Modal Testing of a Flexible Wing On a Dynamically Active Test Fixture Using the Fixed Base Correction Method

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CReW GVT Test - Outline

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CReW GVT using Fixed Base Correction Method

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
  - To simplify future modal tests, FBC method was investigated during the CReW modal testing with wing cantilevered from a static test fixture
  - Promising results - method produced similar wing modal characteristics with two different BC configurations

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.
  - 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 the 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

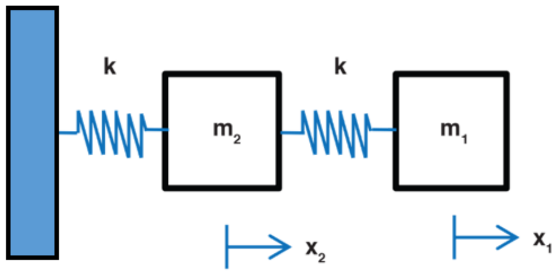
$$a_1 = \begin{bmatrix} \dfrac{-\omega^2(-\omega^2 m_2 + 2k)}{(-\omega^2 m_2 + 2k)(-\omega^2 m_1 + k) - k^2} & \dfrac{-\omega^2 k}{(-\omega^2 m_2 + 2k)(-\omega^2 m_1 + k) - k^2} \end{bmatrix} \begin{Bmatrix} f_1 \\ f_2 \end{Bmatrix}$$

- 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
- 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
  - Use shaker accelerations as references rather than traditional shaker forces when calculating FRFs

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

CReW GVT - Goal, Objective & Success Criteria

- Calibration Research Wing (CReW) Ground Vibration Test (GVT) was tested June 19-22nd, 2017 in NASA Armstrong's Flight Loads Laboratory (FLL)
- Goal: Obtain CReW modal characteristics from the GVT to evaluate the FBC method for future testing
- Objective: Measure primary frequencies, mode shapes & damping using traditional accelerometers with the CReW installed on the Wing Loads Test Fixture (WLTF) table using the FBC method
- Success Criteria: Accurately obtaining the CReW primary frequencies & shape modes (de-coupled the wing from the WLTF table modes) using the FBC method

CReW GVT (June 2017)

CReW GVT – Test Article Description

- Calibration Research Wing (CReW) test article
  - Composite, full-scale, half-span flexible wing
  - Length ≈ 32 ft
  - Weight ≈ 450 lb

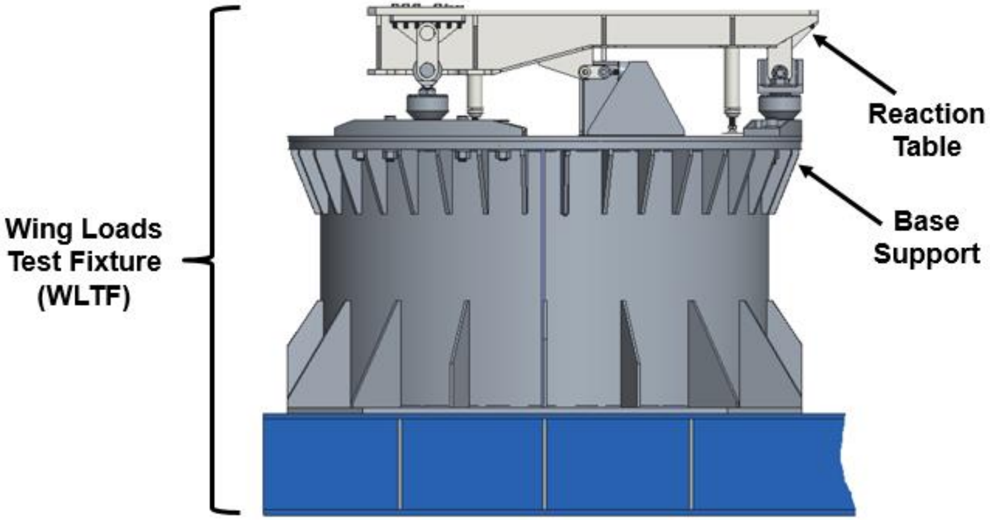
- CReW similar span size as Passive Aeroelastic Tailored (PAT) Wing
  - PAT Wing
    - Towed-steered graphite epoxy, high aspect ratio, semi-span (≈ 39ft) wing box
    - Designed & built for NASA by Aurora Flight Sciences

Calibration Research Wing (CReW)

CReW GVT – Test Setup

- CReW GVT mounted to the WLTF was a pathfinder test for the PAT wing to evaluate the FBC method
- WLTF consists of base support & reaction table
- Reaction table supported by base support with 7 single axis load cells & 4 retractable feet

Wing Loads Test Fixture (WLTF)
Dynamically Active Static Test Fixture

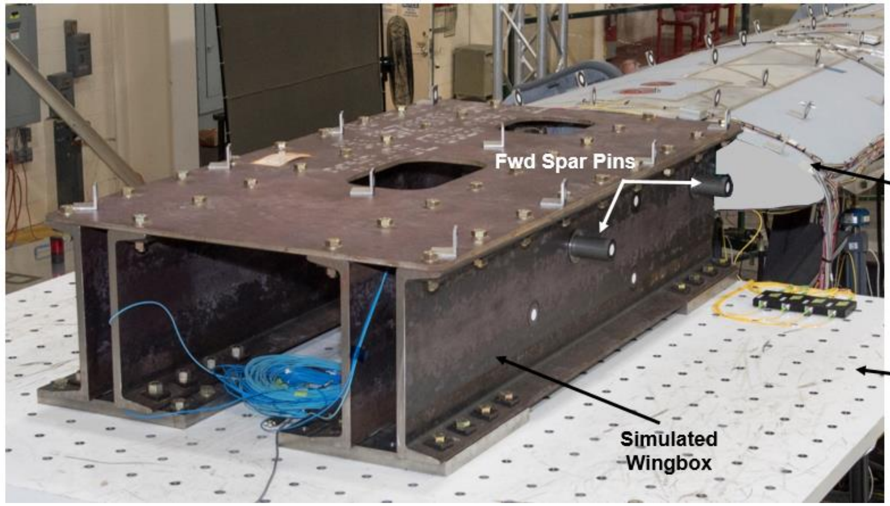


WLTF Reaction Table Supported with
4 Retractable Feet & 7 Load Cells

CReW GVT – Test Setup

- Wing root was cantilevered from the reaction table with aircraft pins to secure the wing spars to a simulated wingbox connected to the reaction table
- Wingtip ≈ 6.5 ft above the lab floor which complicated some of the setup

Wing Root Secured To Reaction Table



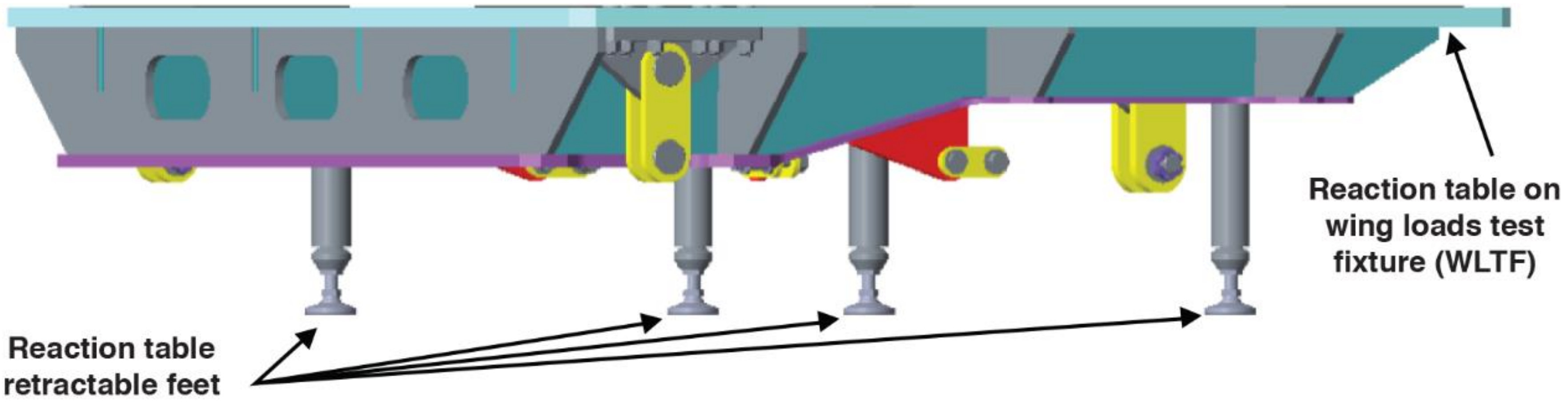
Crew GVT Setup

CReW GVT – Test Configurations

- CReW GVT had two test configurations with 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

