X-56A Structural Dynamics Ground Testing Overview and Lessons Learned

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Outline

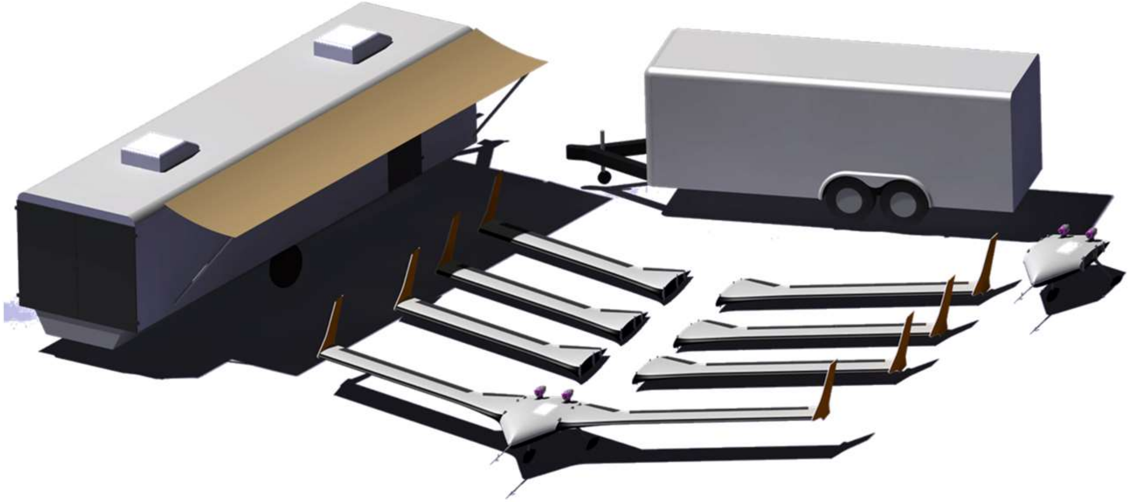
- Background and Motivation
- Ground Vibration Testing
  - Troubleshooting and Resolution
- Moment of Inertia Testing
- Lessons Learned

Background and Motivation

- Next generation aircraft will incorporate cutting-edge technologies that enable higher performance, while increasing structural efficiency through weight reduction.
- However, reducing weight often means reduced stiffness in the structure. Increased flexibility can make aircraft more vulnerable to various aeroelastic phenomena, such as flutter, buffet, buzz, divergence, and adverse gust response.
- The X-56 research vehicle is designed as a high risk aeroelastic aircraft to demonstrate active flutter suppression and gust load alleviation.
- Accurate structural modeling is critical for successful control of a highly flexible aircraft.

X-56 Research Vehicle

- Funded by Air Force Research Laboratory
- Designed by Lockheed Martin Skunkworks
- Delivered to NASA for continued research efforts
- Complete Research System
  - 2 Center Bodies (Fido and Buckeye)
  - 1 Stiff Wing Set
  - 3 Flexible Wing Sets
  - 1 Ground Control Station

