NASA's All-Electric X-Plane
X-57 Mod II Ground Vibration Test

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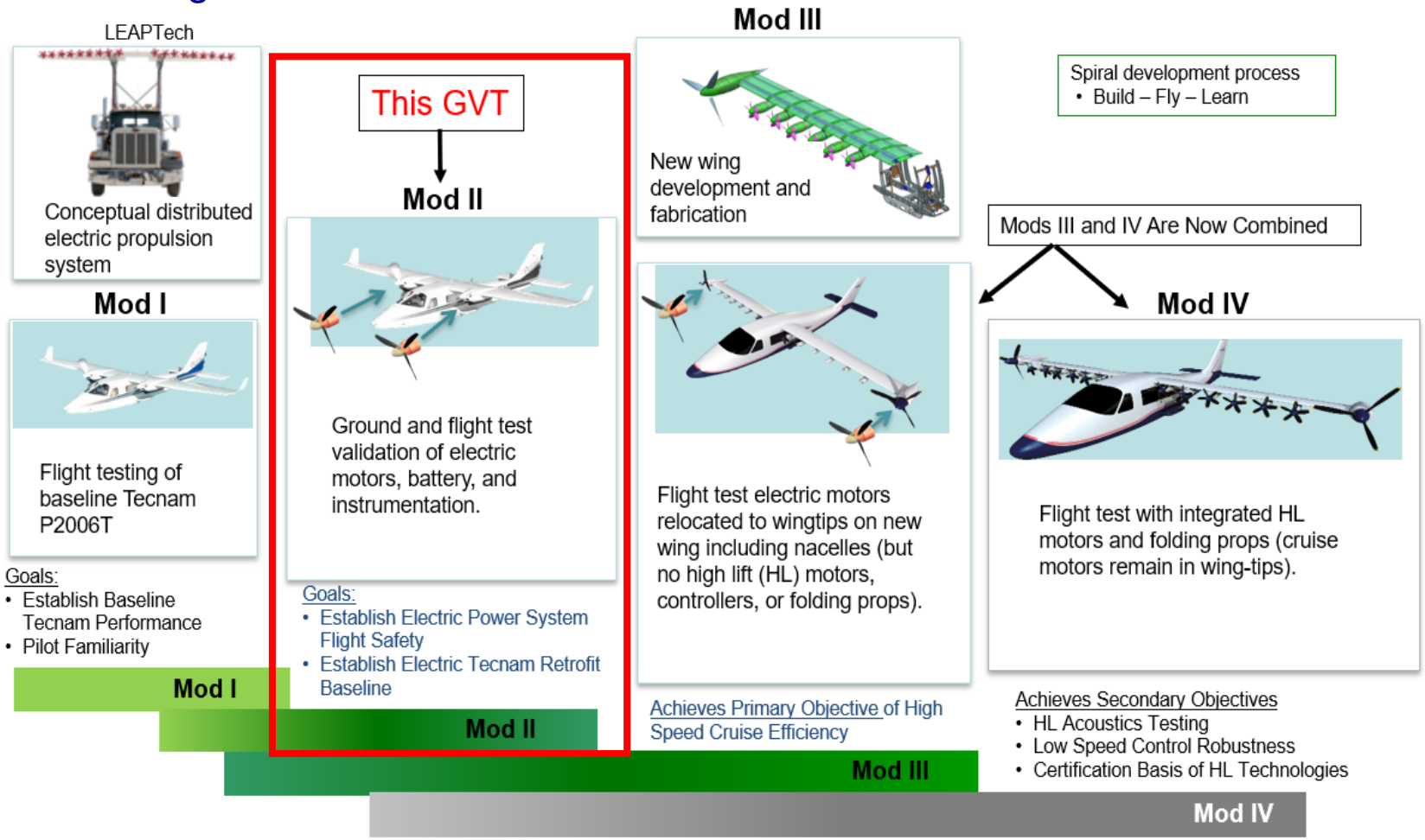
X-57 Background

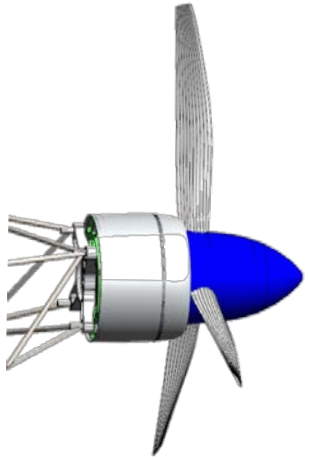
- Ultimate goal of the final X-57 modification is to demonstrate a 500% increase in high-speed cruise efficiency, zero in-flight carbon emissions, and 15 dB reduction in noise levels



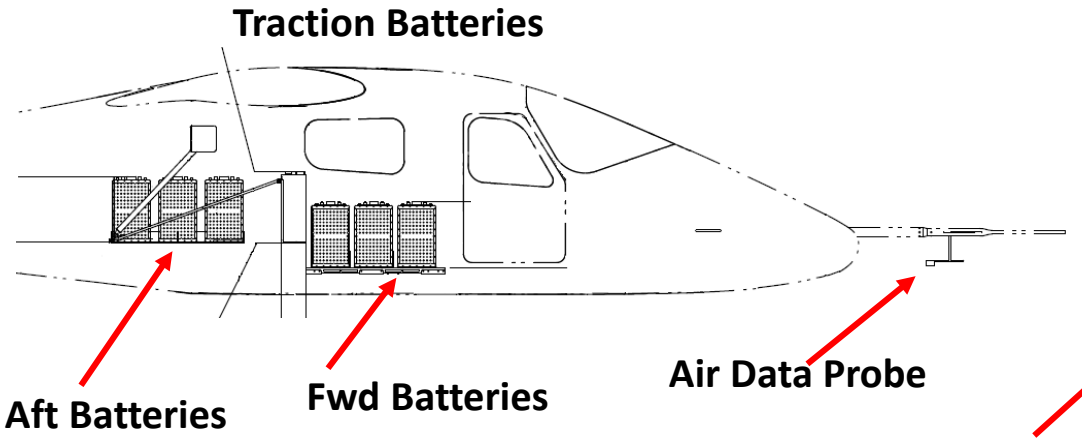
X-57 Mod II Background

- X-57 Mod II aircraft is the Mod I baseline Tecnam P2006T aircraft redesigned with two electric motors powered by traction batteries
- Mod II Modifications
  - Added: Cruise Motors/Mounts (adapters, trusses), Propellers/Hubs, Cruise Motor Controllers (CMCs) Traction Batteries and Air Data Probe
  - Electric motors mounted onto motor adapters and truss which has the new CMCs and then mounted onto the existing firewall