Different Reaction Table Boundary Conditions
Retractable Feet Up & Feet Down



CReW GVT – Instrumentation

- 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 configured for CReW GVT, capable of recording 188 channels
      - Mainframes
        - LAN-XI 11-slot Main frame, 2 qty
      - Modules
        - LAN-XI 4ch input + 2ch output 3160 source modules, 5 qty
          - Capable of running 10 shakers
          - Capable of recording 20 channels
        - LAN-XI 12-channel 3053 input modules, 14 qty
          - Capable of recording 168 channels
  - GVT Software:
    - Ideas Test (acquired time histories)
    - IMAT (all test related analysis & FBC analysis)

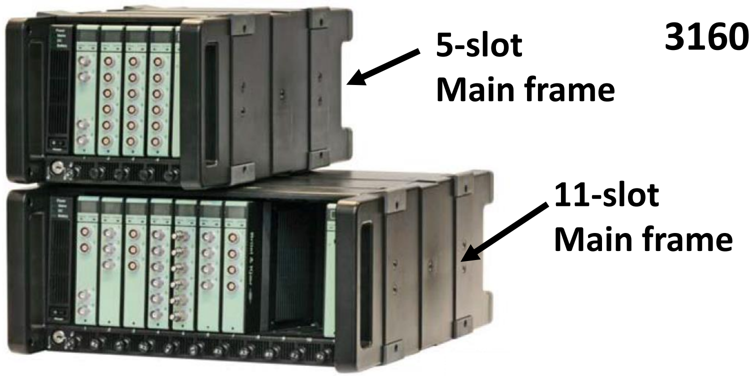
PCB T333B32 Uniaxial Accel

PCB T356A16 Triaxial Accel

PCB 393B04 Seismic Uniaxial Accel

MB Modal 110 Shaker

Brüel & Kjær LAN-XI DAQ



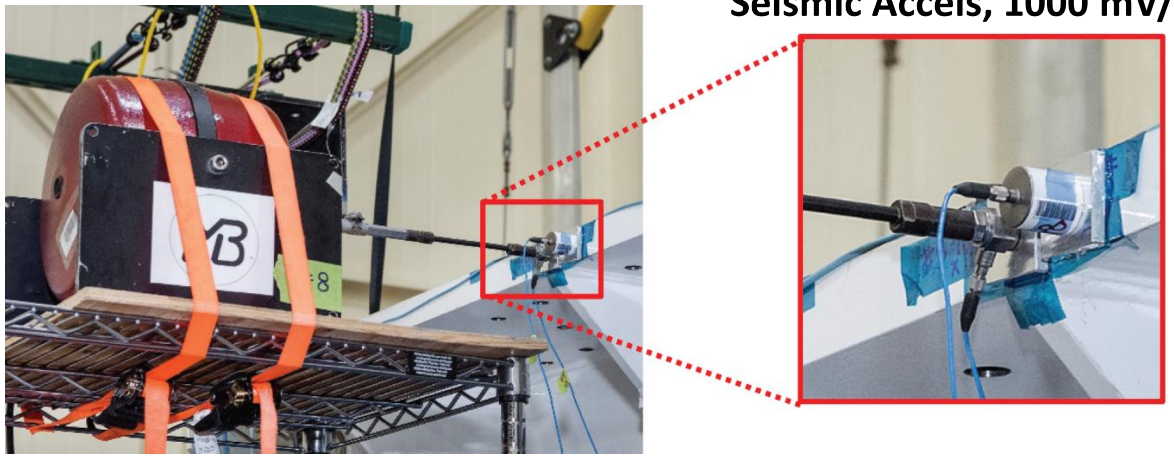
LAN-XI 3160 & 3053 Modules

CReW GVT – Instrumentation

- FBC method desires seismic accelerometers with higher sensitivity (1000 mV/g) at each shaker location in the direction of the hardware being fixed, so shaker accelerometer data could be as clean as possible to calculate the FRF
- Wingtip shaker did not require a seismic accelerometer because the force was used as a reference when calculating the FRF