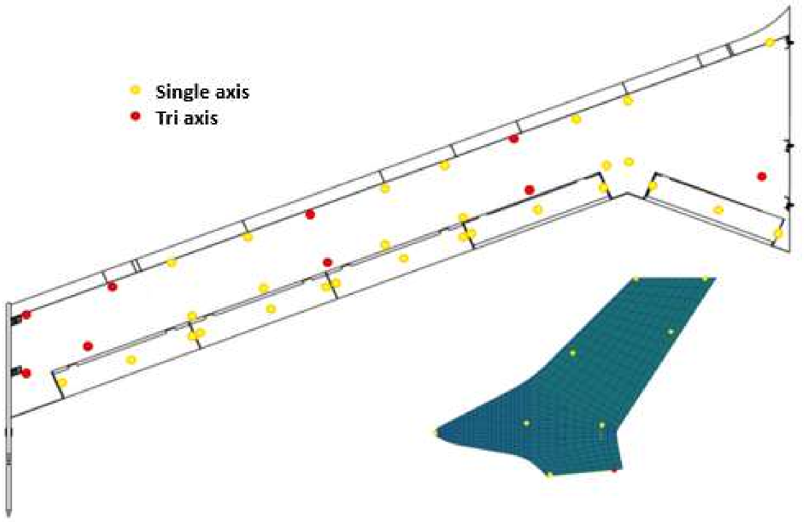


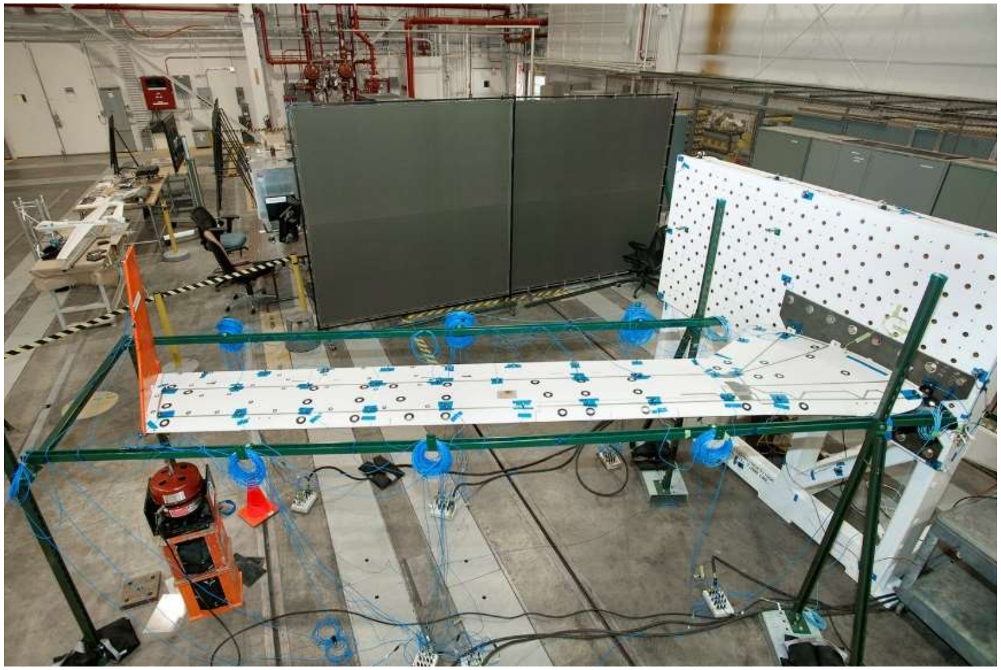
Structural Dynamics Ground Testing

- Lockheed Martin performed initial series of ground tests on Fido centerbody and wing sets
- NASA performed additional series of structural tests on Buckeye centerbody and wing set to address potential fabrication differences and configuration changes
- Buckeye fuselage had increased mass, change in mass distribution, shift in CG
- Wings were made from different batches of composite materials. Needed to verify consistency of fabrication.
- Required high confidence in finite element model (FEM) due to its integral role for developing models directly used in controller development

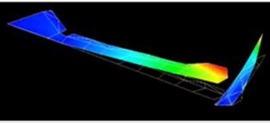
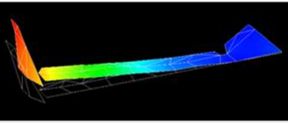
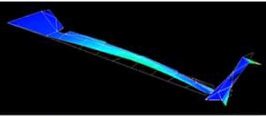
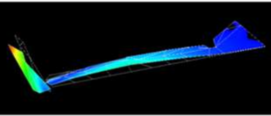
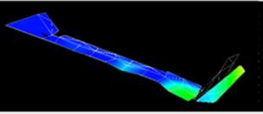
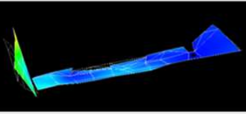
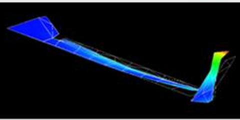
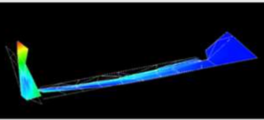
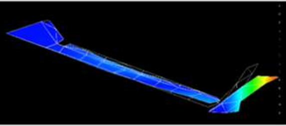
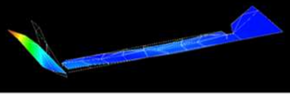
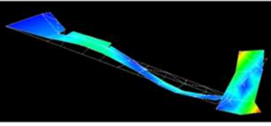
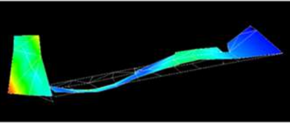
Wing-only Strongback GVT

- Compare and validate frequency response of both left and right wings.
- Determine any manufacturing differences.