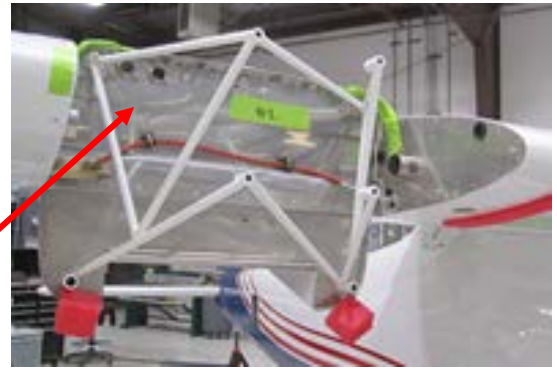
CAD of Motor Mount Truss, Adapter, Motor, Hub, Props & Spinner



X-57 Mod II Aircraft ≈ 2,780 lbs



Motor Mount Truss



X-57 Mod II GVT

- X-57 Mod II Ground Vibration Test (GVT) conducted at NASA Armstrong from Nov. – Dec. 2019
  - Goal: Gather modal data of a near flight ready configuration to correlate and validate the Mod II aircraft beam finite element model (FEM) to the GVT results
  - Two boundary conditions were tested:
    - **Free-Free**: Aircraft on soft support system to simulate free flight conditions
    - **On-Tires**: Aircraft on-tires to characterize on-ground modes for future aircraft ground motor testing safety clearance and taxi tests

Right Electric Cruise Motor

X-57 Mod II GVT, Conducted at NASA Armstrong Fall 2019

https://www.youtube.com/watch?v=wsjdk790JlI

X-57 Mod II GVT - Test Objectives

- Primary Objective: Capture modes that are part of the aircraft predicted flutter & whirl flutter mechanism

Primary Objective	Reasoning
▪ Stabilator Rotation ▪ Fuselage 1st Vertical Bending (F1VB)	▪ Modes predicted in pre-test FEM that were part of Classical Flutter Mechanism
▪ Motor Assembly Vertical Bending ▪ Motor Assembly Lateral Bending	▪ Modes predicted in pre-test FEM that were part of Whirl Flutter Mechanism
▪ Aircraft Rigid Body Modes	▪ To characterize soft support system effectiveness

- Secondary Objective: Capture fuselage lateral bending & torsion modes, wing modes, and landing gear modes
- Tertiary Objective: Capture higher order wing modes and control surface modes