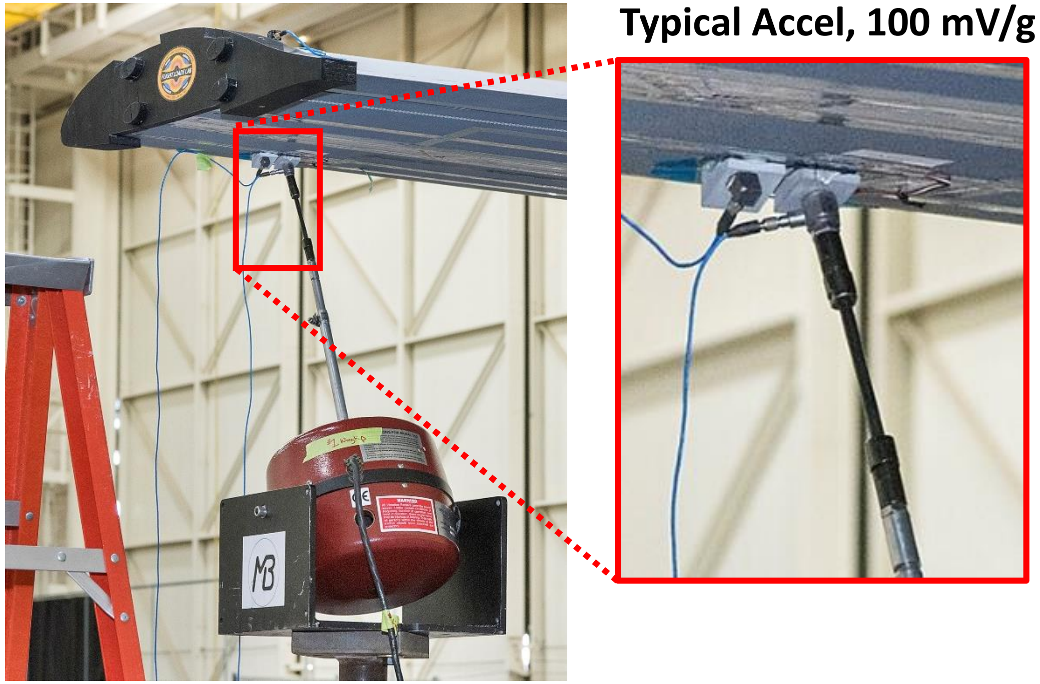
“Fixed” Shaker Locations

Seismic Accels, 1000 mV/g



Wingtip Shaker

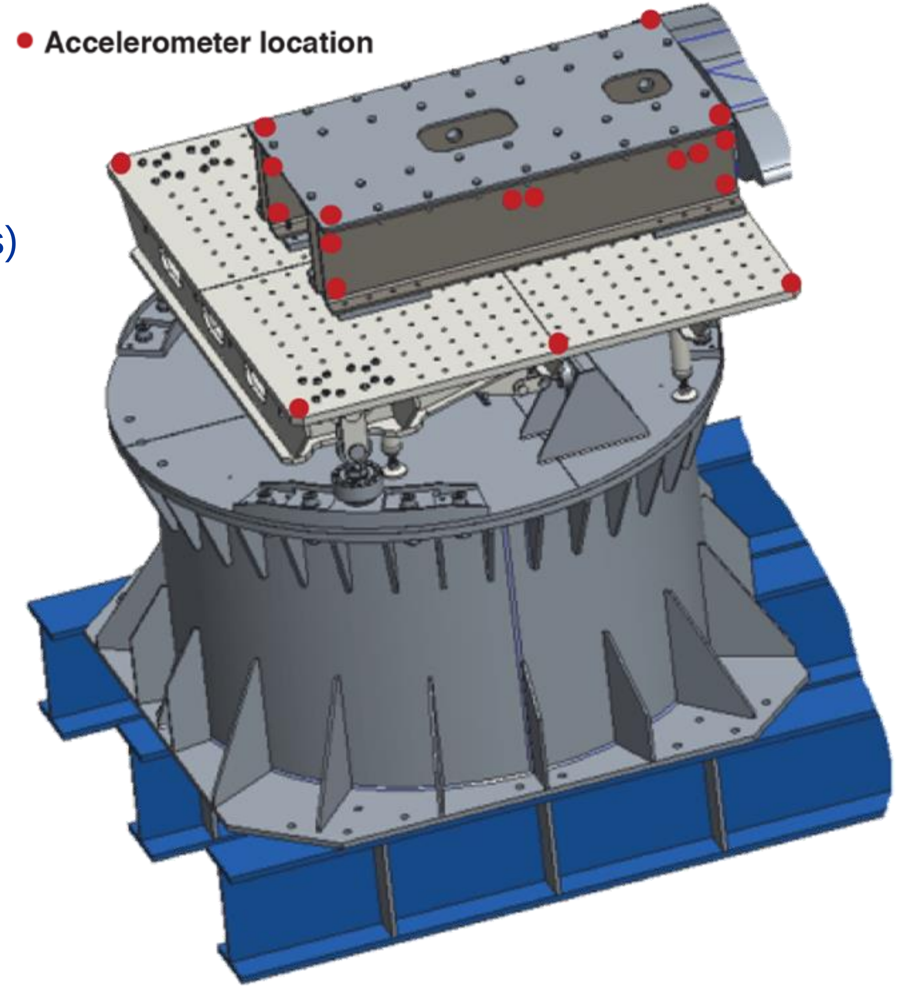
Typical Accel, 100 mV/g



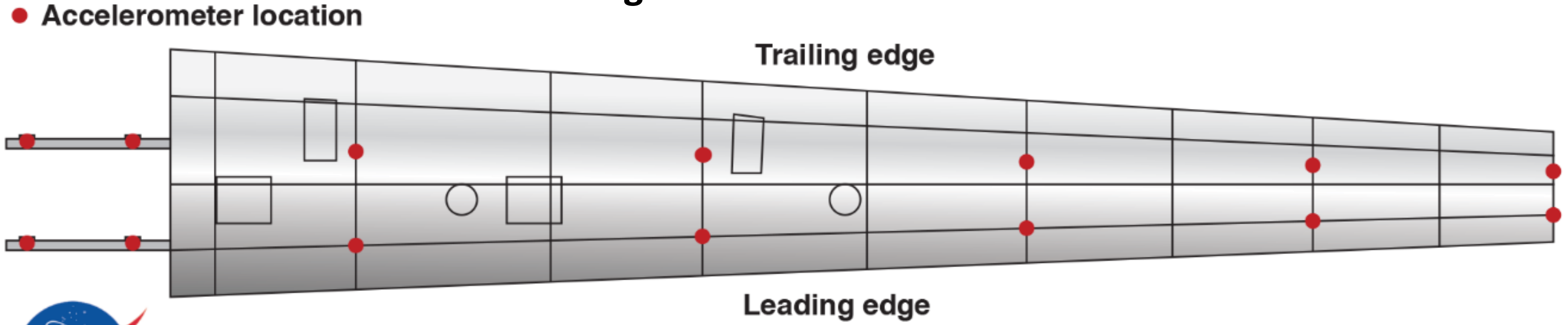
CReW GVT – Accelerometer Layout

- CReW GVT included accels on the wing like traditional modal testing, but implementing the FBC method also required numerous accels on the WLTF reaction table & the simulated wingbox hardware connected to the reaction table
- Total of 41 accel locations for measuring 117 DOF responses to acquire desired mode shapes of wing & test fixture needed to implement the FBC technique
  - Wing & wing spars ⇒ 14 accel locations, triaxial accels (measured 42 DOFs)
  - WLTF reaction table & simulated wingbox hardware ⇒ 27 accel locations, majority triaxial accels (measured 75 DOFs)
- Data acquisition system measured 137 channels for testing
  - 117 accel measured as responses
  - 10 shaker force transducers measured as references
  - 10 shaker seismic accels measured as responses & later used as references for FBC method

WLTF Accelerometer Locations



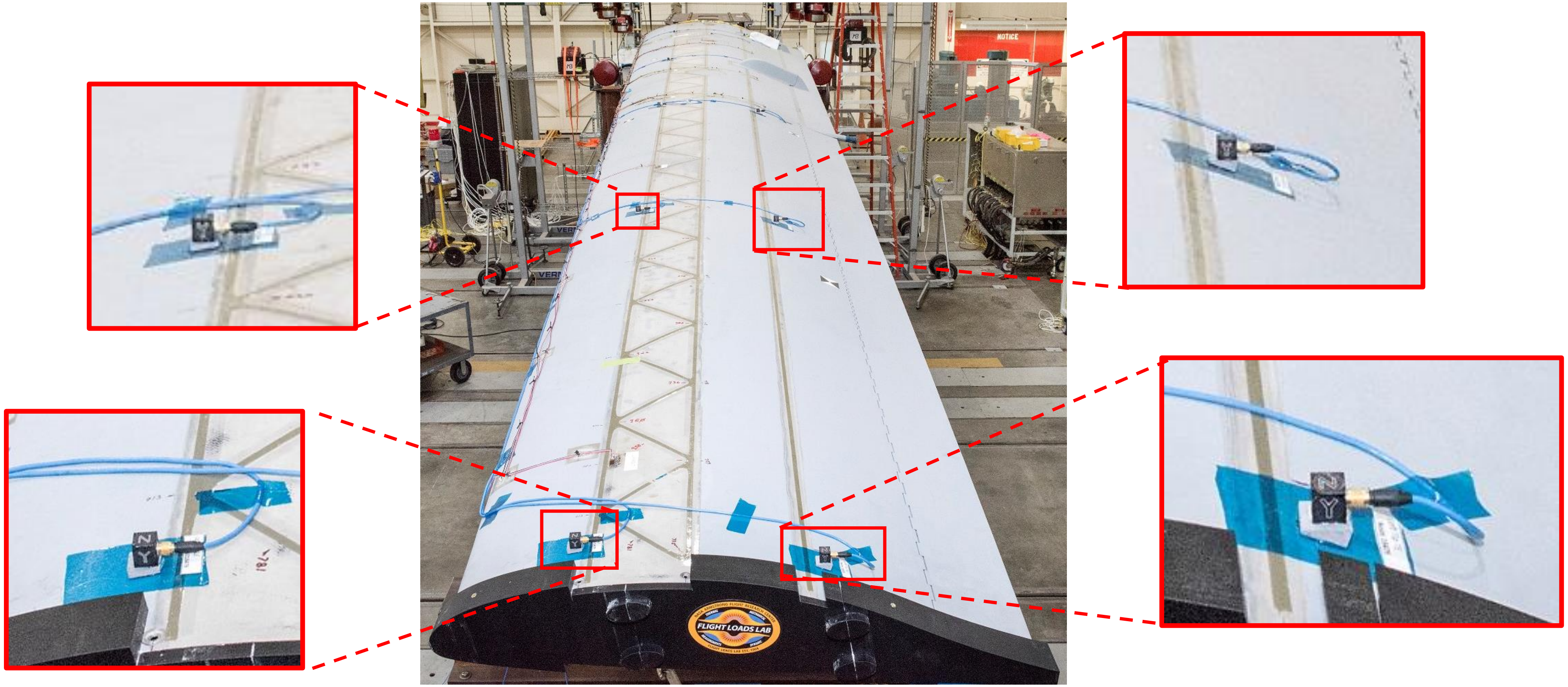
Wing Accelerometer Locations



CReW GVT – Accelerometer Photos

- All accel nodes in global coordinate system wrt WLTF
  - X+ (out Trailing Edge), Y+ (out Outboard), Z+ (up)

