X-56 Ground Vibration Test and Model Correlation

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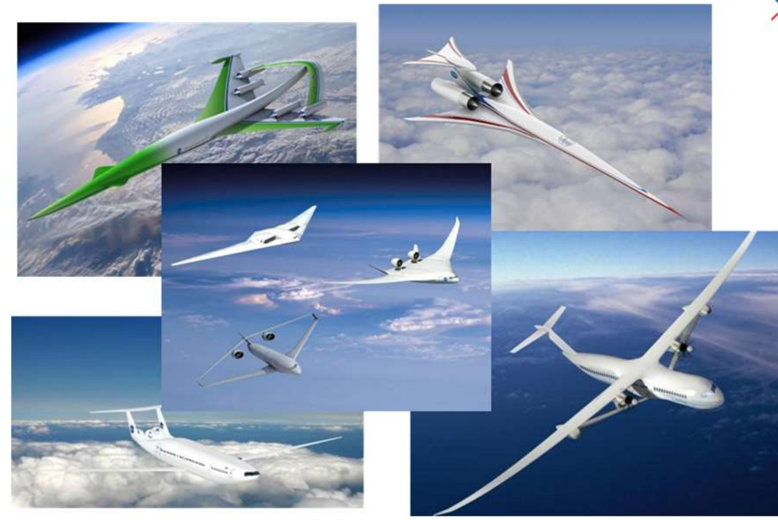
Outline

- Background and Motivation
- Ground Vibration Testing
- FEM Model Development and Correlation
- Troubleshooting and Resolution

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 and subsequently increased flexibility. This increased flexibility can make aircraft more vulnerable to various aeroelastic phenomena, such as flutter, buffet, buzz, divergence, and 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.



Ground Vibration Test

- Conducted multiple GVTs in different aircraft and test configurations
- Acquired damping, frequency, and mode shape for each GVT test configuration
- Characterized unique properties and behaviors of the fuselage centerbody and Flex Wing set #3
- Data used for FEM model update and tuning in order to reduce model uncertainties between numerical and experimental modal data
- Obtained fiber optic strain sensor (FOSS) and photogrammetry data in order to evaluate the feasibility of the FOSS sensor system for use as part of an active flutter and/or shape control architecture.

Free – Free Full Fuel Configuration: One Bungee Suspension Assembly

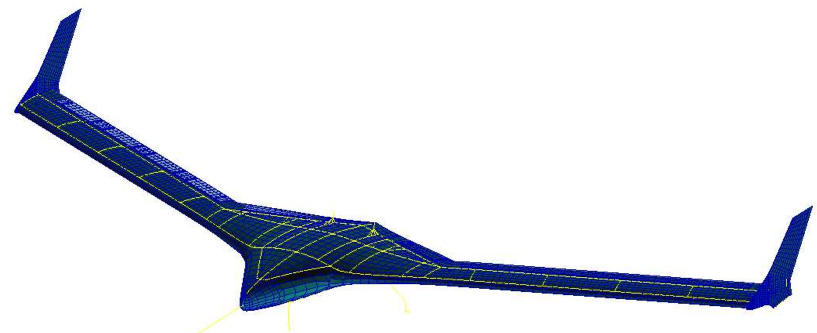
X-56A Aircraft GVT Data Collection

Free – Free Empty Fuel Configuration: One Bungee Suspension Assembly with Vertical Shaker on Fuselage

- 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

FEM Model Development

- Lockheed Martin developed X-56 finite element model
  - Modeled using MSC NASTRAN
  - 8000+ Nodes
  - Updated using GVT data from Fido vehicle at Lockheed Martin
- NASA Buckeye vehicle consists of similarly designed fuselage and flexible wing sets.
  - Model updated using Buckeye GVT data at AFRC