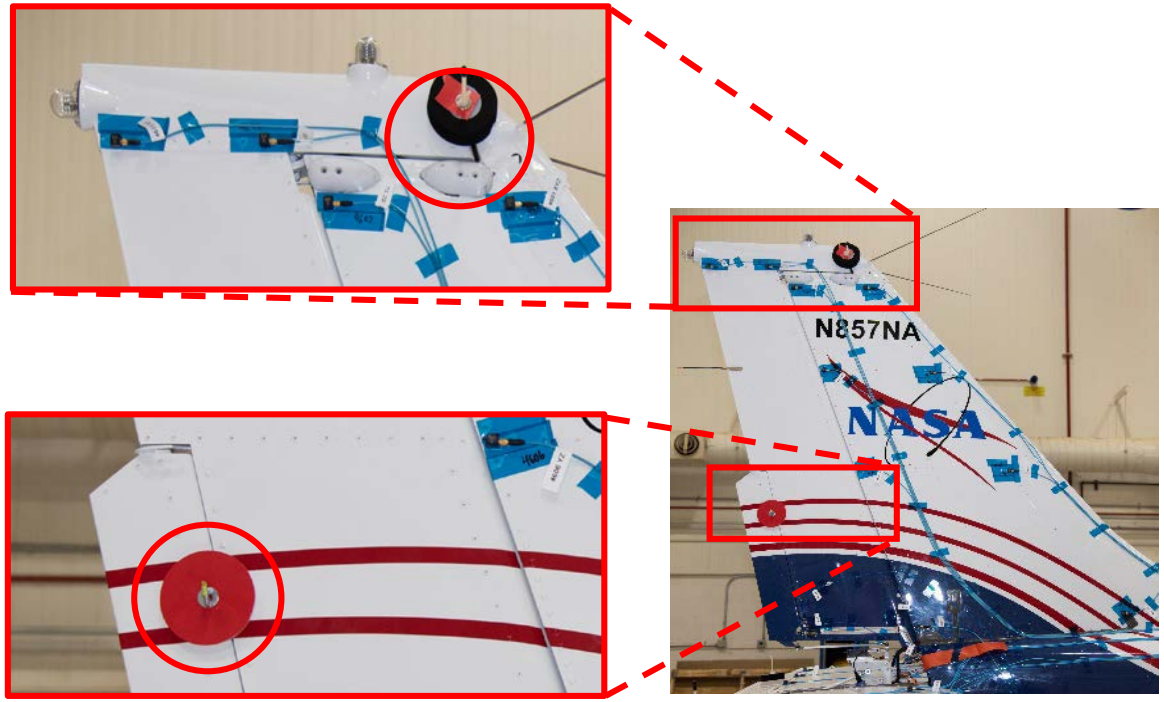
X-57 Mod II GVT – Test Setup Overview

X-57 Mod II GVT Test Setup on Soft Supports

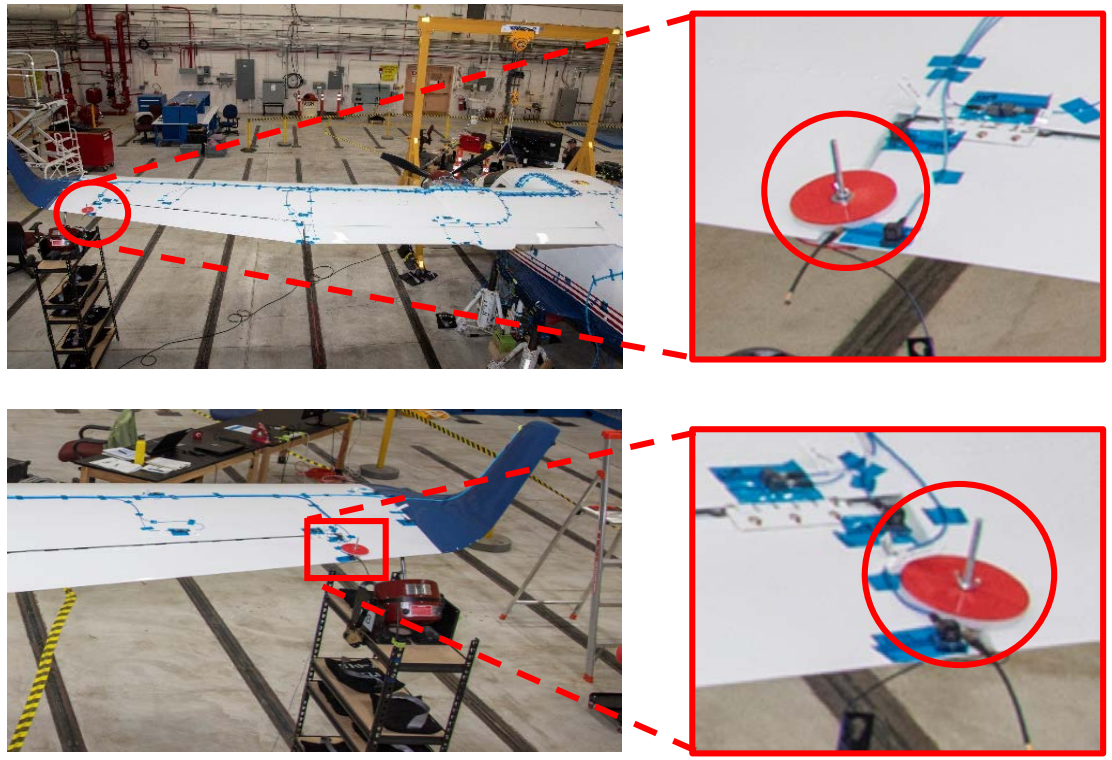
X-57 Mod II GVT – Locking Devices

- Locking devices are a common method used to constrain moving components during GVTs which can dominate the desired structural modes
  - Control surfaces were locked to constrain motion, unless that surfaces was the mode of interest
  - Yoke & pedal locks used to simulate pilot contact with yoke & pedals for steady level flight & also prevent motion in control surfaces

Rudder & Rudder Trim Tab Gust Locks

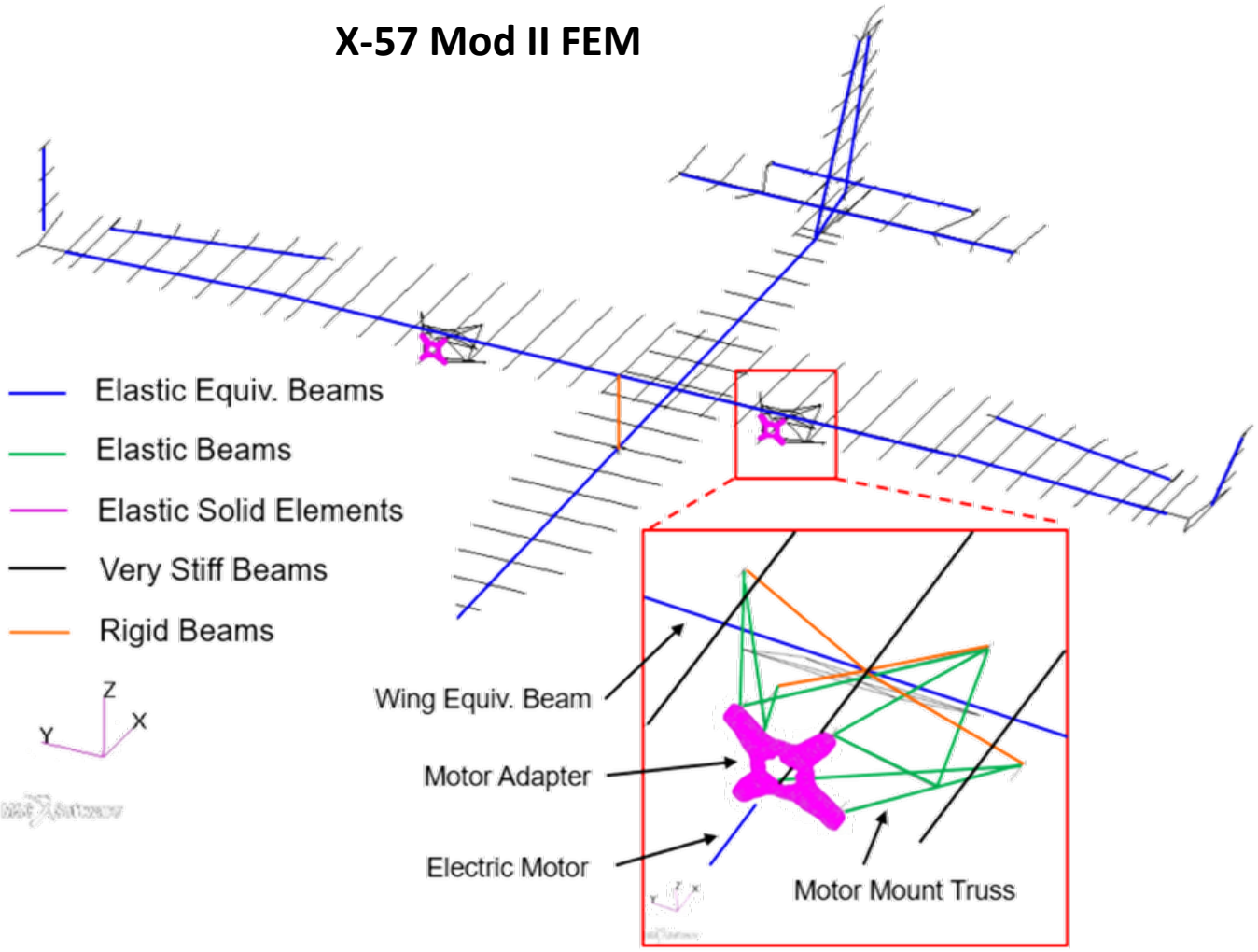


Aileron Gust Locks



X-57 Mod II GVT – Finite Element Model (FEM)

- X-57 Mod II FEM is a highly modified version of original Tecnam P2006T FEM provided by the manufacturer
  - Due to proprietary nature of the original FEM, Mod II pre-test FEM comparisons to GVT results are not shown in this presentation
- Aircraft primary structure, control surfaces and electric motors are modelled by elastically equivalent beams while retaining the same mode shapes and frequencies
- Wing and fuselage are rigidly connected
- Stiff beams and springs used for visualization