Wing Triaxial Accels

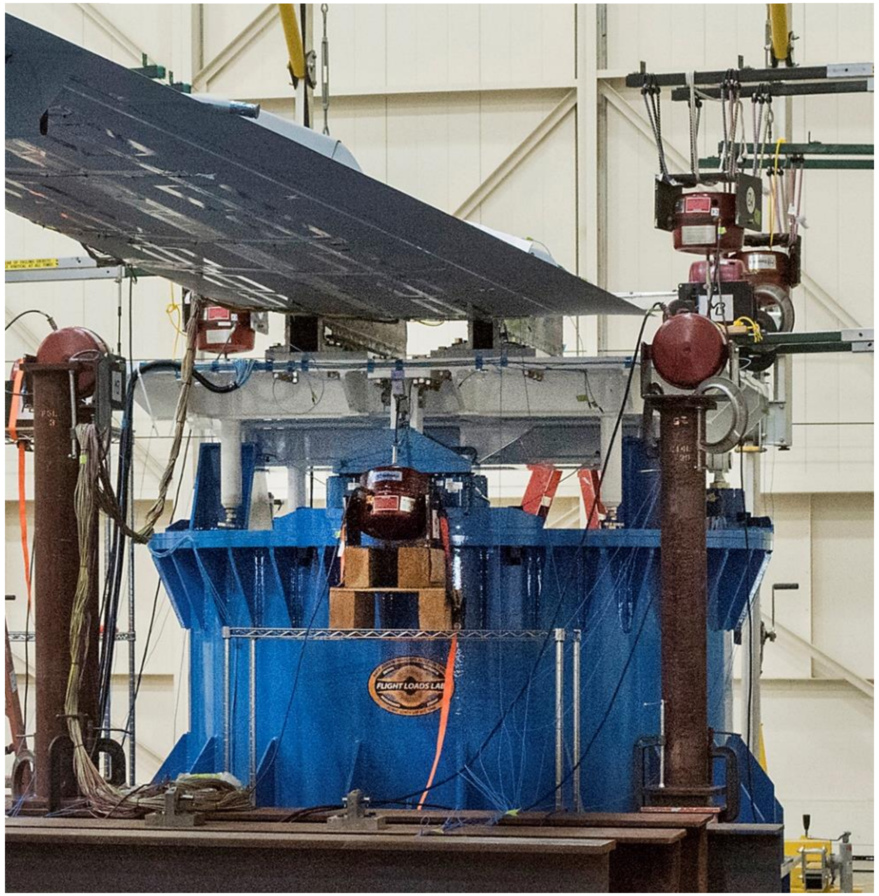


CReW GVT – Shaker Layout

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

Wingtip Shaker

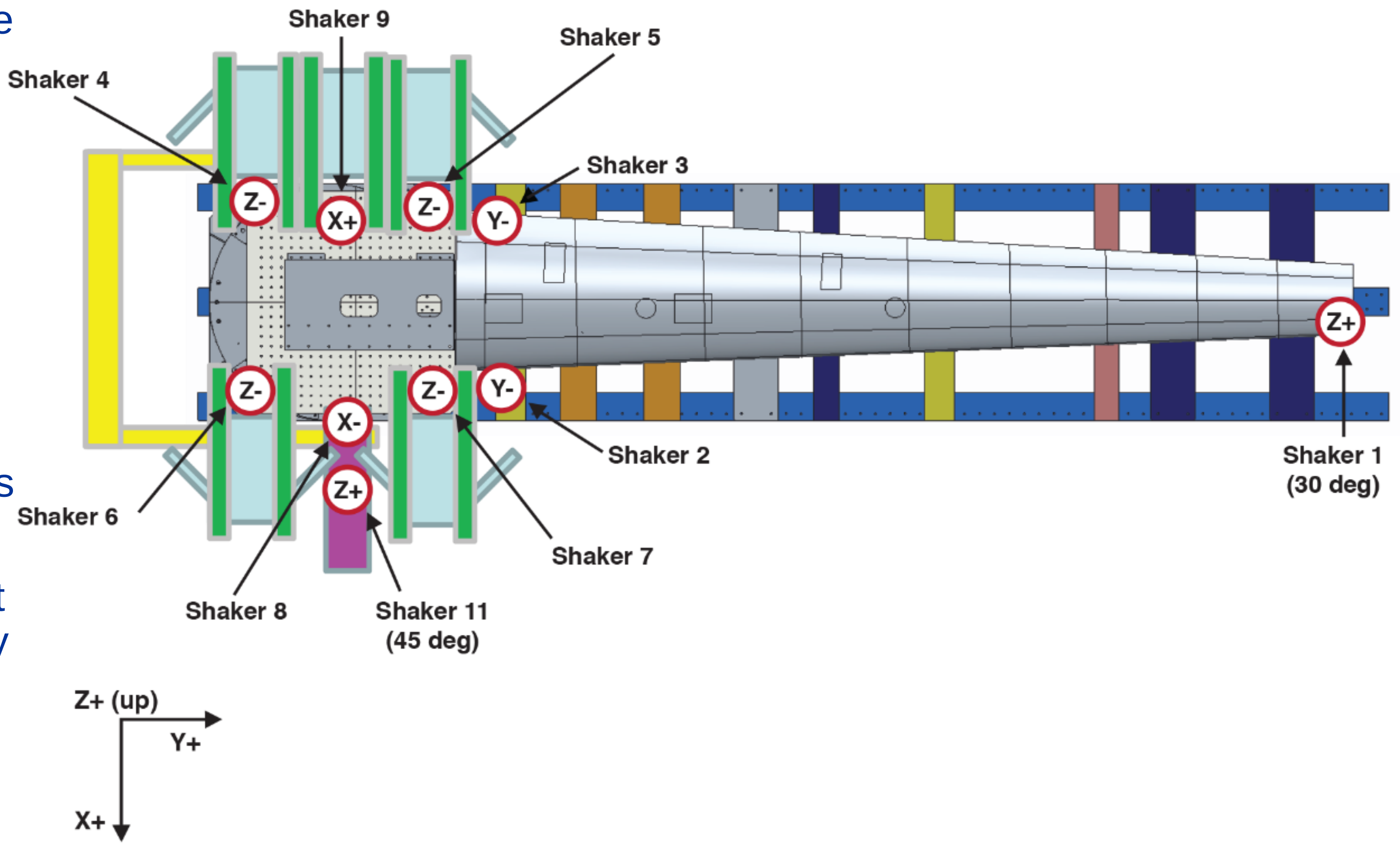
“Fixed” WLTF Shaker Locations



CReW GVT – Shaker Layout

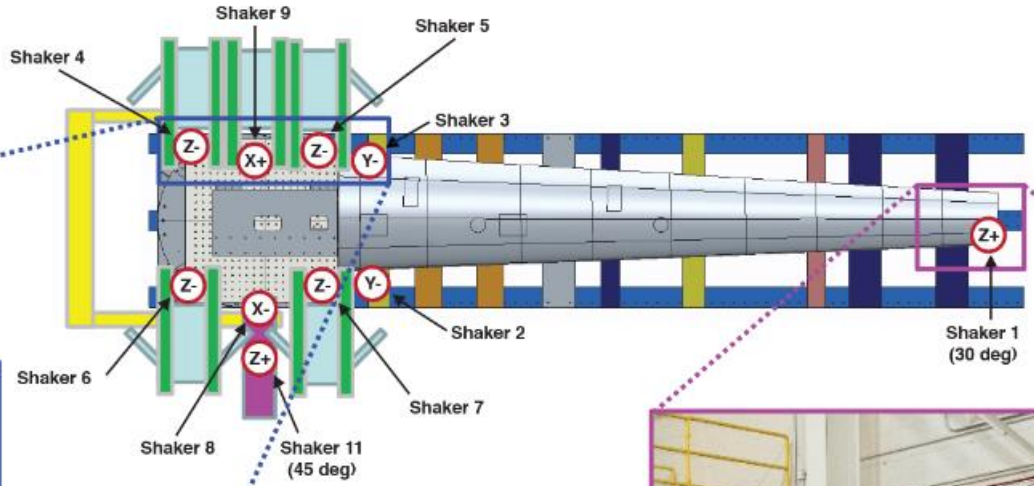
- Shaker placement around the WLTF was adjusted to excite primary base modes & maximize the capability of the FBC to decouple the base modes from the wing modes
- Shaker direction on reaction table is important & eliminates the effect of the reaction table from moving in the shaker direction
- A few different shaker configurations were attempted to find optimal shaker configuration which fixed the reaction table
    - Final shaker ⇒ 10 shakers: 1 on wingtip & 9 on fixture table which fixed nine DOFs on the reaction table
- Shakers supported by various types of support stands along with some shakers suspended by bungees from modified multi-purpose lifts
- Higher shaker forces were required on the reaction table