Wing-only GVT results

Mode number	Mode shape (left wing)	Mode shape (right wing)	Frequency difference between left and right wing, %
1			-0.73
2			0.86
3			-0.12
4			0.08
5			4.54
6			3.36

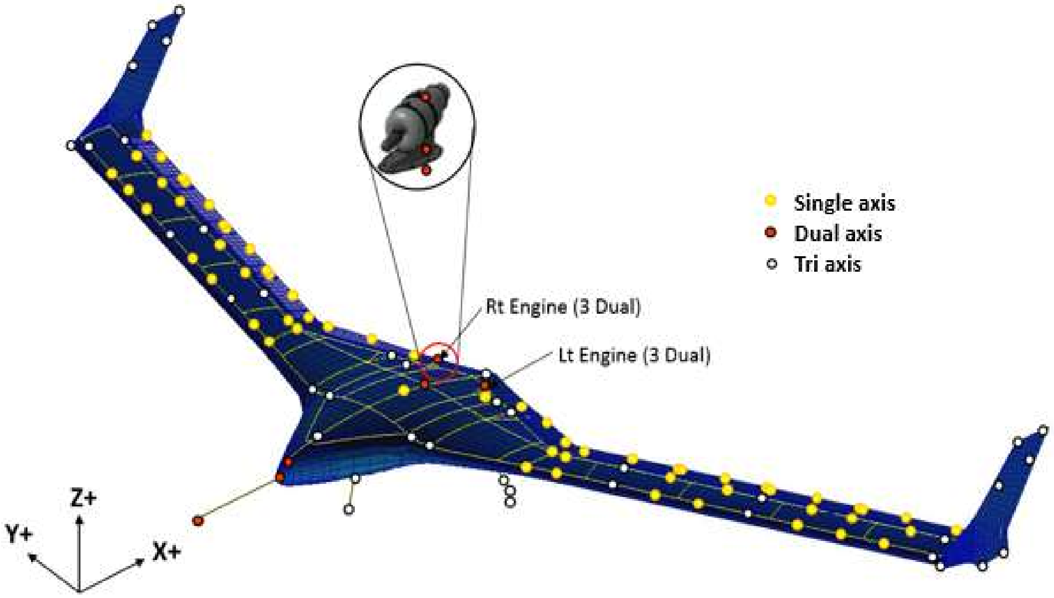
Conclusion: The left and right wings had similar structural dynamic properties

Full Vehicle Ground Vibration Test

- Conducted multiple GVTs in different aircraft, test, and fuel configurations
- Acquired damping, frequency, and mode shape for each GVT test configuration
- Data used for FEM model update and tuning in order to reduce model uncertainties between numerical and experimental modal data

