Aeroelastic Model Tuning for Precise Flutter Prediction

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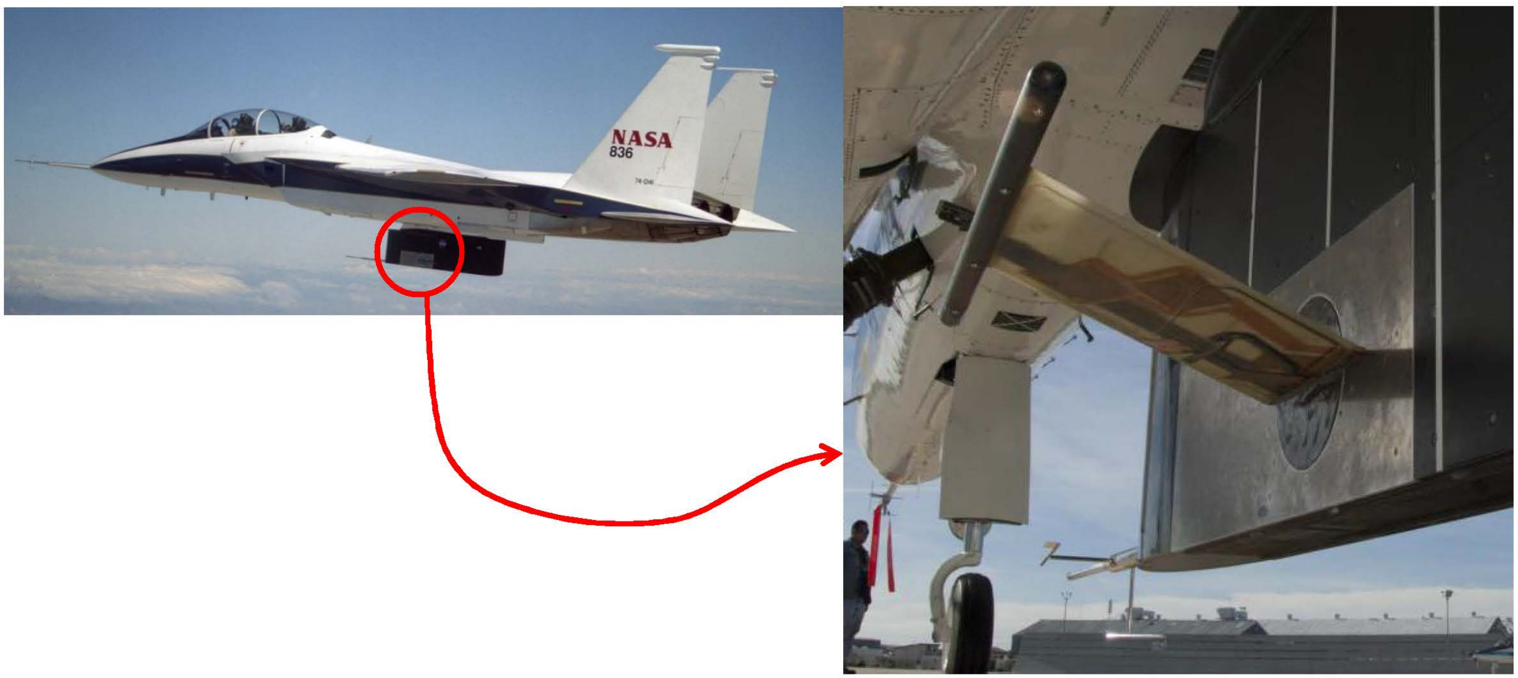
Overview

Objectives

- ❑ This work is supported by the Aeronautics Research Mission Directorate (ARMD) Subsonic Fixed Wing (SFW) and Supersonics (SUP) projects under Fundamental Aeronautics (FA) program.
- ❑ The primary objective of this study is to reduce uncertainties in the unsteady aerodynamic model of an aircraft to increase the safety of flight.