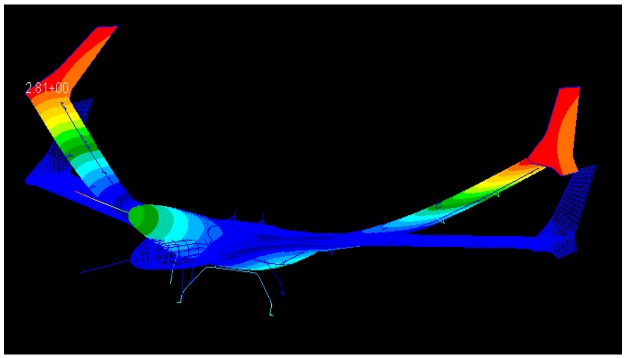
Structural Model Correlation

- Requirements: NASA Standard (NASA-STD-5002)
  - Agreement between test and analysis frequencies shall, as a goal, be within 5% for the significant modes
  - No requirement for non-primary modes: Rule of thumb is to correlate within 10% for all other modes.
- Requirements shall apply to two fuel cases: empty and full for simultaneous correlation
- Correlate primary and secondary modes to within 5%, all others within 10%:
  - 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)

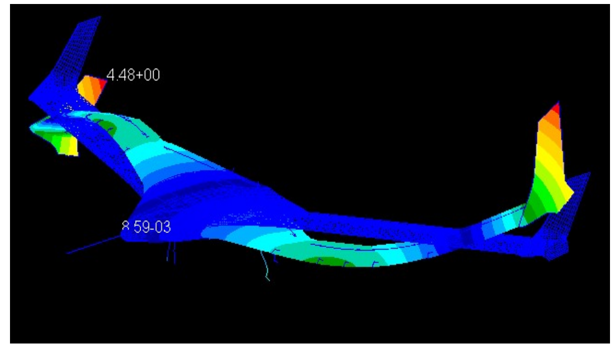
Mode	Normalized Contribution to Flutter Mode
Primary Mode	>12%
Secondary Mode	4%-12%
Tertiary Mode	<4%

- Preliminary flutter analysis determined primary and secondary flutter modes based on modal contributions to each flutter mode: body freedom flutter (BFF), symmetric wing bending torsion (SWBT), and antisymmetric wing bending torsion (AWBT)
- Sum of primary and secondary flutter modes should exceed 90% of total flutter contribution

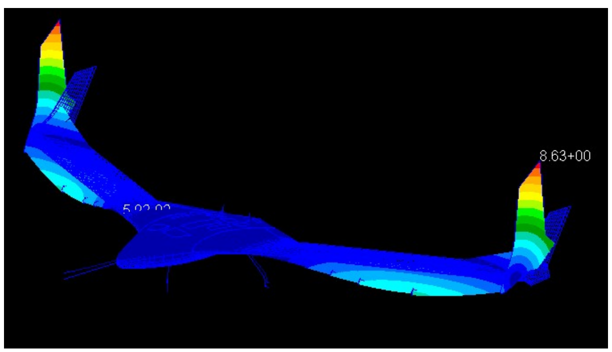
Primary Mode Shapes



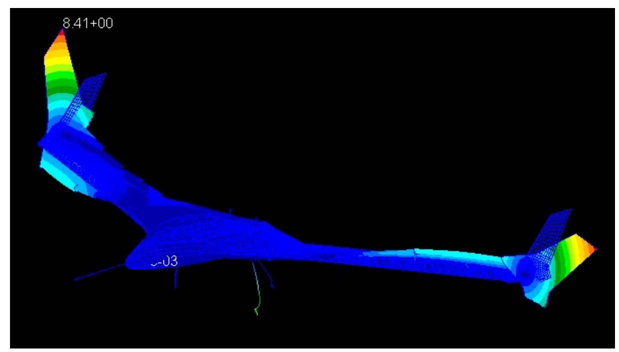
Mode 7: Symmetric Wing 1st Bending (SW1B)



Mode 8: Antisymmetric Wing 1st Bending (AW1B)



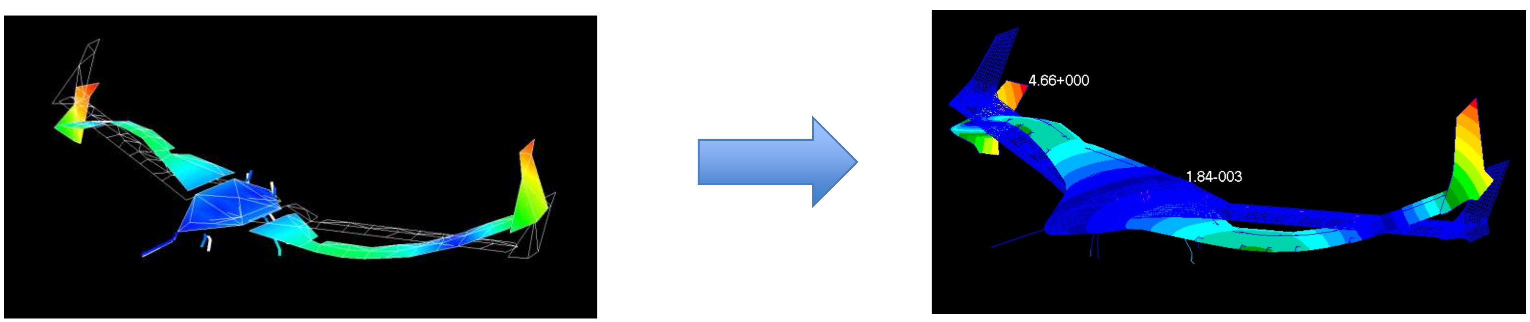
Mode 9: Symmetric Wing 1st Torsion (SW1T)