X-57 Mod II GVT - Test Configurations

- **Free-Free: On Soft Supports**
  - To simulate free-free boundary condition flight and to separate the aircraft rigid body modes from its elastic modes
  - Multiple tests were conducted on the aircraft at a variety of different shaker locations in order to excite the target modes
  - Yoke & pedals were locked for the most part, except for one test case that when the yoke was free in order to excite the Stab Rotation mode
  - Gust locks on the aileron and rudder, as well as the stab counterweight, were either installed or removed from time to time depending on the target mode to be excited
- **On-Tires**
  - To verify the taxi ground modes prior to flight and cross-check with the on soft support modes for any significant differences
  - Also to obtain the baseline characterization of the motor assembly modes for safety clearance of near-term ground motor testing before flight
  - Yoke & pedals were locked, all gust locks were removed, and stab counterweight was off
  - For the motor test, aileron & rudder gust locks were installed as well as the stab counterweight
- Additional last minute configuration was added during the GVT by exciting on the A-Frame lifting device directly in order to ensure there was no coupling to the aircraft modes of interest

X-57 Mod II GVT - Test Matrix

Setup	Significance	Objective Mode(s)	Excitation Location(s) & Direction	Excitation Type	Cockpit Controls	Gust Locks	Stab Counterweight
Free-Free on Soft Supports	Primary	A/C Rigid Body	Fuselage/Wing	Manual Push	Yoke & Pedals Locked	Aileron & Rudder	On
	Primary	Stab Rotation	Aft Fuselage Vert	1 Shaker	Yoke & Pedals Locked	Aileron & Rudder	On/Off
	Primary	Stab Rotation	Aft Fuselage Lat, 30° Vert / 60° Lat	1 Shaker	Yoke Free, Pedals Locked	Aileron & Rudder	On/Off
	Primary	Fuselage Vert/Lat	Aft Fuselage Vert	1 Shaker	Yoke & Pedals Locked	Aileron & Rudder	On/Off
	Primary	Motor Vert/Lat	Prop Hub Vert, 45° Sym/Anti-Sym	2 Shakers	Yoke & Pedals Locked	Aileron & Rudder	On
	Secondary	Wing Bend, F/A, & Torsion	Wingtip TE Vert, 60° Vert / 30° F/A (Sym & Anti-Sym)	1 or 2 Shakers	Yoke & Pedals Locked	Aileron & Rudder	On
	Secondary	Fuselage Torsion & Vert Tail Bend	Vertical Tail Lateral	1 Shaker	Yoke & Pedals Locked	Aileron & Rudder	On/Off
	Secondary	Main Landing Gear	MLG Lat, 45° Lat	2 Shakers	Yoke & Pedals Locked	Aileron & Rudder	On
	Tertiary	Aileron Rotation	Wingtip TE 60° Vert / 30° F/A (Sym & Anti-Sym)	2 Shakers	Yoke & Pedals Locked	Rudder	On
	Tertiary	Rudder Rotation	Vertical Tail Lateral	1 Shaker	Yoke & Pedals Locked	Aileron	On
	Secondary	A/C Modes	Repeat ideal excitation locations	1 or 2 Shakers	Yoke & Pedals Locked	None	Off
On Tires	Secondary	A/C Taxi Modes & Flt Accels	Repeat ideal excitation locations	1 or 2 Shakers	Yoke & Pedals Locked	None	Off
	Primary	Motor Vert/Lat	Prop Hub Vert, 45° Sym/Anti-Sym	2 Shakers	Yoke & Pedals Locked	Aileron & Rudder	On
A-Frame Test	Tertiary	A-Frame	Vert Beam Lat, 30°Lat / 60° Long	2 Shakers	Yoke & Pedals Locked	Aileron & Rudder	On

X-57 Mod II GVT - Soft Supports

- To create the GVT Free-Free boundary condition, the Mod II aircraft was suspended around the nose bulkhead with the 2-ton A-Frame (via a single bungee, chain hoist, & lifting strap) and at each of the main landing gears (3 bungees on each MLG suspended on bungee support beams supported by two 5-ton jacks)
- MIL-C-5651B, Type II bungees (1080HD loops) produced by SBC Industries (Huntsville, AL)
  - Bungees were characterized prior to GVT ≈ 1 Hz
- Aircraft modes did not couple with soft supports
- Soft support system eliminated the need for overhead crane support and a critical lift
- Soft supports easy & efficient to come on/off – took crew ≈ 10 minutes
- Used same bungees throughout GVT with no need to swap out any bungees

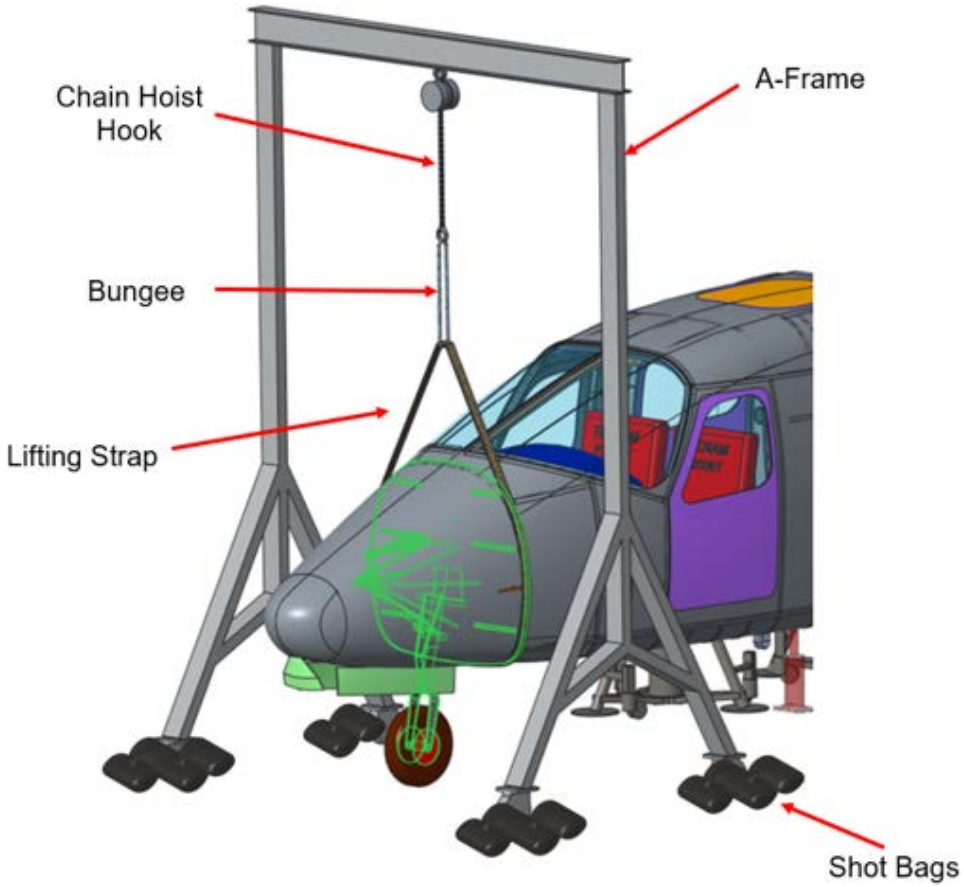
X-57 Soft Support System

1080HD Bungee Loop

X-57 Mod II GVT - Fuselage Nose Soft Support

- Single bungee attached to chain hoist hook, and top of lifting strap, using two 6.5-ton shackles
- Lifting strap wrapped around aircraft nose bulkhead
- High-friction material placed in between lifting strap and fuselage surface to guard against slippage
- A-frame wheels chocked using shot bags and mechanical wheels locked to prevent castoring
- Nose wheel remained on and nose gear strut unlocked