Free – Free Full Fuel Configuration:
One Bungee Suspension Assembly

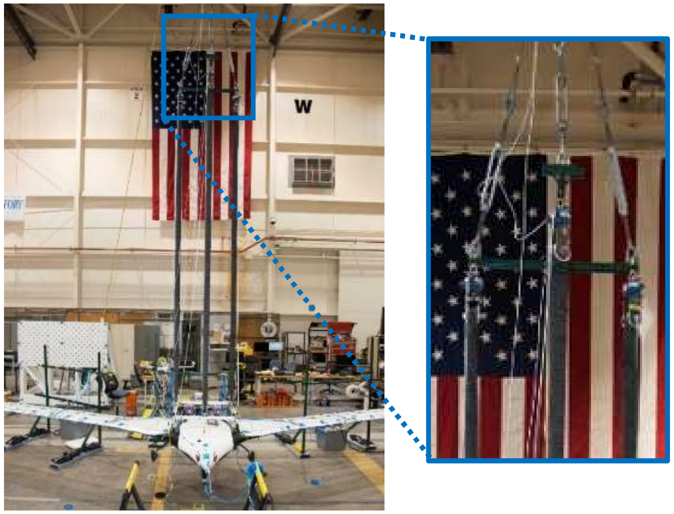
X-56A Aircraft GVT Data Collection



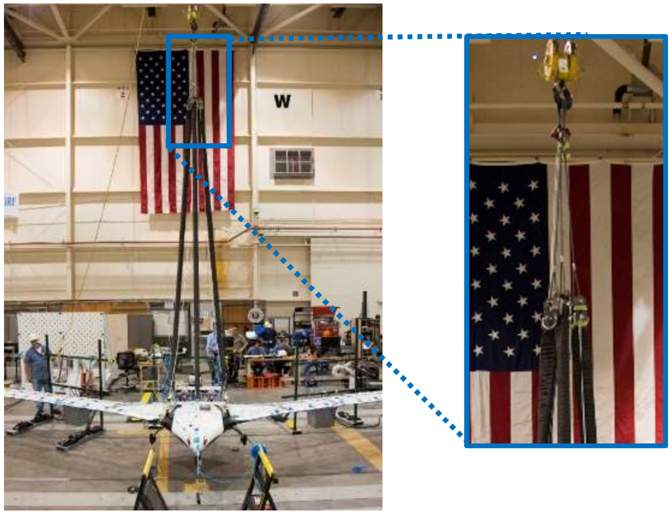
- GVT accelerometers
  - 119 accelerometer locations
  - 227 aircraft channels
  - 32 soft support system channels
- FOSS
- High-speed photogrammetry
  - Only for the left wing
  - 250 frames/sec
- Aircraft flight accelerometers

Progression of Soft Support Set-up

Challenges in the soft support boundary condition:



Original Three Bungee Suspension System with Spreader Bar ⇒

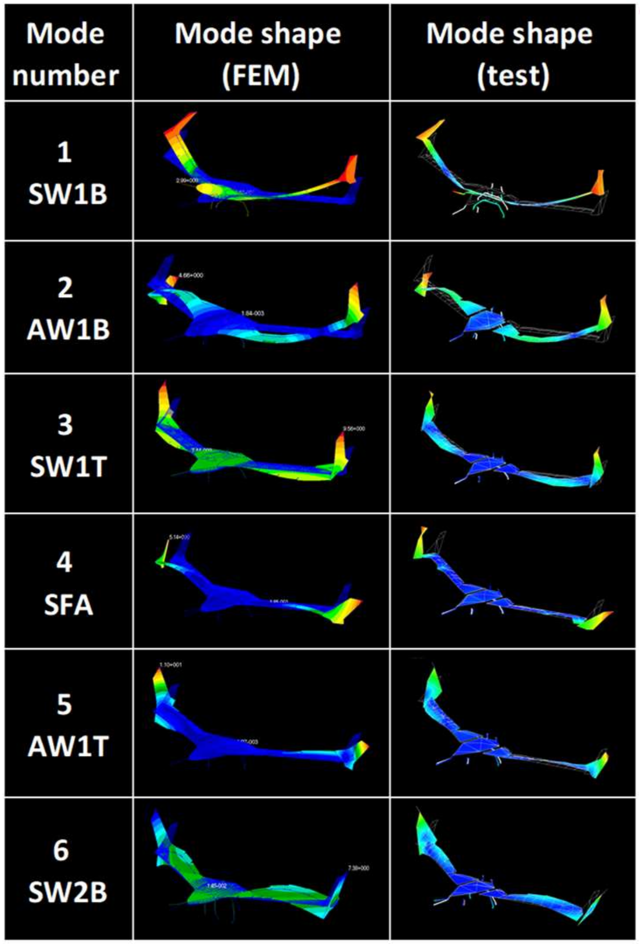


Modified Three Bungee Suspension System without Spreader Bar ⇒

Single Bungee Suspension System

Primary Mode Shapes

Mode number	GVT mode shape	Difference between FEM and test: Empty fuel, percent	Difference between FEM and test: Full fuel, percent
1	Symmetric Wing 1st Bending (SW1B)	-6.09	2.01
2	Antisymmetric Wing 1st Bending (AW1B)	-6.39	-3.31
3	Symmetric Wing 1st Torsion (SW1T)	-0.62	0.36
4	Symmetric Fore-Aft (SFA)	-0.04	-1.25
5	Antisymmetric Wing 1st Torsion (AW1T)	1.63	1.27
6	Symmetric Wing 2nd Bending (SW2B)	-1.31	-0.21