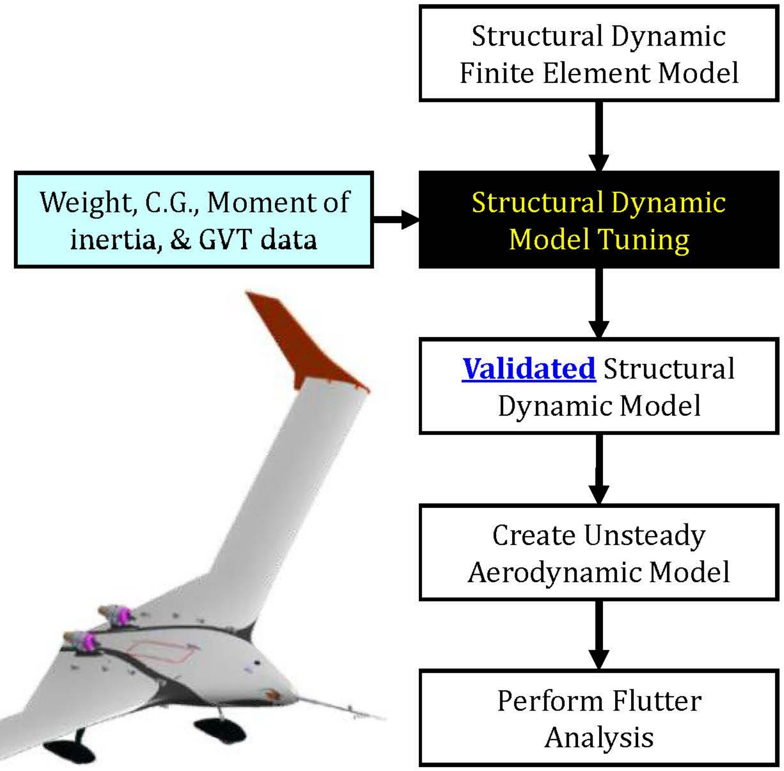


- ❑ This model tuning technique is applied to improve the flutter prediction of the Aerostructures Test Wing 2.

Structural Dynamic Model Tuning

Flutter Analysis Procedure @ NASA Armstrong

- Finite Element Structural Dynamics Model of a New or Modified Aircraft or Spacecraft
  - From Industry
  - In-house creation
- Quality of FE Model ??
  - Validate Structural Dynamic Finite Element Model using Test Data and **<u>Update if needed</u>**
  - Uncertainties in the structural dynamic model will propagate into other disciplines, such as aeroelasticity and con**trol law design**
- Flutter Analysis
  - Based on validated FE Structural Dynamic Mode**l**
    - Uncertainties in the structural dynamic mode**l are minimized** through the use of "model tuning technique"



MUTT or X56A

Model Correlation Requirements

- **References**
  - MIL-STD-1540C   Section 6.2.10
  - NASA-STD-5002   Section 4.2.6.d
  - AFFTC-TIH-90-001 (Structures Flight Test Handbook)
- **Frequency correlation**
  - Primary modes: within **5%** (NASA-STD) or **3%** (MIL-STD) of test frequencies
  - Secondary modes: within **10%** of test frequencies (no comments in standards)
- **Mass orthogonality**
  - Use orthogonality matrix: $\mathbf{\Phi_G}^T \mathbf{M} \mathbf{\Phi_G}$
    - $\mathbf{\Phi_G}$ = mode shape from GVT
    - $\mathbf{M}$ = analytical mass matrix
  - Primary modes: off-diagonal terms should be less than **10%** (0.1 when diagonal is 1.0)
  - Secondary modes: no comments in standards
- **Mode shape correlation**
  - Use cross-orthogonality matrix: $\mathbf{\Phi_G}^T \mathbf{M} \mathbf{\Phi_A}$
    - $\mathbf{\Phi_A}$ = mode shape from analysis
  - Primary modes: off-diagonal terms should be less than **10%** (0.1 when diagonal is 1.0)
  - Secondary modes: no comments in standards

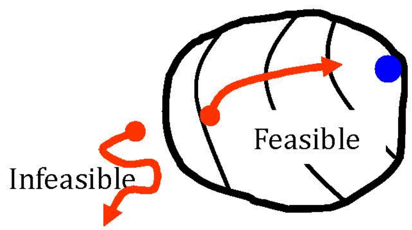
Structural Dynamic Model Tuning Procedure