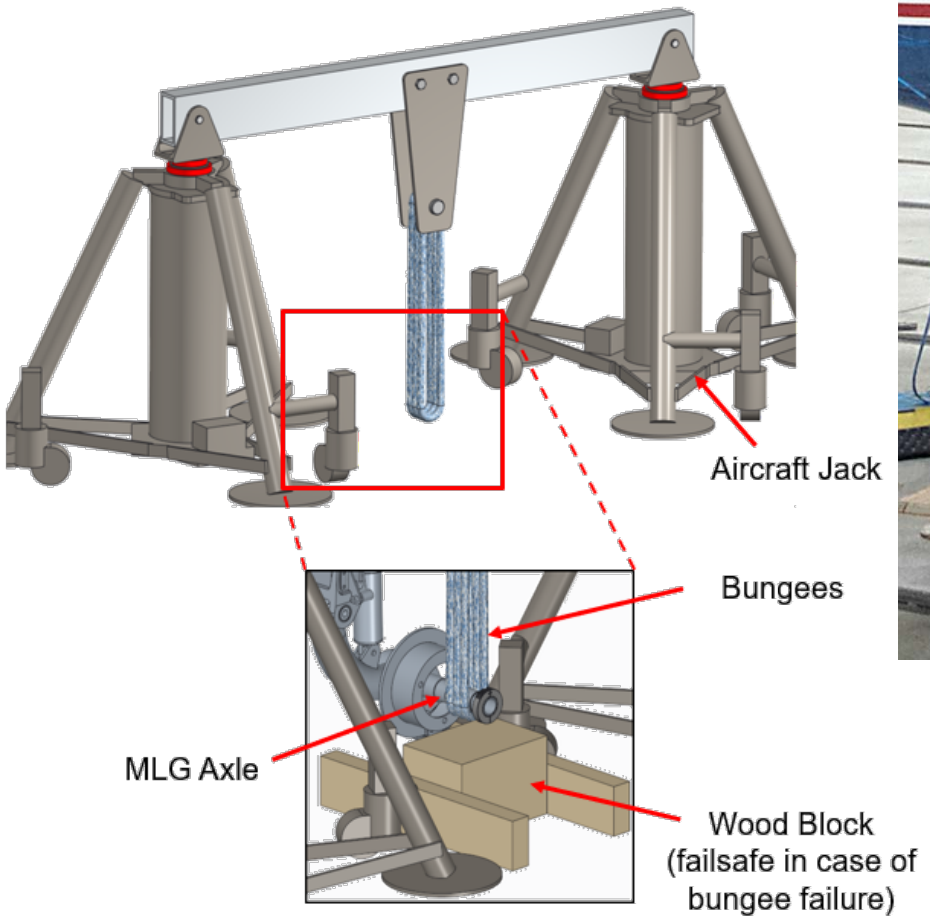
X-57 Nose Soft Support



X-57 Mod II GVT - Main Landing Gear Soft Support

- Two 5-ton Regent Model 985S jacks were positioned on each side of the aircraft around the axle and interfaced to the MLG soft support beam
- Three bungee loops were linked between the jack soft support beam to MLG axle
- MLG soft support setup was duplicated on both axles

X-57 Main Landing Gear (MLG) Soft Support



X-57 Mod II GVT - GVT Equipment

- Accelerometers (all 100 mV/g)
  - PCB T356A16 triaxial accels
  - PCB T333B32 uniaxial accels
  - PCB T333B uniaxial accels
- Excitation System
  - Shaker: MB Dynamics Electromagnetic Modal 110, 3 qty
- Data Acquisition system: Brüel & Kjær LAN-XI
  - Mainframes – Daisy chained together thru network switch
    - LAN-XI 11-slot Main frame, 2 qty
    - LAN-XI 5-slot Main frame, 2 qty
  - Modules - Capable of recording 344 channels (if needed)
    - LAN-XI 4-channel Input + 2-channel Output 3160 Source Module, Qty 2
    - LAN-XI 12-channel 3053 Modules, 27 qty
    - LAN-XI 6-channel 3060 Modules, 2 qty
- GVT Software
  - BK Connect