Mode number	Mode shape (FEM)	Mode shape (test)
1 SW1B		
2 AW1B		
3 SW1T		
4 SFA		
5 AW1T		
6 SW2B		

GVT Data Troubleshooting

- Added fuel mass should **decrease** the first bending frequency due to increased inertia
- Frequency shift from fuel weight was observed in the FEM and during subsequent flights
- The fuselage contributes significantly to the SW1B mode; therefore any external factors that can affect the fuselage dynamics can affect SW1B

Empty Fuel

Mode #	Mode	GVT (normalized freq)	FEM (normalized freq)
7	SW1B	1.000	1.061
8	AW1B	1.622	1.726
9	SW1T	3.561	3.539
10	SFA	4.001	4.000
11	AW1T	4.190	4.122

Full Fuel

Mode #	Mode	GVT (normalized freq)	FEM (normalized freq)
7	SW1B	0.997	0.977
8	AW1B	1.659	1.714
9	SW1T	3.539	3.526
10	SFA	3.901	3.950
11	AW1T	4.166	4.113

% Frequency Shift due to Fuel Load	
GVT	**FEM**
-0.33%	**-7.93%**
2.25%	**-0.71%**
-0.63%	**-0.37%**
-2.50%	**-1.25%**
-0.58%	**-0.21%**

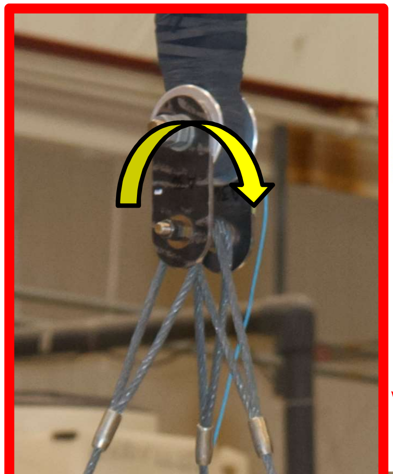
🟩 Primary Mode

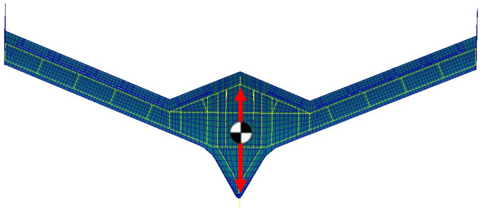
🟪 Secondary Mode

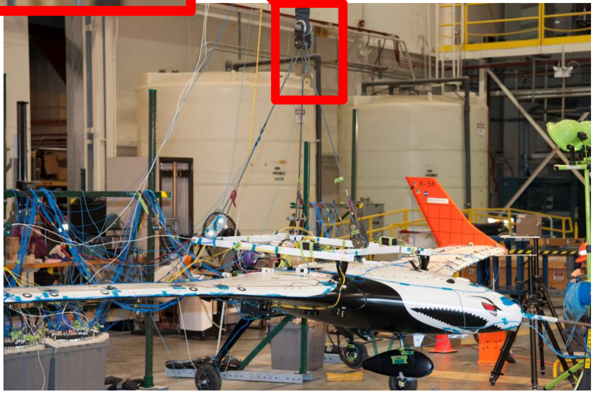
Notes:
* Free-Free GVT results calculated from single bungee configuration.
* Baseline FEM only models vehicle, no GVT lifting hardware is included
* All frequencies are normalized with respect to measured SW1B empty fuel

Bungee Set-up Scrutinized

- Vehicle was still free to pivot about sling-bungee connection (offset vehicle Y-axis)
- X_{CG} (fore-aft) of the vehicle shifts along the direction of the vehicle pitching motion between the empty and full fuel condition
- Metal wire slings will readjust attitude of vehicle to ensure vehicle CG is directly below bungee
- A sensitivity analysis on the bungee X-location was performed to determine its affect on rigid body and flexible modes