#3

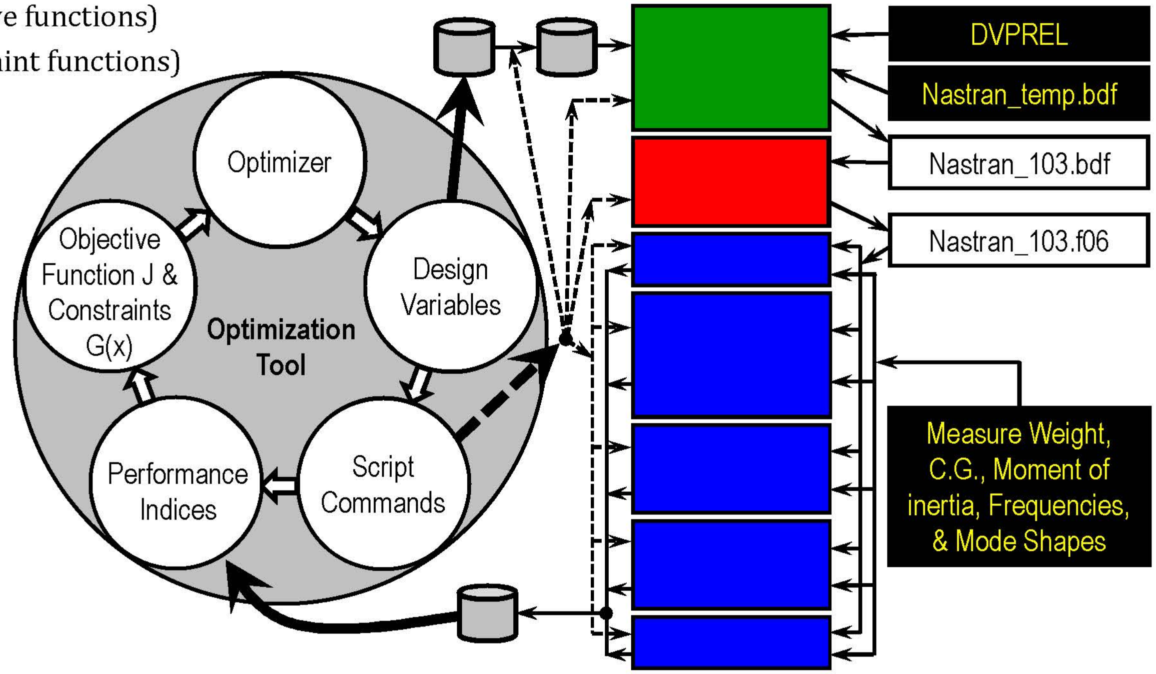
- Minimize “objective functions” using Object Oriented Optimization (O^3) tool which leverages existing tools and practices, and allows the easy integration and adoption of new state-of-the-art software.
- Optimization Problem Statement

  Minimize $J = \sum_i w_i j_i$ (performance index i selected for objective functions)

  Such that $j_k \leq \epsilon_k$ (performance index k selected for constraint functions)



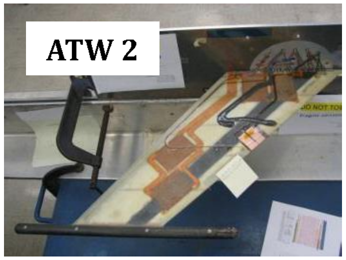
Starting design variable should belong to feasible domain to guarantee improvement.

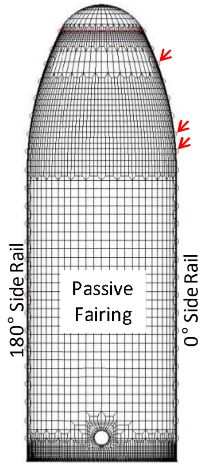


- Pak, C.-g., “Finite Element Model Tuning using Measured Mass Properties and Ground Vibration Test Data,” *ASME Journal of Vibration and Acoustics*, Vol. 131, Issue 1, February 2009.
- Pak, C.-g. and Lung, S.-f., “Flutter Analysis of the Aerostructures Test Wing with Test Validated Structural Dynamic Model,” *AIAA Journal of Aircraft*, Vol. 48, No. 4, 2011, pp. 1263-1272.
- Pak, C.-g. and Truong, S., “Creating a Test-Validated Finite-Element Model of the X-56A Aircraft Structure,” *AIAA Journal of Aircraft*, Vol. 52, No. 5, 2015, pp. 1644-1667.