Mode 11: Antisymmetric Wing 1st Torsion

Structural Model Correlation

- Primary updates:
  - Main Landing Gear finite element model (FEM) geometry and stiffness
  - Mass and ballast updates
  - Decreased winglet bolt stiffness
  - Increased engine connection stiffness
  - Wing material properties: modulus of elasticity, shear modulus, inertias
- Parameters were updated using hand tuning and feedback from utilizing an in-house Object Oriented Optimization (O^3) Tool



Example: Correlating Anti-Symmetric 1st Wing Bending (AW1B) from GVT data to FEM

Frequency Correlation

Empty Fuel

mode	Mode Order (NMO)	%error	Target Error
1	SW1B	2.77	5%
2	AW1B	3.84	5%
3	SW1T	0.35	5%
4	SFA	-2.23	10%
5	AW1T	1.88	5%
6	SW2B & S MLG Lat	3.00	5%
7	A MLG Lat & AWL	3.61	5%
8	S MLG Lat & SWL	0.36	10%
9	Boom Lat	2.45	10%
10	AWL w/Boom Lat	2.65	10%
11	Boom Vert	-0.24	10%
12	AW2B	7.60	10%
13	SWL	6.50	10%
14	AWL w/ slight A Eng Lat	4.20	10%
15	AWL w/ A Eng Lat	-2.88	10%
16	S Eng Lat	4.02	10%
17	SW3B	-2.85	10%
18	AW3B	-0.51	10%
19	SW2T w/ SWL	1.17	10%
20	AW2T	4.46	10%
21	S MLG FA	-3.48	10%
22	A MLG FA	-3.28	10%

Full Fuel

mode	Mode Order (NMO)	%error	Target Error
1	SW1B	-4.86	5%
2	AW1B	0.83	5%
3	SW1T	0.49	5%
4	SFA	-0.94	10%
5	AW1T	2.20	5%
6	SW2B & S MLG Lat	2.74	5%
7	A MLG Lat & AWL	3.52	5%
8	S MLG Lat & SWL	-0.03	10%
9	Boom Lat	4.32	10%
10	AWL w/Boom Lat	1.09	10%
11	Boom Vert	-3.87	10%
12	AW2B	8.88	10%
13	SWL	9.06	10%
14	AWL w/ slight A Eng Lat	-1.89	10%
15	AWL w/ A Eng Lat	3.48	10%
16	S Eng Lat	-4.62	10%
17	SW3B	-2.13	10%
18	AW3B	4.59	10%
19	SW2T w/ SWL	2.79	10%
20	AW2T	5.43	10%
21	S MLG FA	-2.07	10%
22	A MLG FA	-3.13	10%

Model Update Summary

- Satisfied all Requirements for NASA Standard (NASA-STD-5002)
  - Test and analysis frequencies within 5% for the significant modes (primary and secondary)
  - All non-primary modes correlated to within 10%
- Mode shape correlation for primary modes correlated well, cross orthogonality check showed all off-diagonal terms for primary modes were <0.1
- Possible error in SW1B GVT data. Minimal frequency shift measured between empty and full fuel configurations. FEM analysis always shows a frequency shift.

GVT Data Troubleshooting

- GVT data between empty and full fuel mass conditions showed minimal frequency shift of the first flexible mode, symmetric wing first bending (SW1B)
- However, this frequency shift is expected because it was observed in the FEM and during flights. The shift also makes physical sense because added mass should decrease the first bending frequency due to the increased inertia.
- The fuselage contributes significantly to the SW1B mode. Therefore any external factors that can affect the fuselage dynamics is especially important in flexible modes such as SW1B.