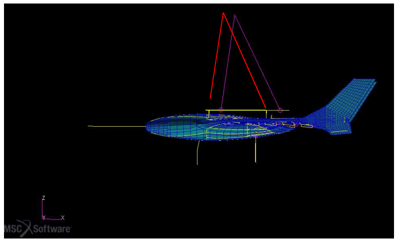
Varying FEM Bungee Pivot Point Results

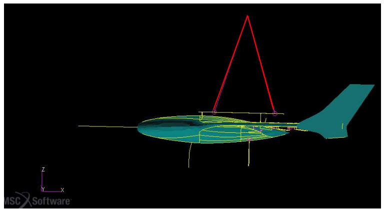
Pivot Forward

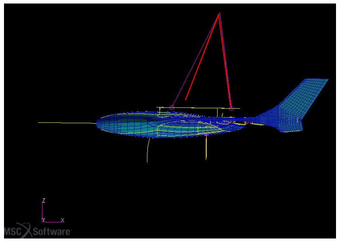
Pivot Neutral

Pivot Aft

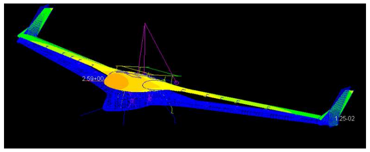
Bungee Pivot Location

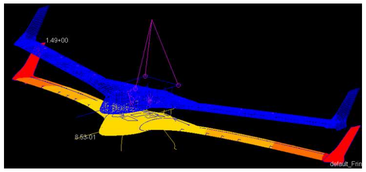


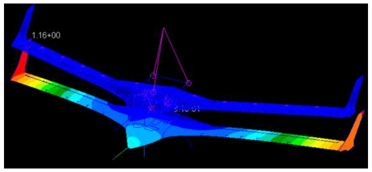


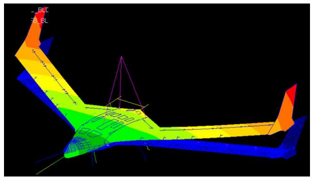


Rigid Body “Plunge” Mode

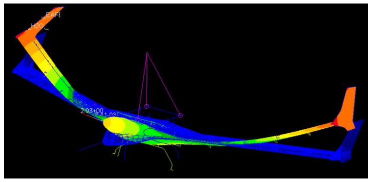


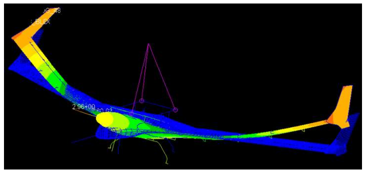


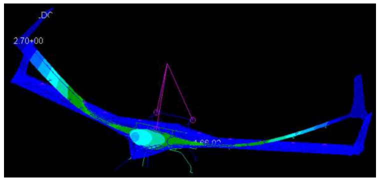


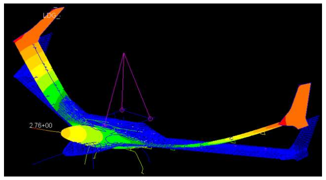