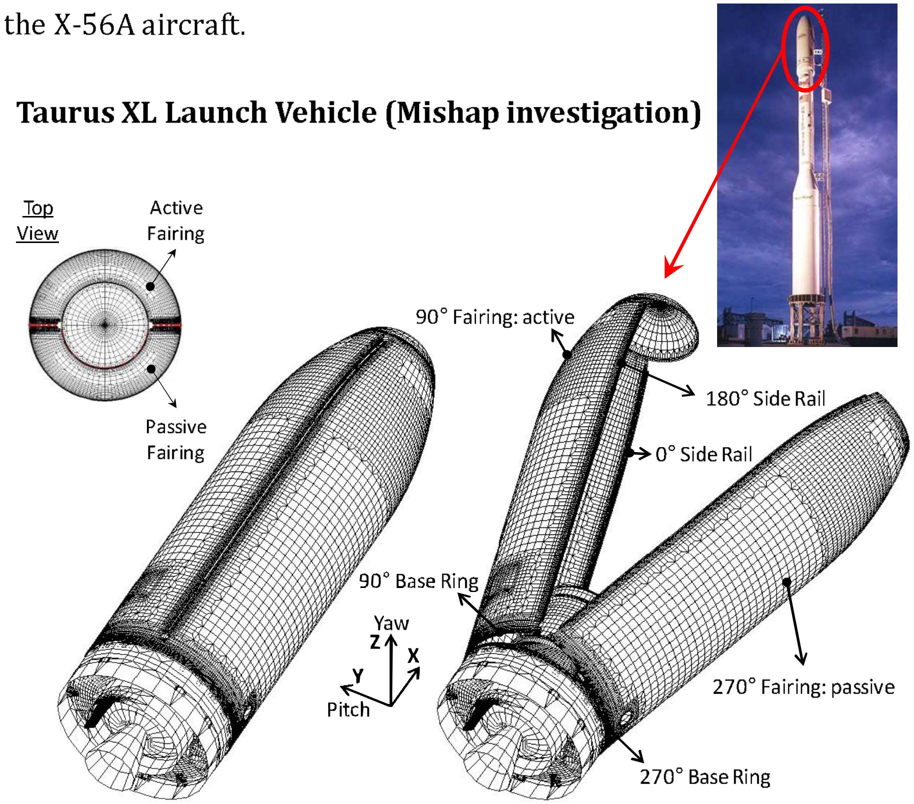
Previous Applications

- X-37 Drogue Chute Test Fixture
- Quiet Spike Boom
- Aerostructures Test Wing 2
- Glory Mishap Investigation: Use "Topology Optimization"
- This model tuning technique will be applied to improve the flutter prediction of the X-56A aircraft.





Taurus XL Launch Vehicle (Mishap investigation)

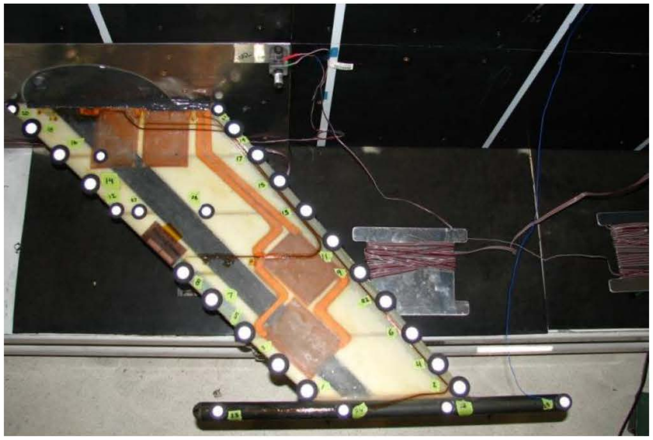


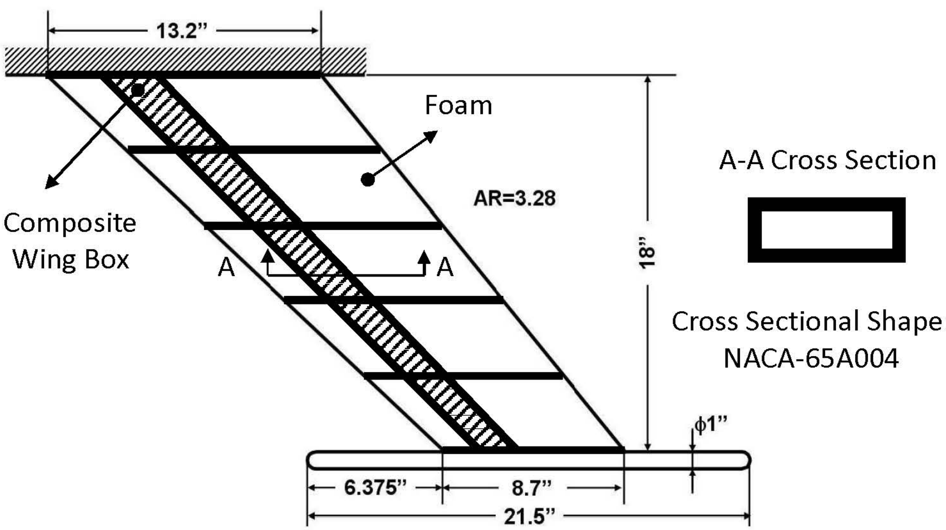
Topology Optimization

Also used during mishap investigation to figure out mishap configuration.

