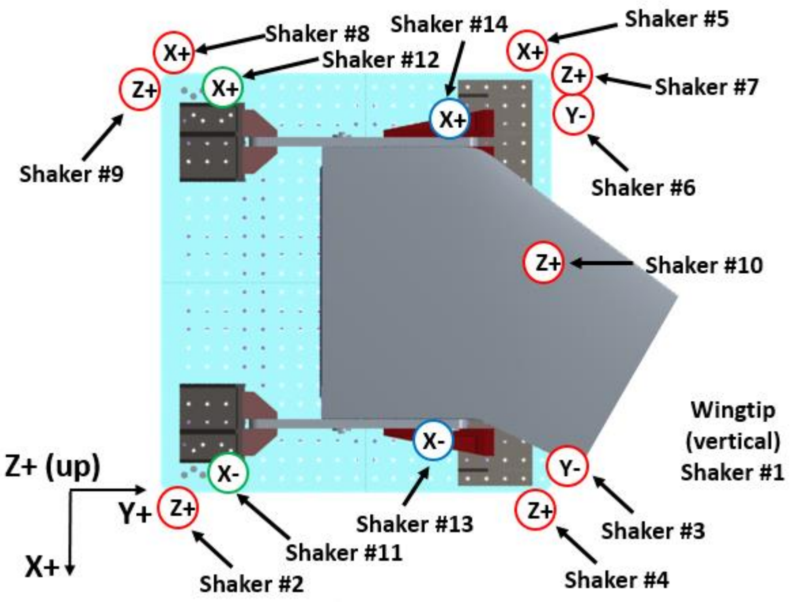
Config. 1 (Initial Pass): 10 Shakers



Config. 2 (Second Pass): 12 Shakers

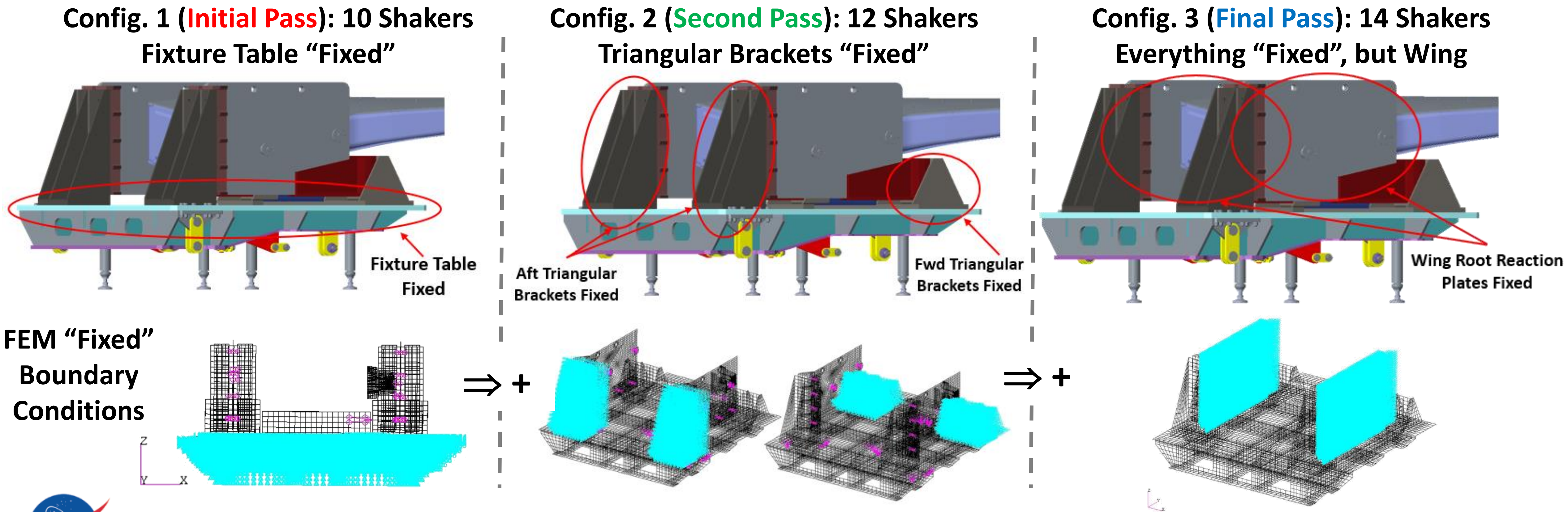


Config. 3 (Final Pass): 14 Shakers



PAT Wing GVT Shaker Layouts & FEM Boundary Conditions

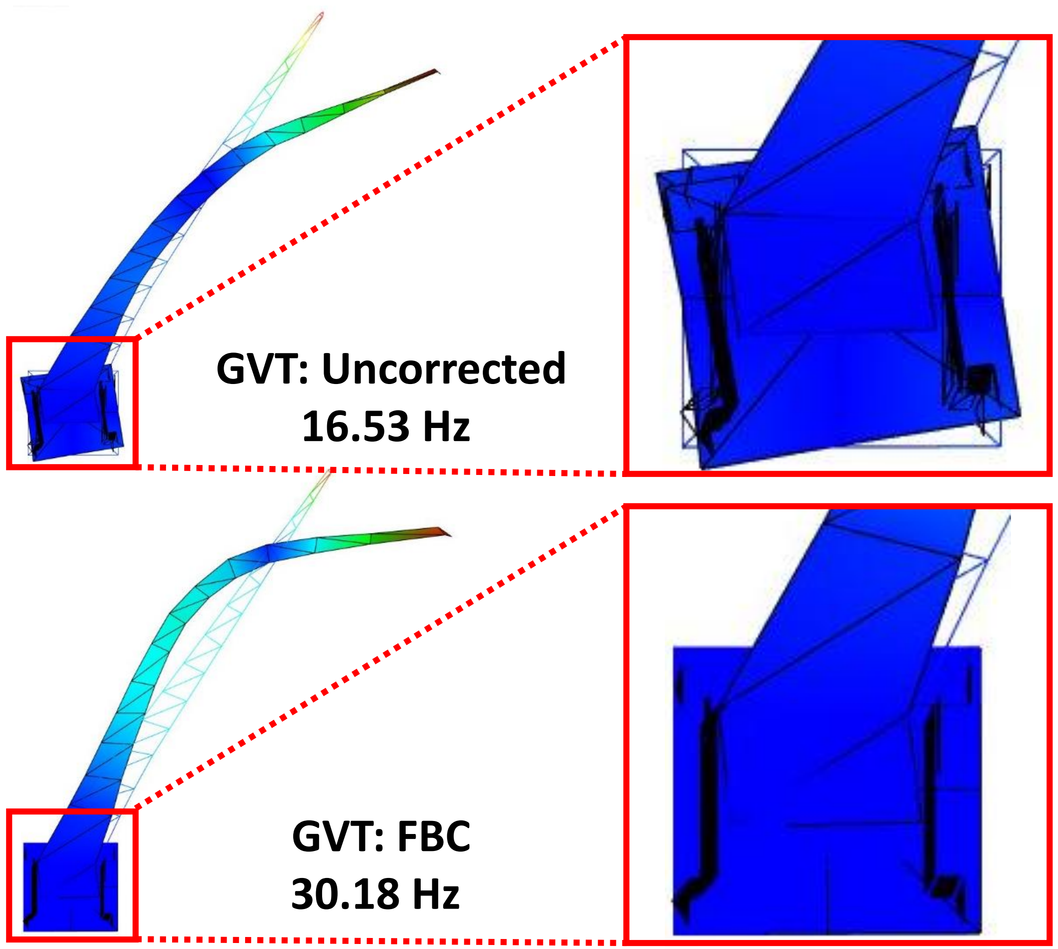
- FEM "Fixed" boundary conditions were applied to all nodes on related hardware
  - Config. 1 (Initial Pass): 10 shakers – 9 on fixture table, 1 on wingtip
  - Config. 2 (Second Pass): 12 shakers – Added 2 on aft triangular brackets (lateral)
  - Config. 3 (Final Pass): 14 shakers – Added 2 on wing root 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