SW1B









0.41 RB “plunge mode”
1.05 SW1B mode

0.37 RB plunge mode
1.08 SW1B Mode

0.35 RB plunge mode
0.99 SW1B Mode

0.38 Hz RB “plunge” mode
1.03 Hz SW1B Mode

Empty Fuel

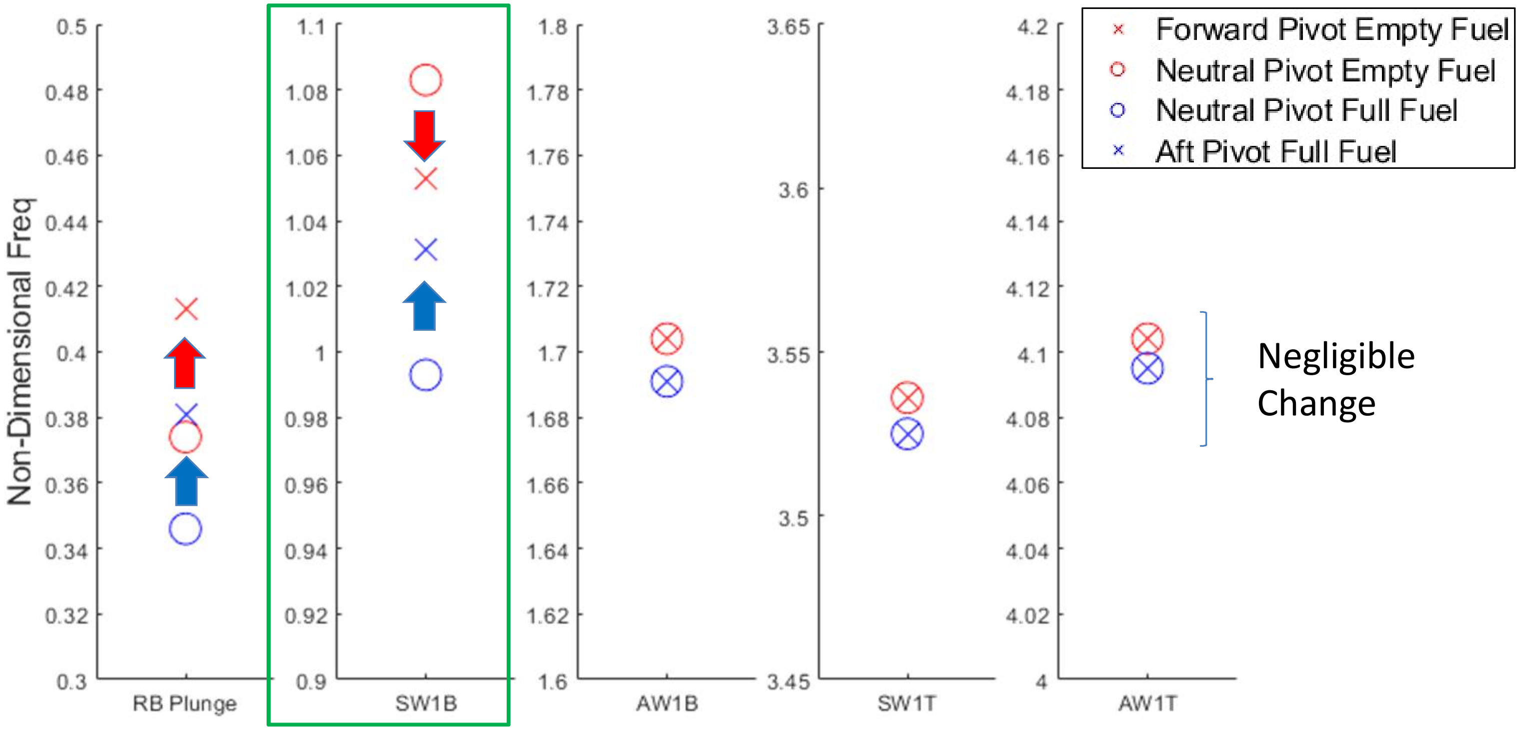
Full Fuel

SW1B frequencies approach each other when changing pivot location to account for CG shift

* All frequencies are normalized with respect to measured SW1B empty fuel

Examining other flexible modes

- Only the SW1B and rigid body plunge mode changes when fore-aft (X) location of pivot changes.
- Pivot location negligibly affects other primary flexible modes