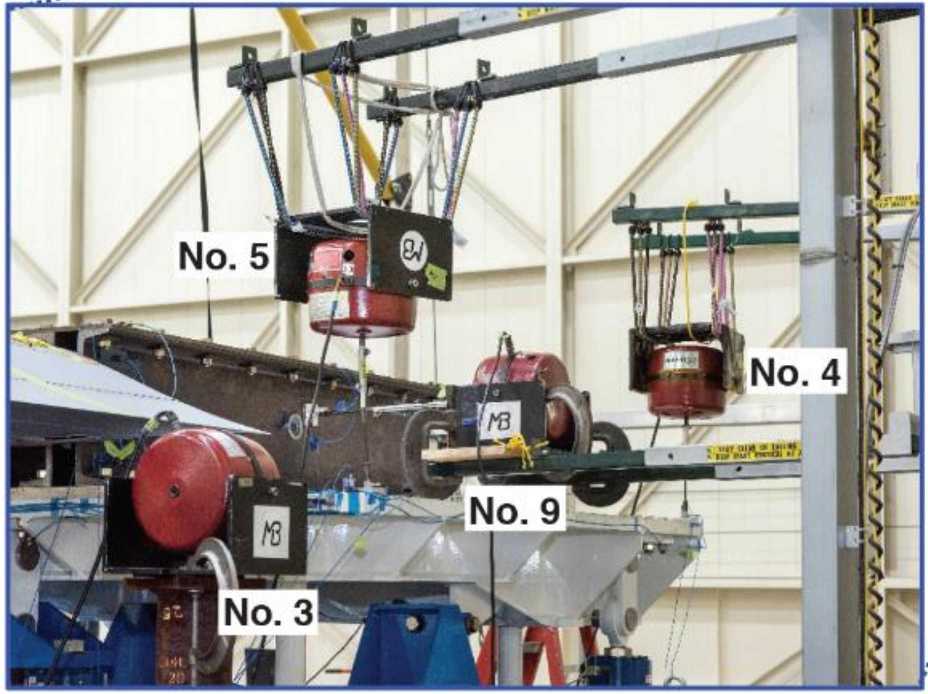
Crew GVT Shaker Layout for FBC Method



CReW GVT – Shaker Layout

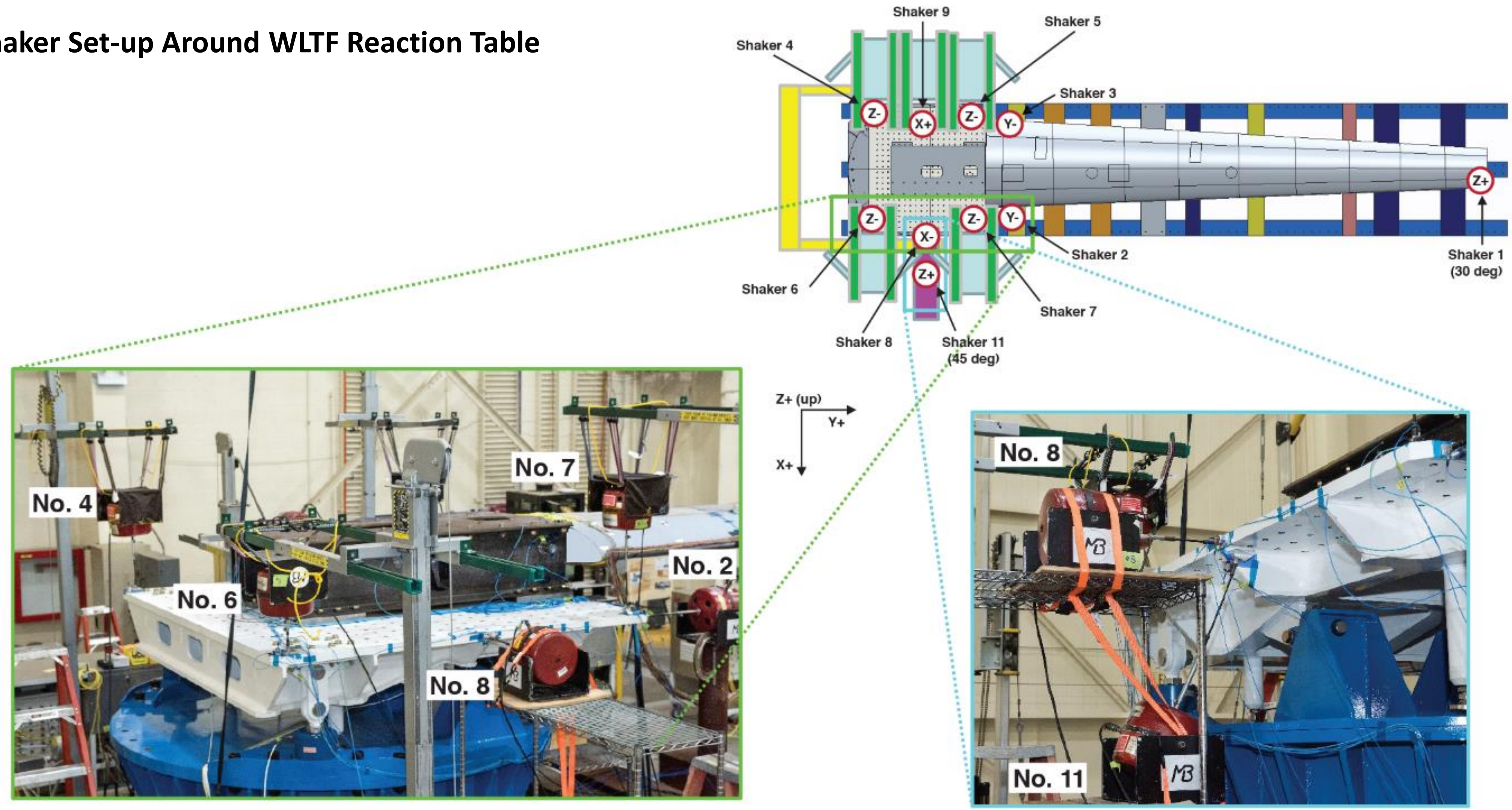
Shaker Set-up Around WLTF Reaction Table





CReW GVT – Shaker Layout

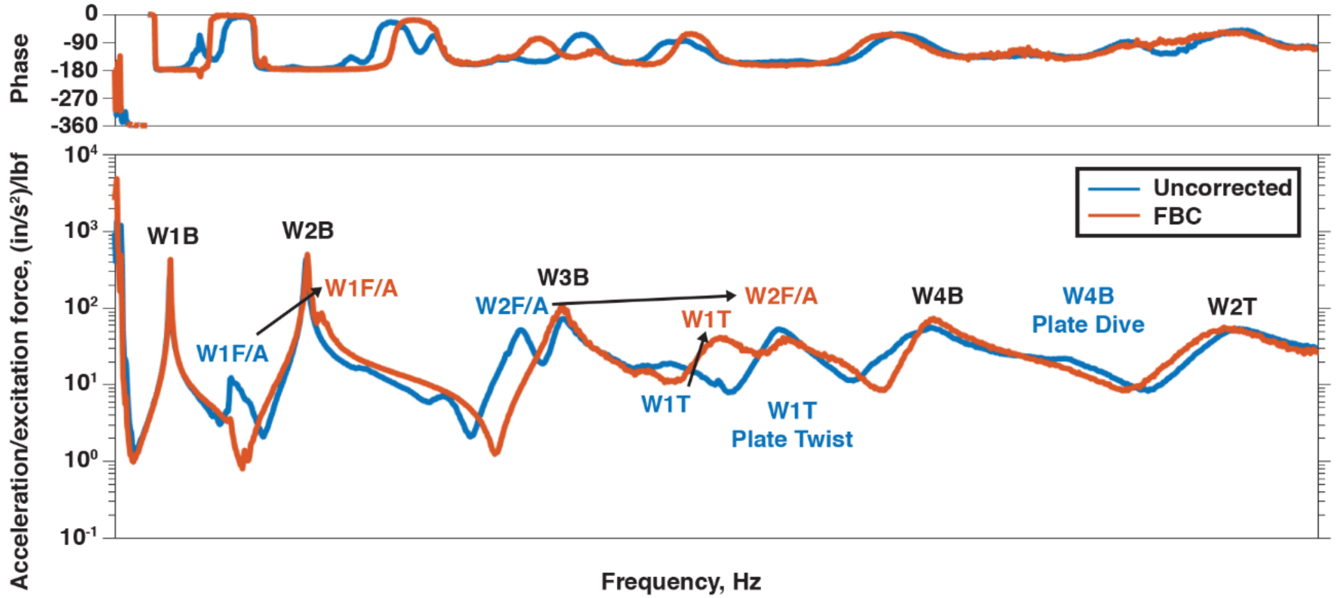
Shaker Set-up Around WLTF Reaction Table