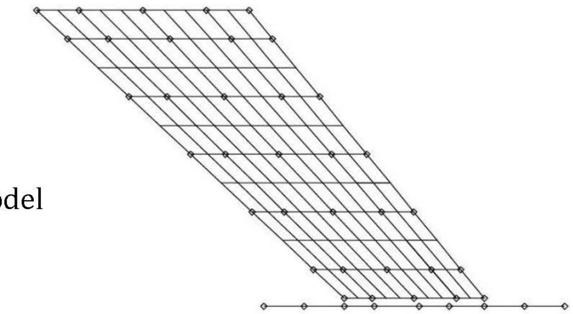
Structural Dynamic & Unsteady Aerodynamic Models

#2

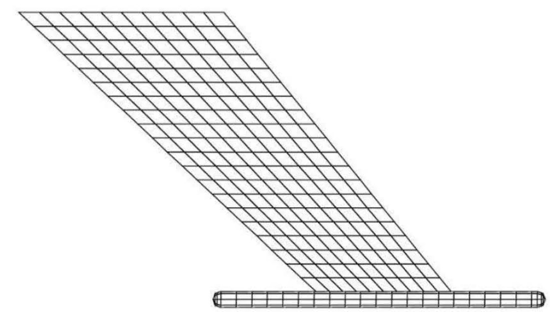




- ❑ Structural Dynamic Finite Element Model
  - ❖ Based on MSC/NASTRAN code
  - ❖ Use ATW1 Structural Dynamic Finite Element Model (265 nodes)
  - ➢ ATW1 & ATW2: Based on same drawing
  - ❖ Use 10 modes for the flutter analysis