PCB T356A16 Triaxial Accel

PCB T333B32 Uniaxial Accel

PCB T333B Uniaxial Accel

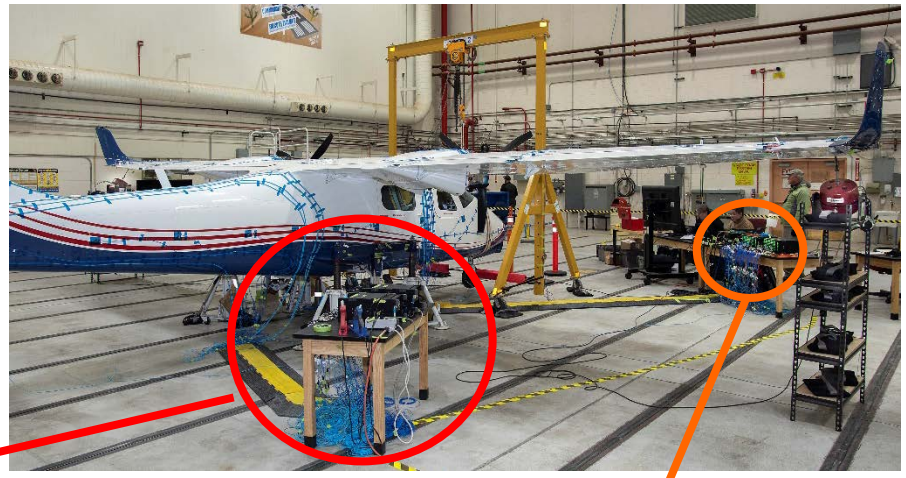
MB Modal 110 Shaker

B&K LAN-XI Main Frame

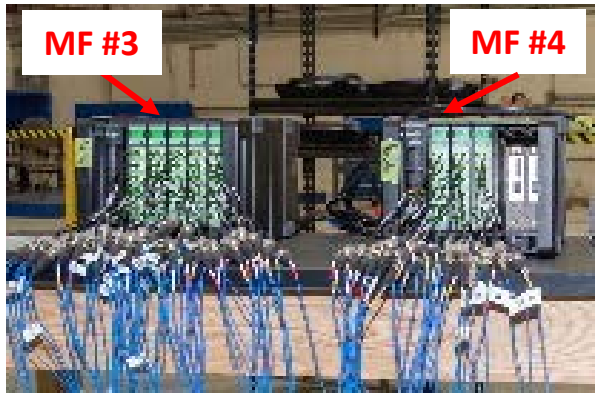
LAN-XI Module

X-57 Mod II GVT – LAN-XI DAQ Setup

- LAN-XI DAQ frontend setup: Four mainframes (two 11-slot & two 5-slot) capable of driving 4 shakers & recording 344 channels with network switch daisy chaining modules
  - Fwd aircraft setup
    - MF#1: two source module (3160) & nine 12-channel input module (3053)
    - MF#2: eleven 12-channel input module (3053)
  - Aft aircraft setup
    - MF#3: five 12-channel input modules (3053)
    - MF#4: three 12-channel input modules (3053)