Results – Feet Up Config: Uncorrected vs. Fixed Base Correction

- Frequency Response Function (FRF)
  - Wing bending modes coupled the least with WLTF since WLTF is stiffer vertically than in other directions
  - Wing fore/aft & torsion modes coupled the most with WLTF & required significant correction
    - Notable frequency shifts when using FBC: W1F/A, W2F/A & W1T modes
  - Reaction Table Plate motion
    - Uncorrected FRF shows two modes where the base was excited
      1. W1T with a plate twisting motion on the reaction table
      2. W4B with a plate dive motion on the reaction table
    - FBC FRF shows both plate mode peaks disappear when using the FBC method
      - Shows FBC technique is adequate for removing the effects of base motion from the GVT results

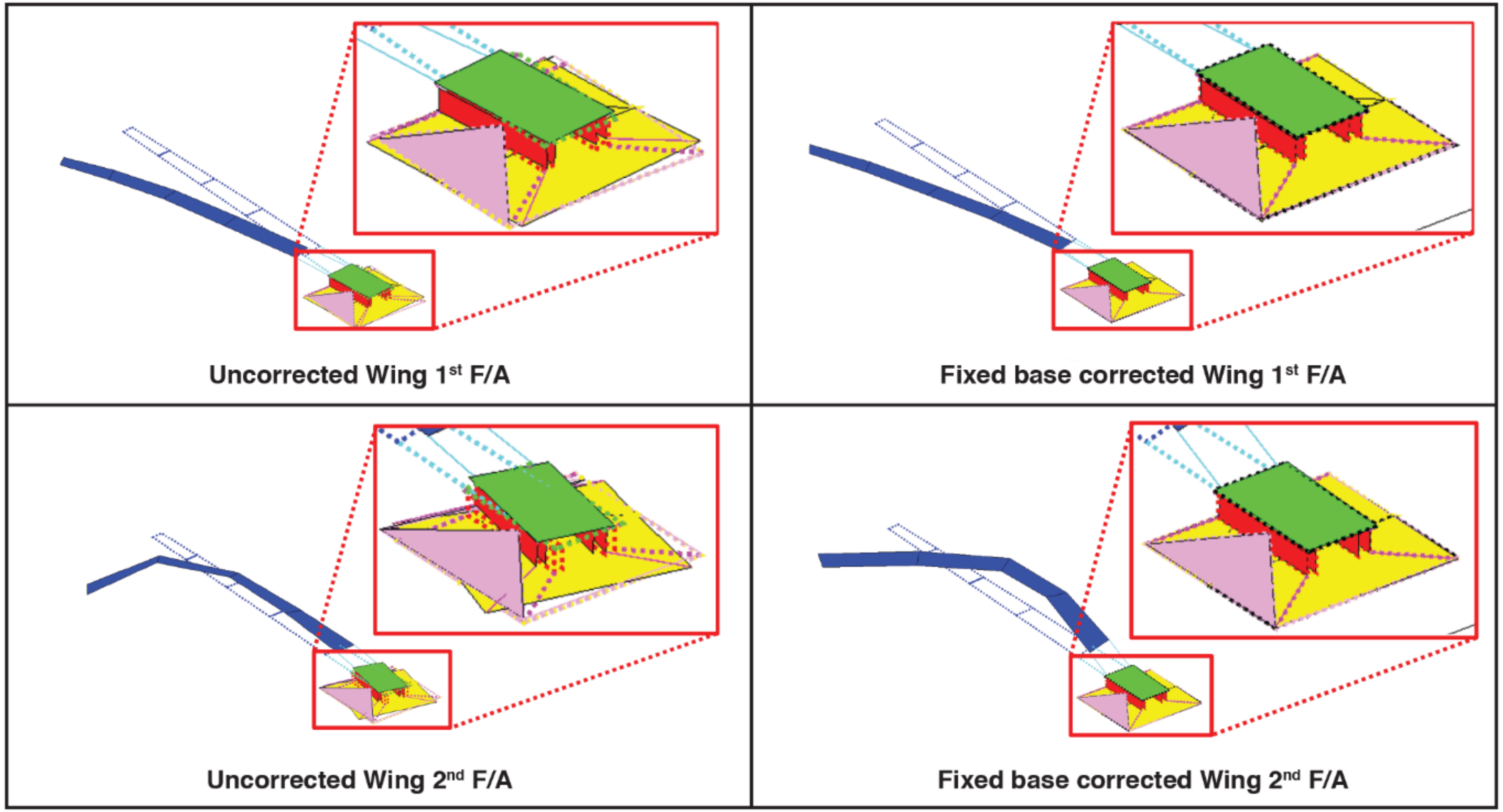
Feet Up: Uncorrected vs. FBC
Wingtip Frequency Response Function



Results – Feet Up Config: Uncorrected vs. Fixed Base Correction

- Promising sign of the effectiveness of the FBC method
- FBC mode shapes show very little base deflection
- Uncorrected mode shapes show significant base rotation
  - W2F/A mode appears to have more base motions than W1F/A mode
- 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

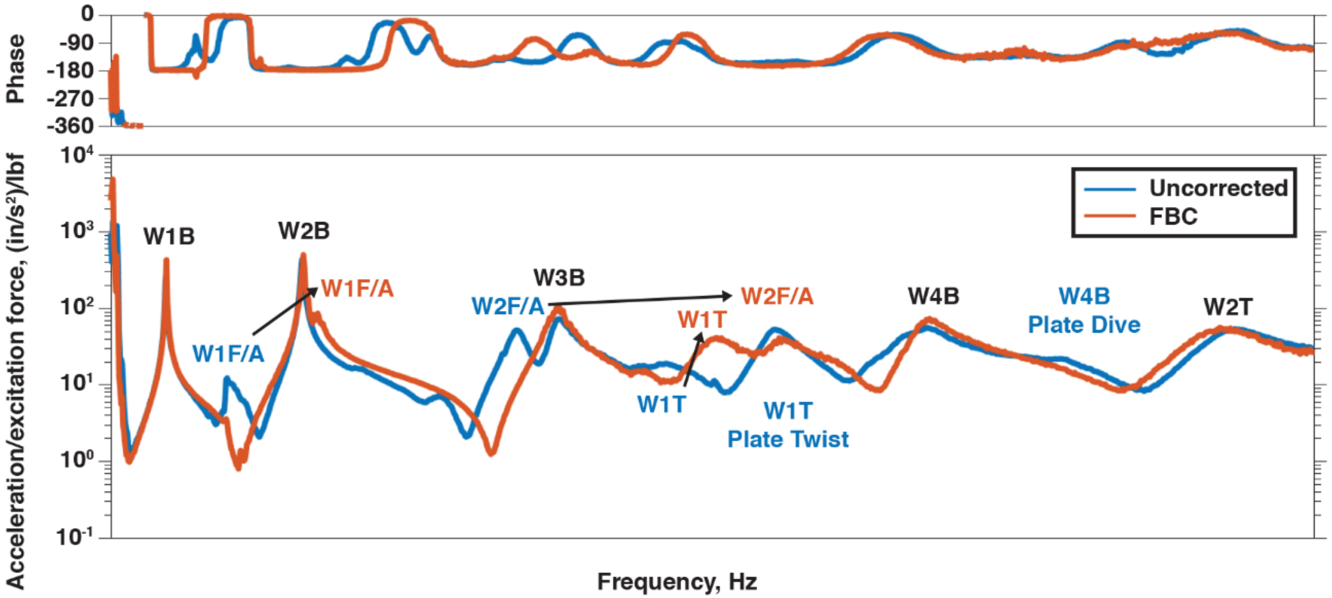
Feet Up: Uncorrected vs. FBC
Mode Shapes: Wing 1st Fore/Aft & Wing 2nd Fore/Aft