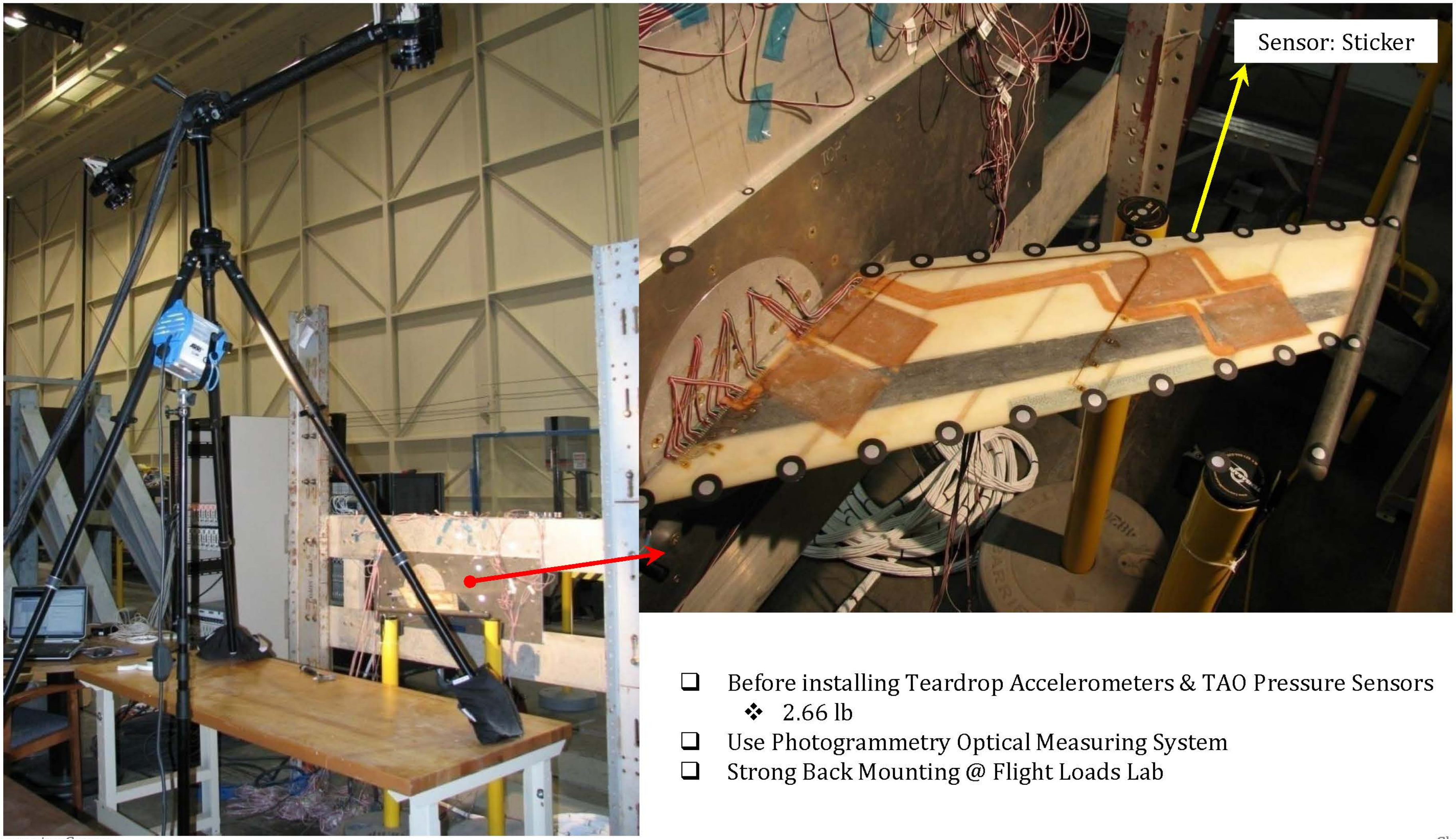


- ❑ Unsteady Aerodynamic Model
  - ❖ Based on ZAERO code
  - ❖ 416 elements
  - ❖ Select 16 reduced frequencies between 0 & 1
  - ❖ Mach = .60, .75, .82, and .95
  - ❖ Linear Theory
  - ❖ Use Matched Flutter Analysis



Test Setup: #1 GVT (Strong Back Mounting)