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



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)
Cross MAC GVT vs. FEM

FEM/Test Cross MAC Table

		FEM Shapes								Test	Test
		1	2	3	4	5	6	7	8	CRSS	CRSS
Test Shapes		3.39	10.45	11.35	22.64	31.98	37.46	51.94	55.54	3%	All
1	3.48	99	29							99	100
2	10.05	31	98		40					99	100
3	11.02			97		26				98	100
4	21.22		35		99		41			99	100
5	30.15			41		96				98	100
6	35.23				31		96		20	98	100
7	52.20						20	62	29	79	100
8	56.67							42	57	75	100
CRSS	3%	99	99	98	99	98	98	79	75		
CRSS	All	100	100	100	100	99	99	100	99		

14 Shaker Test Combined Results
GVT: Fixed Base Correction vs. FEM

Test Mode No.	FEM Mode No.	Test Freq (Hz)	FEM Freq (Hz)	Freq % Diff	Test Mode Description
1	1	3.48	3.39	-2.4	1st Wing Bending
2	2	10.05	10.45	4.0	2nd Wing Bending
3	3	11.02	11.35	3.0	1st Wing Fore/Aft
4	4	21.22	22.64	6.7	3rd Wing Bending
5	5	30.15	31.98	6.1	2nd Wing Fore/Aft
6	6	35.23	37.46	6.3	4th Wing Bending
7	7	52.20	51.94	-0.5	5th Wing Bending (FEM: 1st wing Torsion)
8	8	56.67	55.54	-2.0	1st Wing Torsion (FEM: 5th Wing Bending)

Note: Modes switch order when corrected

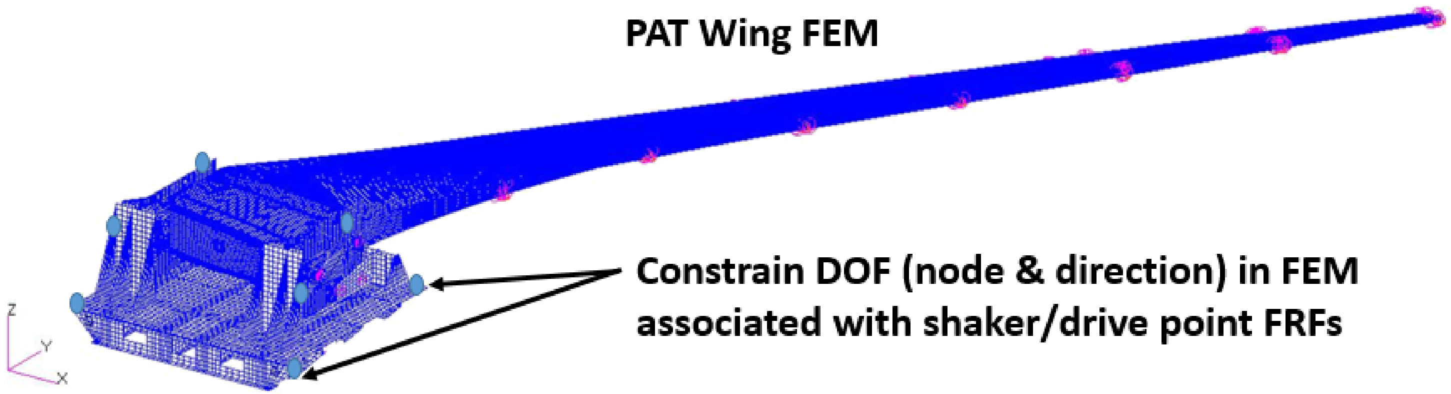
Note: FEM assumes everything but wing is fixed

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