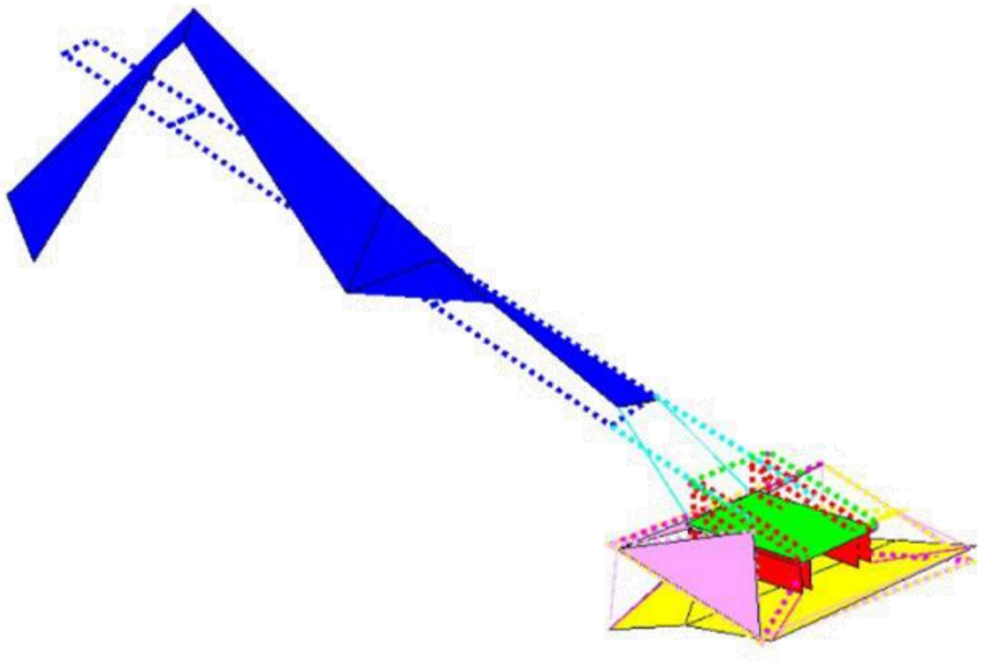
Results – Feet Up Config: Uncorrected vs. Fixed Base Correction

- Uncorrected FRF shows the peaks of two reaction table plate modes
  - These plate modes both disappear when applying the FBC method, showing that the method is able to remove base excitation and more cleanly show the motion of the wing mode shapes

Feet Up: Uncorrected vs. FBC
Wingtip Driving Point Frequency Response Function



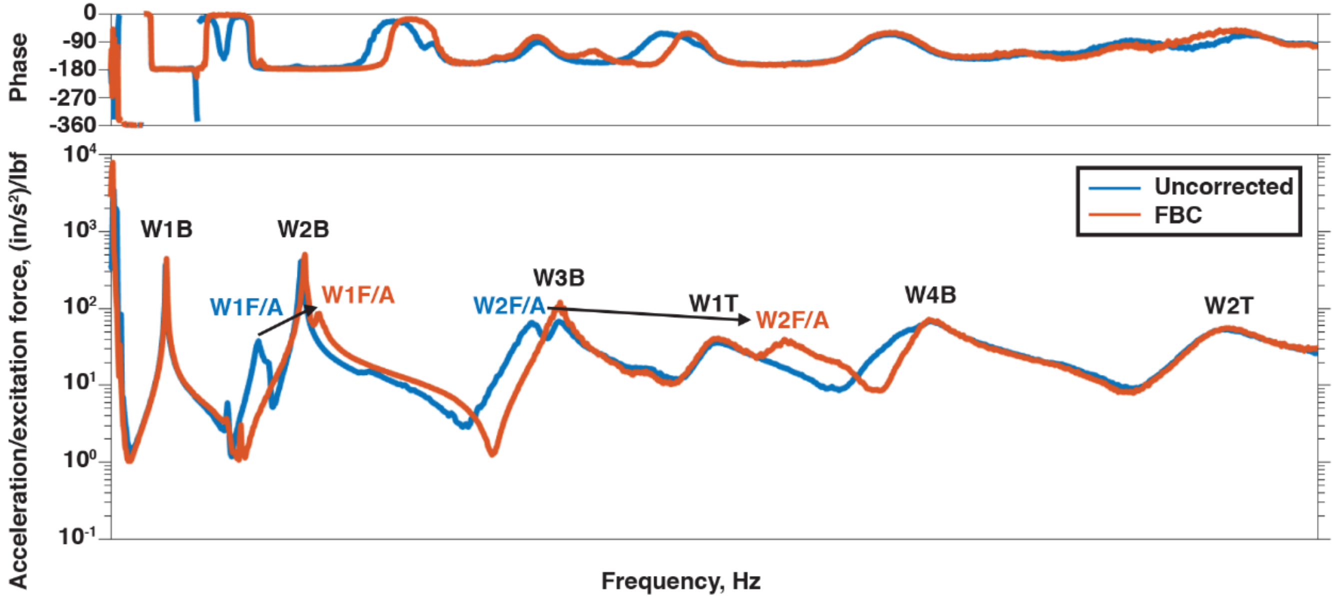
Wing 4th Bending With Reaction Table Dive Plate, Mode Disappears With FBC



Results – Feet Down Config: Uncorrected vs. Fixed Base Correction

- Net result of putting the reaction table feet down was to move the uncorrected wing torsion modes closer to the corrected wing torsion modes
    - Feet down helped stiffen the wing torsion modes, but did little to stiffen the wing bending and fore/aft modes
- Essentially, using the accelerations of the four vertical shakers on the reaction table corners (shakers 4-7) as references fixed the corners of the table in the vertical direction for the Feet up boundary condition, which meant that adding the four reaction table feet vertical supports did not help to further stiffen the base