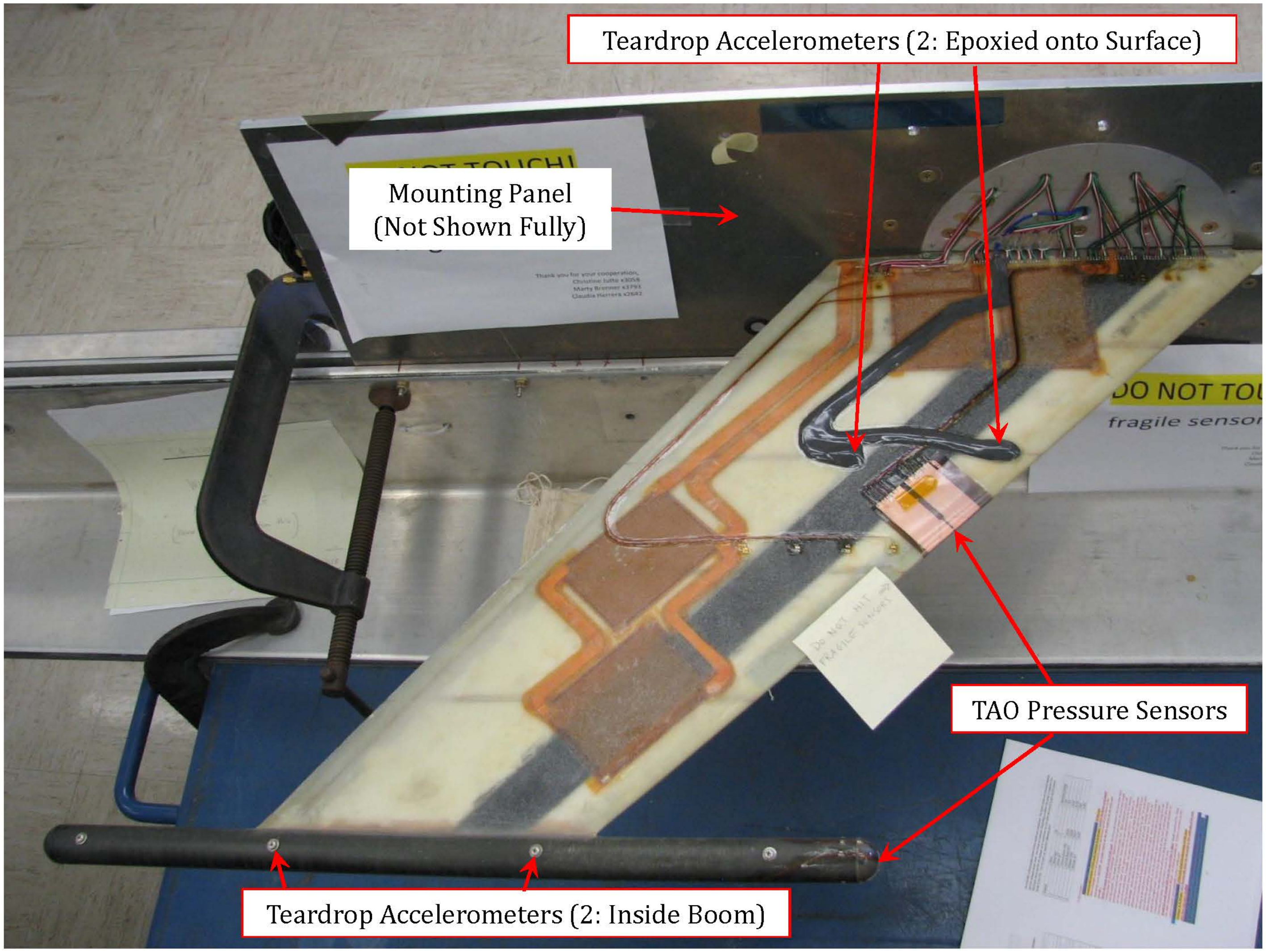
#2



- Before installing Teardrop Accelerometers & TAO Pressure Sensors
  - 2.66 lb
- Use Photogrammetry Optical Measuring System
- Strong Back Mounting @ Flight Loads Lab