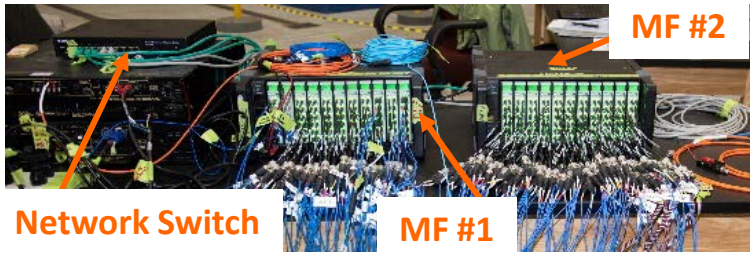


LAN-XI DAQ Aft Aircraft Setup

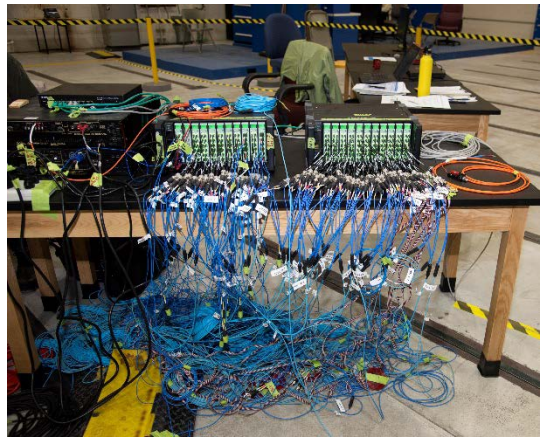


For MLG soft support & aft aircraft accels

LAN-XI DAQ Fwd Aircraft Setup

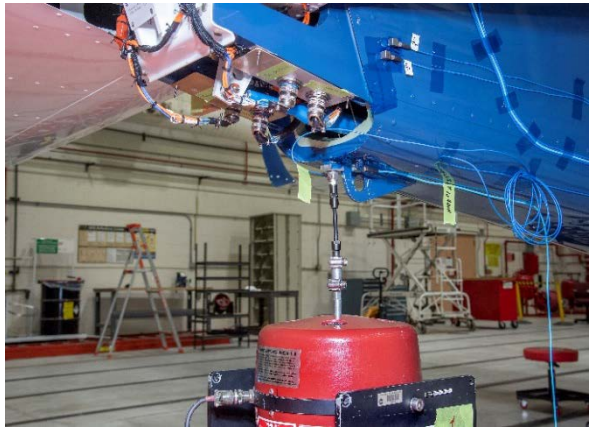


For fwd aircraft accels & A-frame



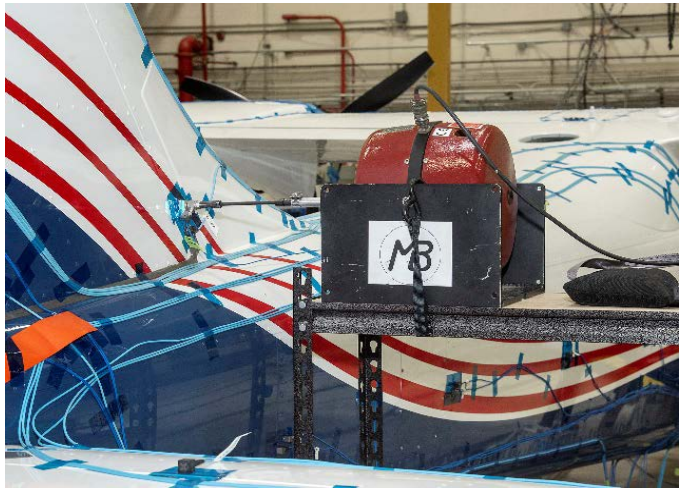
X-57 Mod II GVT – Shaker Setup

Motor Prop Hub



Aft Fuselage

Right Wingtip

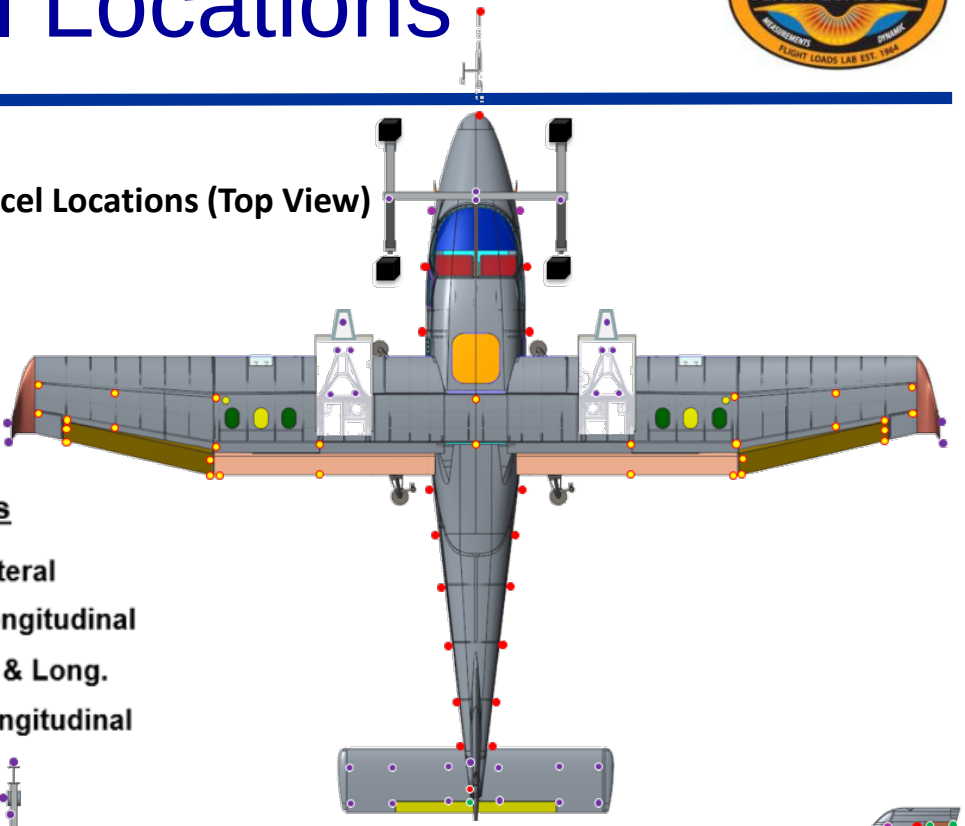


Vertical Tail

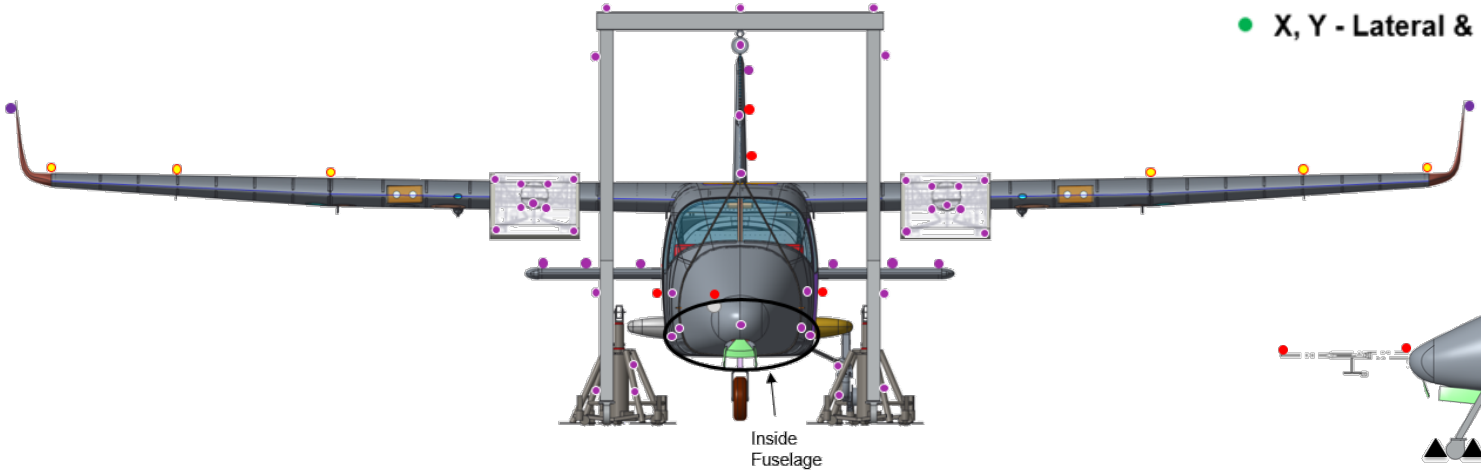
Main Landing Gear

X-57 Mod II GVT - Accel Locations

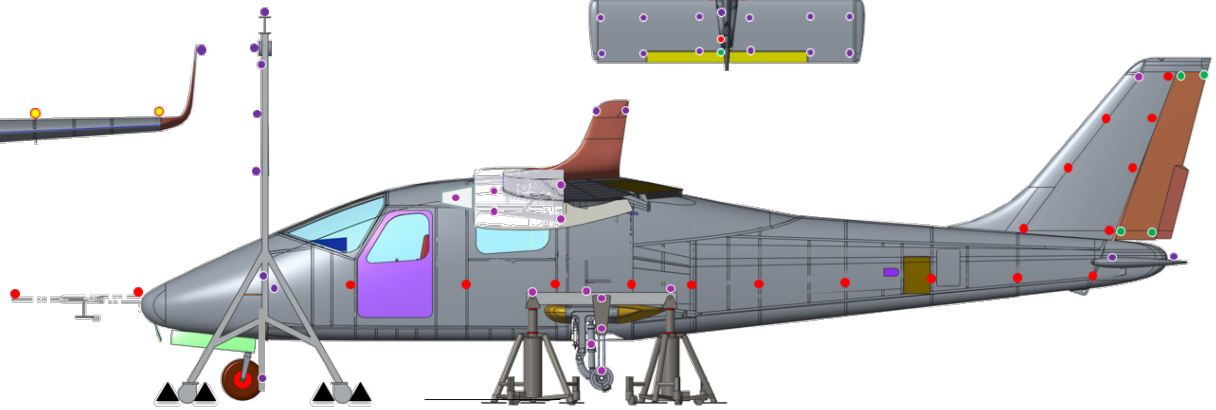
- Free-Free
  - 127 accelerometer locations measuring 318 degrees of freedom (DOF)
- On-Tires
  - Soft support accelerometers removed
  - 113 accelerometer locations measuring 276 DOF



X-57 Mod II GVT Accel Locations (Top View)



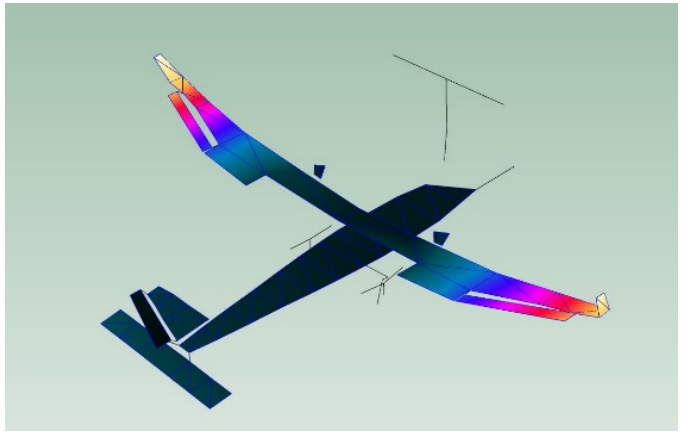
X-57 Mod II GVT Accel Locations (Front View)