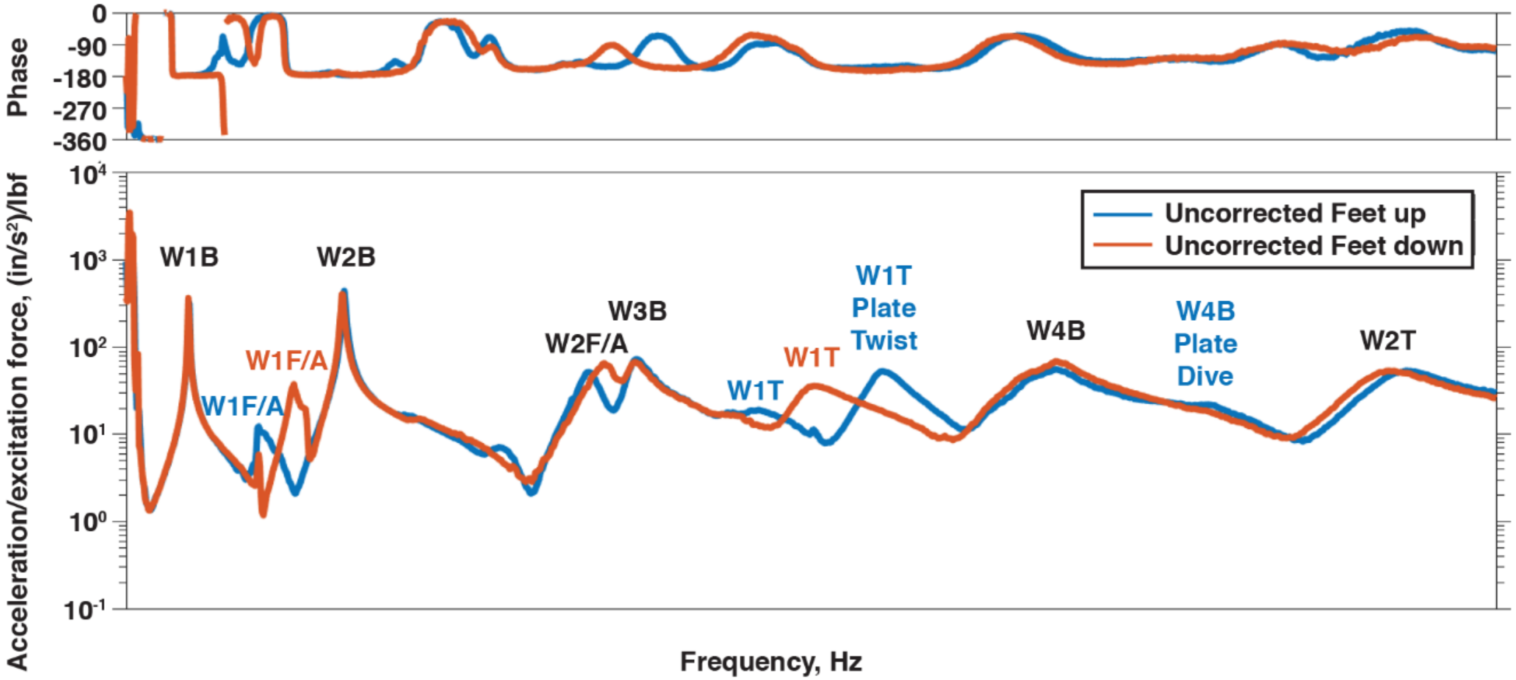
Feet Down: Uncorrected vs. FBC
Wingtip Frequency Response Function



Results – Feet Up vs. Feet Down: Uncorrected

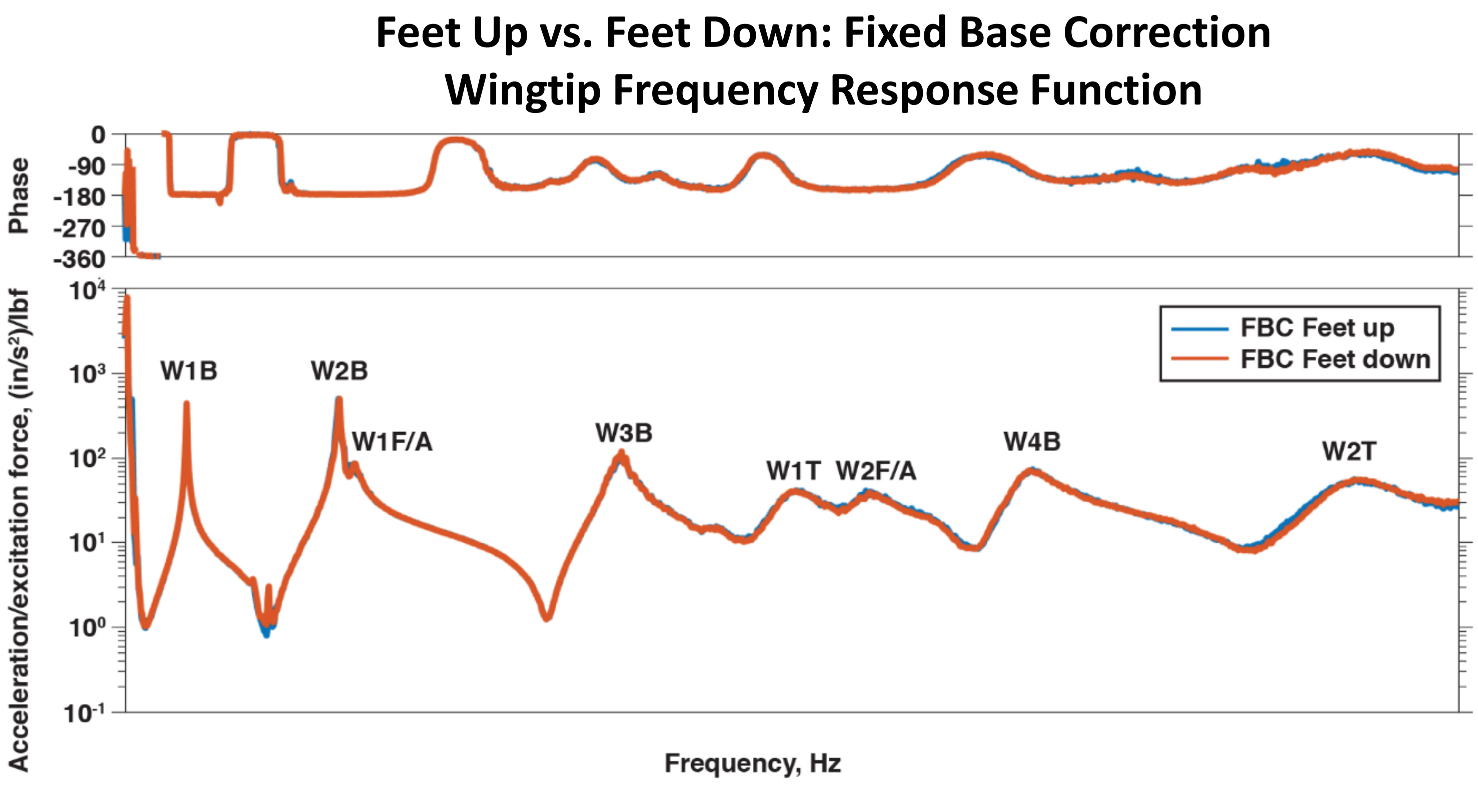
- Feet Up & Feet Down Uncorrected results shows wing fore/aft & torsion modes are very different due to their differences in boundary conditions

Feet Up vs. Feet Down: Uncorrected
Wingtip Frequency Response Function



Results – Feet Up vs. Feet Down: Fixed Base Correction

- Feet Up & Feet Down FBC results line up very well
  - Phases & magnitudes of the 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



Results – Feet Up vs. Feet Down: Uncorrected & Fixed Base Correction

- Feet Up & Feet Down are very similar for FBC frequencies, while there are some large frequency differences for Uncorrected results
  - W1F/A & W1T modes showed the largest changes
- Results show FBC technique has potential for simplifying GVT setups by giving more boundary condition options while still giving accurate wing modal results

Feet Up vs. Feet Down: Uncorrected & FBC Frequency Percent Difference

No.	Mode Shape Description	Percent Difference, Uncorrected: Feet Up & Feet Down Frequency Results	Percent Difference, FBC: Feet Up & Feet Down Frequency Results
1	Wing 1st Bending, W1B	0.4	0.05
2	Wing 2nd Bending, W2B	0.8	-0.45
3	**Wing 1st Fore/Aft, W1F/A**	**-21.3**	**-0.04**
4	Wing 3rd Bending, W3B	0.1	-0.03
5	**Wing 1st Torsion, W1T**	**-8.5**	**0.02**
6	**Wing 2nd Fore/Aft, W2F/A**	**-3.1**	**0.12**
7	Wing 4th Bending, W4B	0.3	-0.04
8	**Wing 2nd Torsion, W2T**	**1.3**	**-0.36**

Summary

- CReW modal results show the feasibility of using the fixed base correction (FBC) method to decouple the wing and test fixture modes for a long flexible wing mounted to a dynamically active static test fixture

- FBC method
  - Apply excitation to desired fixed boundary hardware with multiple independent shakers where there are at least as many independent sources as there are independent boundary deformations in the test article frequency range of interest
  - Uses the shaker boundary accelerations (seismic accels) as independent references when calculating the frequency response functions
  - Technique produced similar wing modal characteristics with two different BC configurations
  - Results produce test results with reliable boundary conditions to replicate in analytical models
  - Method has potential to change how modal testing is traditionally done and will save projects cost and schedule time by no longer needing an independent setup for modal testing

- Lessons learned during CReW modal testing were used to extend the FBC technique to the Passive Aeroelastic Tailored wing test article and assist in giving analysts an accurate set of fixed base modes for use in model correlation

Questions