Approaches same frequency for SW1B

Negligible Change

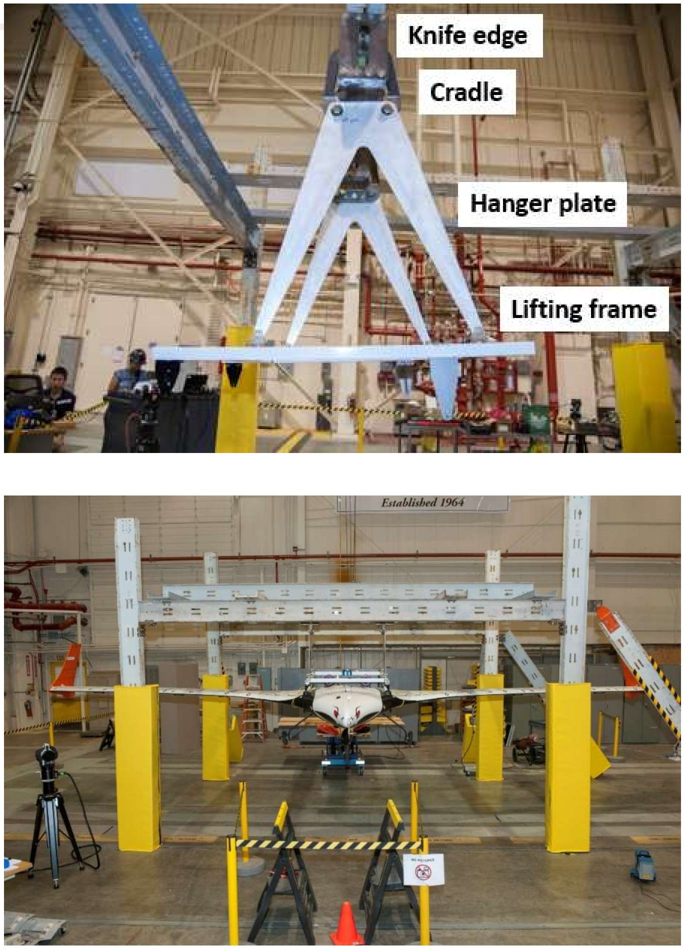
Moment of Inertia Test

Objective: Measure pitch MOI using compound pendulum method

$$I_{yy\_vehicle} = \frac{w_1 {T_1}^2 L_1}{4\pi^2} - \frac{w_2 {T_2}^2 L_2}{4\pi^2} - \frac{w_3 {L_3}^2}{g}$$

Configuration	Description	Pendulum length	Fuel condition
A	Lifting hardware only	Long	N/A
B	Lifting hardware only	Short	N/A
C	X-56A + lifting hardware	Short	Empty
D	X-56A + lifting hardware	Long	Empty

Calculated pitch moment of inertia was within 2.5% between short and long pendulum configurations



MOI Test Configuration

Lessons Learned

Wing-only Strongback Ground Vibration Test:

- Install additional tri-axial accelerometers at the winglet for better resolution of mode shapes.
- Power-on actuators to prevent drooping from excitations.

Full-Aircraft Ground Vibration Test:

- Additional scrutiny is required when using multiple bungees because of the increased risk of coupling between bungees or with the rigid-body modes of the flexible vehicle.
- Eliminate all potential degrees of freedom (that is, the metal sling rotation around the bungee) that could interfere with the rigid-body structural modes.
- Perform pre-test analysis with various boundary conditions to identify potential boundary-condition sensitivities for obtaining quality data.
- When possible, instrument the soft-support system (bungees and hardware) to verify their independence from the structural modes and to assist with any required troubleshooting.
- Ensure that the bungees are sufficiently flexible, and minimize interference in all degrees of freedom of interest.

Aircraft Pitch Moment of Inertia Test:

- When using knife-edges, curved-out V-channels further reduce friction.
- Use multiple sources for period measurement as a sanity check for accurate data.

Acknowledgements

- NASA Aeronautics Advanced Air Vehicles Program and the Advanced Air Transport Technology Project
- Air Force Research Lab
- Lockheed Martin Skunkworks
- Armstrong Flight Loads Lab
- ATA Engineering

Questions

Backup Reference Slides

X-56A Aircraft GVT Excitation Cases

- Shaker
  - Left & Right wings (45° & 90°)
  - Fuselage Fwd (Vert & Lat)
  - Fuselage Aft (Vert)
- Impact Hammer
  - Nose boom (Vert & Lat)
  - Nose landing gear (Fwd/Aft & Lat)
  - Main landing gear (Fwd/Aft & Lat)
  - Engines (Lat)
  - Left & Right wings (Vert)

Shaker

Impact Hammer

- Primary Modes:
    - Symmetric Wing 1st Bending (SW1B)
    - Antisymmetric Wing 1st Bending (AW1B)
    - Symmetric Wing 1st Torsion (SW1T)
    - Antisymmetric Wing 1st Torsion (AW1T)
- Secondary Modes
    - Symmetric Wing 1st Bending and Symmetry Main Landing Gear Lateral (SW1B & S MLG Lat)
    - Antisymmetric Wing 1st Bending Lateral and Antisymmetric Winglets (A MLG Lat & AWL)