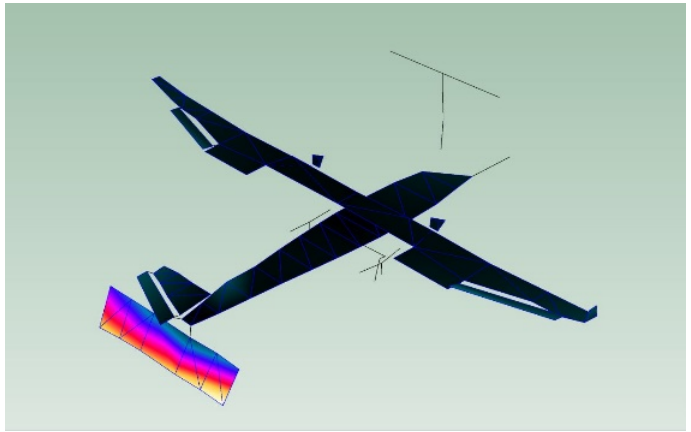
X-57 Mod II GVT Accel Locations (Lt Side View)

X-57 Mod II GVT – Aircraft Results

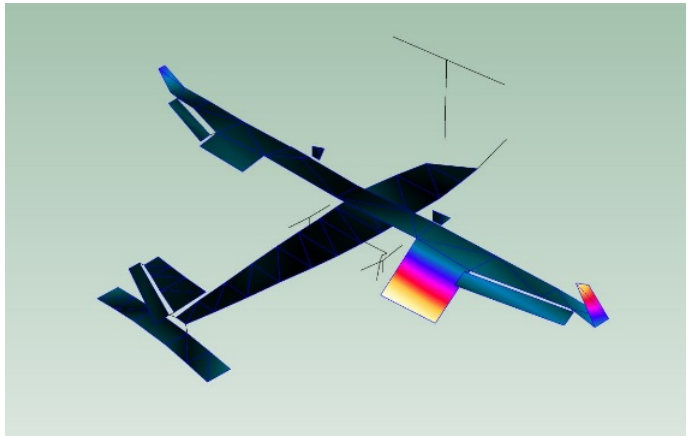
- GVT results processed in BK Connect with different parameter estimation techniques for both setups: Free-Free vs. On-Tires
- Many modes were found during the GVT that were missing in the pre-test FEM
- Asymmetries were seen between the left and right sides of the vehicle, particularly in the control surfaces, and were seen in all of the test configurations
- GVT modes for On-Tires setup do not necessarily follow the order in the Free-Free setup, with several modes not observed or missing
- Several modes from the Free-Free setup are coupled together in the On-Tires setup case



Sym Wing 1st Bending (SW1B)
7.83 Hz



Stabilator Rotation
14.17 Hz



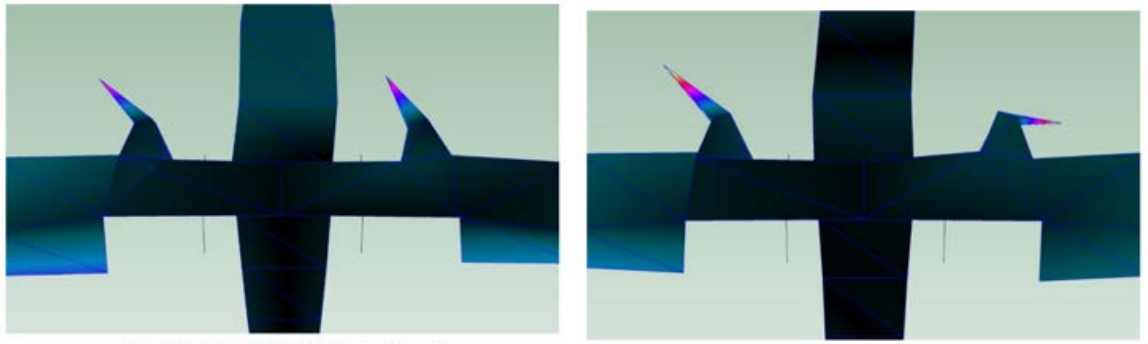
Sym Flap Rotation
34.40 Hz

X-57 Mod II GVT – Motor Results

- Motor results will focus on comparisons of the two main setups: Free-Free vs. On-Tires
  - Stab counterweight block installed, all control surfaces locked and cockpit locks (yoke & pedals) on
- Post-processing a bit tedious as motion from the wings and control surfaces tend to dominate over any motion from the motor assemblies
- Motor modes fell between 29 – 35 Hz for both setups, with the anti-symmetric motor lateral mode being the most different between setups
- Similar to the aircraft results, asymmetries were observed again between the left and right motor assemblies

Motor Mode Description	Free-Free Damped Frequency (Hz)	On-Tires Damped Frequency (Hz)	% Difference from Free-Free
Anti-Sym Motor Lateral	29.77	34.85	17.06%
Sym Motor Lateral	30.03	29.70	-1.08%
Anti-Sym Motor Vertical	34.28	33.43	-2.50%
Sym Motor Vertical	34.38	34.43	0.16%

Lateral Motor Modes



Anti-Symmetric Motor Lateral (Top View)

Symmetric Motor Lateral (Top View)

X-57 Mod II GVT – Rigid Body Results

- Aircraft rigid body tests were performed while the aircraft was installed on soft supports in order to identify the approximate frequencies of the 6 different rigid body modes and to evaluate the frequency separation between the highest rigid body mode (1.06 Hz) and the first aircraft elastic mode (7.83 Hz)
- Manual excitation was provided from test engineers and shakers were not used for rigid body tests

Rigid Body Mode	Average Damped Frequency (Hz)
Rigid Body Yaw	0.47
Rigid Body Lateral	0.53
Rigid Body Fore/Aft	0.68
Rigid Body Pitch	1.00
Rigid Body Roll	1.05
Rigid Body Plunge/Bounce	1.06

Rigid Body Roll Excitation

Rigid Body Fwd/Aft Excitation

X-57 Mod II GVT - Summary & Path Forward

- GVT assisted in understanding Mod II vehicle's modal characteristics
- Pre-test FEM did not capture all modes that appeared in GVT
- Asymmetries were present on both sides of the aircraft and were particularly visible in the control surfaces and motor assemblies
- On-Tires GVT showed some coupling of modes that were not seen in the Free-Free GVT
- Follow-on tasks include:
  - Updating post-test Mod II FEM to match the GVT results
  - Performing both Mod II classical and whirl flutter analyses to verify flight envelope flutter margins
  - Prepping for Mod II flight testing next year

Thank You

https://www.youtube.com/watch?v=wsjdk790JlI