Minimal frequency shift observed in for SW1B from empty and full fuel GVT data

Empty Fuel

Mode # wrt GVT (orig)	New GVT Count	Mode	GVT (normalized freq)	FEM (normalized freq)	Error	Target Error
7	1	SW1B	1.000	1.061	-6.09%	5%
8	2	AW1B	1.622	1.726	-6.39%	5%
9	3	SW1T	3.561	3.539	0.62%	5%
10	4	SFA	4.001	4.000	0.04%	5%
11	5	AW1T	4.190	4.122	1.63%	5%

Full Fuel

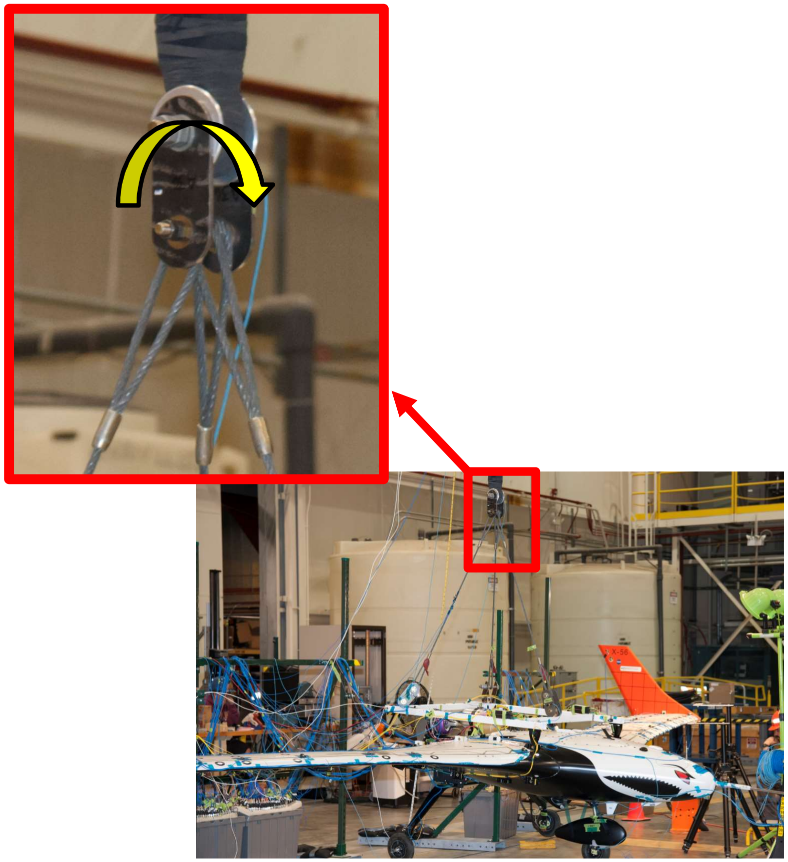
Mode # wrt GVT	New GVT Count	Mode	GVT (normalized freq)	FEM (normalized freq)	Error	Target Error
7	1	SW1B	0.997	0.977	2.01%	5%
8	2	AW1B	1.659	1.714	-3.31%	5%
9	3	SW1T	3.539	3.526	0.36%	5%
10	4	SFA	3.901	3.950	-1.25%	5%
11	5	AW1T	4.166	4.113	1.27%	5%

* Free-Free GVT results calculated from single bungee configuration.

* Baseline FEM only models vehicle, no GVT lifting hardware is included

Bungee Set-up Scrutinized

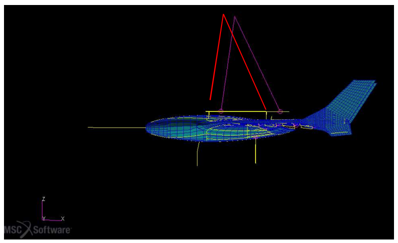
- The vehicle is still free to pivot about sling-bungee connection (offset vehicle Y-axis)
- This pivoting degree of freedom is relevant because the X_{CG} (fore-aft) of the vehicle shifts between the empty and full fuel condition, along the direction of the vehicle pitching motion
- Physics dictates that the single bungee and 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

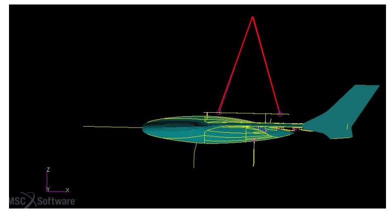


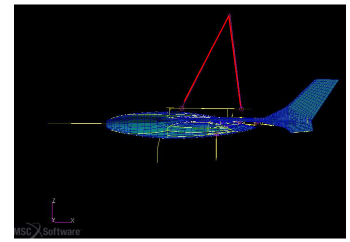
Varying Bungee Pivot Point Results

Pivot Forward | Pivot Neutral | Pivot Aft

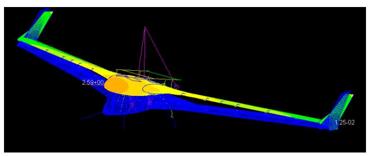
Bungee Pivot Location

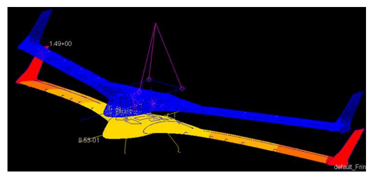


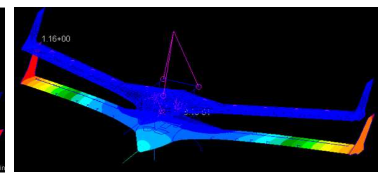


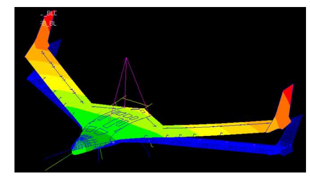


Rigid Body “Plunge” Mode

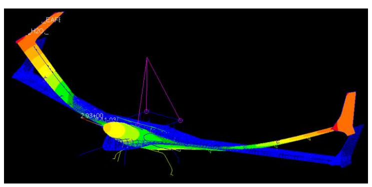


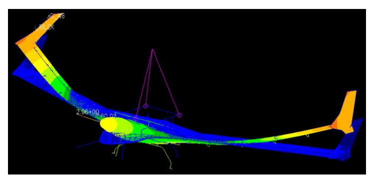


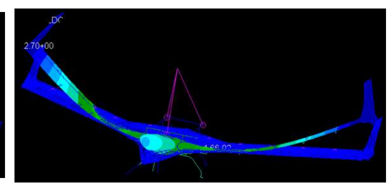


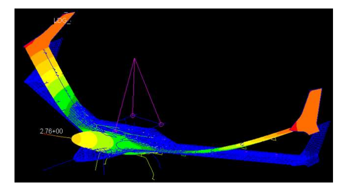


SW1B









0.41 Hz RB “plunge mode”
1.05 Hz SW1B mode
Empty Fuel

0.37 Hz RB plunge mode
1.08 Hz SW1B Mode
Empty Fuel

0.35 Hz RB plunge mode
0.99 Hz SW1B Mode
Full Fuel

0.38 hz RB “plunge” mode
1.03 Hz SW1B Mode
Full Fuel

Forward pivot Decreases EF SW1B frequency

Aft pivot Increases FF SW1B frequency

Examining other flexible modes

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

	Empty Fuel		Full Fuel	
Mode	**Forward Pivot- EF**	**Neutral Pivot -EF**	**Neutral Pivot -FF**	**Aft Pivot-FF**
RB Plunge Mode	0.413	0.374	0.346	0.381
SW1B	**1.053**	**1.083**	**0.993**	**1.031**
AW1B	1.704	1.704	1.691	1.691
SW1T	3.536	3.536	3.525	3.525
AW1T	4.104	4.104	4.095	4.095

Negligible Change

GVT Modeling Conclusions

- The location of the bungee pivot has a direct effect on the SW1B mode, but has negligible effect on other flexible modes
- Changing the location of the bungee pivot causes the rigid body plunge mode to change as well. As the pivot moves away from the neutral pivot location, the plunge mode exhibits more of a pitching motion
- The rigid body plunge/pitch motion closely mimics the fuselage motion in SW1B but is negligible in the other primary flexible modes
- Although the bungee pivot location does not completely account for non-shifting SW1B based on fuel load, the bungee pivot location does appear to have been a dominant factor in obtaining accurate measurements of SW1B. All other flexible modes are not affected by this and have been consistent with what has been predicted from the FEM and observed in flight.

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