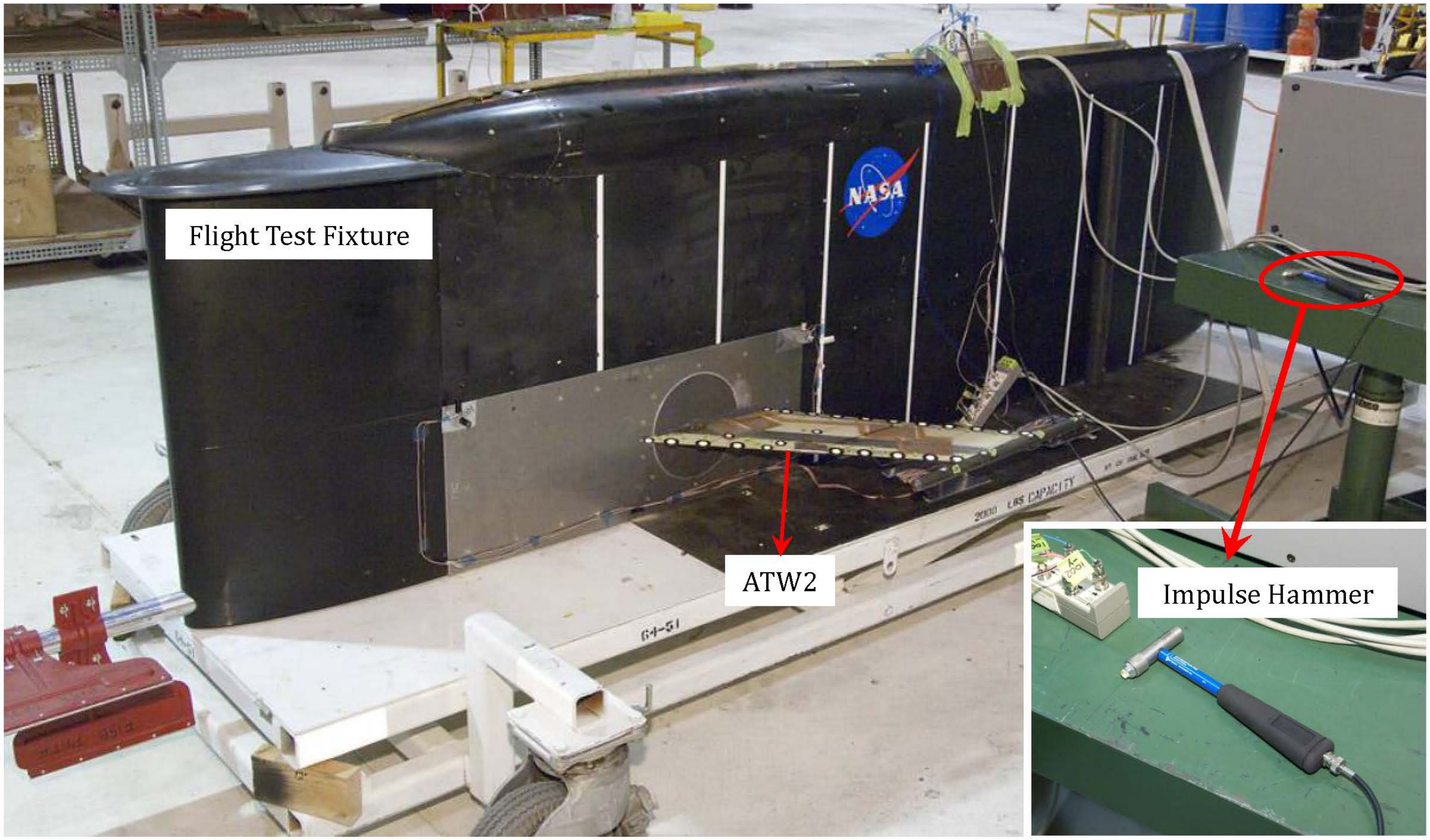
Additional Sensors for Flight Test

Bottom View



Test Setup: #2 GVT (FTF Mounting)

- After installing 4 Teardrop Accelerometers & 2 TAO Pressure Sensors
- Flight Test Fixture Mounting @ F-15B Hanger
- Flight Test Fixture was lot heavier than ATW2.
  - FTF ≈ 500 lb vs. ATW2 ≈ 2.66 lb: 500/2.66=188 >> 10



Test Setup: #3 GVT (FTF Mounting under F-15)

#2

- After installing under the Center Fuselage Pylon
- Add Flexibilities between Flight Test Fixture & Center Fuselage Pylon

Summary of the Modal Participation Factors

#2

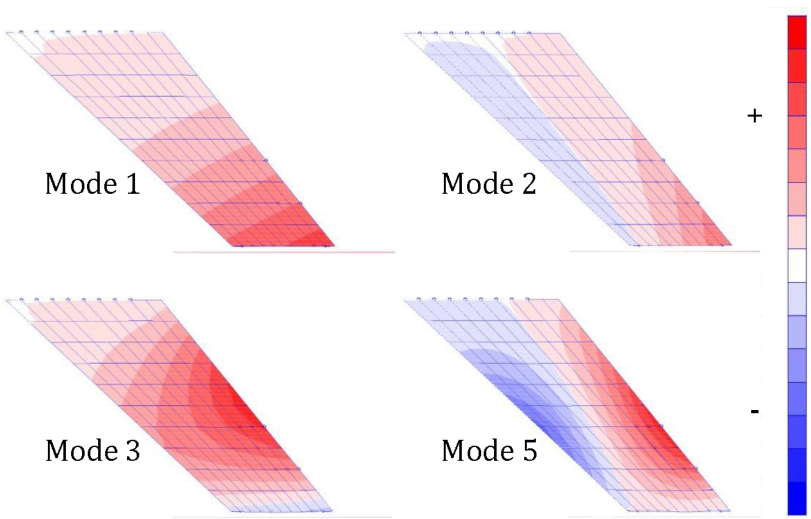
Mode	Frequency	Modal Participation Factor							
		Mach = 0.60		Mach = 0.75		Mach = 0.82		Mach = 0.95	
1	**17.60 Hz**	**68.1 %**	**95.5 %**	**72.9 %**	**96.2 %**	**75.0 %**	**96.6 %**	**79.7 %**	**97.6 %**
2	**23.26 Hz**	**22.2 %**		**18.3 %**		**16.8 %**		**13.6 %**	
3	**93.99 Hz**	**5.2 %**		**5.0 %**		**4.8 %**		**4.3 %**	
4	135.4 Hz	0.0 %	4.5 %	0.0 %	3.8 %	0.0 %	3.4 %	0.0 %	2.4 %
5	163.1 Hz	3.3 %		2.9 %		2.6 %		1.9 %	
6	174.5 Hz	0.0 %		0.0 %		0.0 %		0.0 %	
7	257.5 Hz	0.7 %		0.6 %		0.5 %		0.3 %	
8	391.6 Hz	0.0 %		0.0 %		0.0 %		0.0 %	
9	394.3 Hz	0.1 %		0.1 %		0.1 %		0.0 %	
10	445.6 Hz	0.4 %		0.3 %		0.3 %		0.2 %	

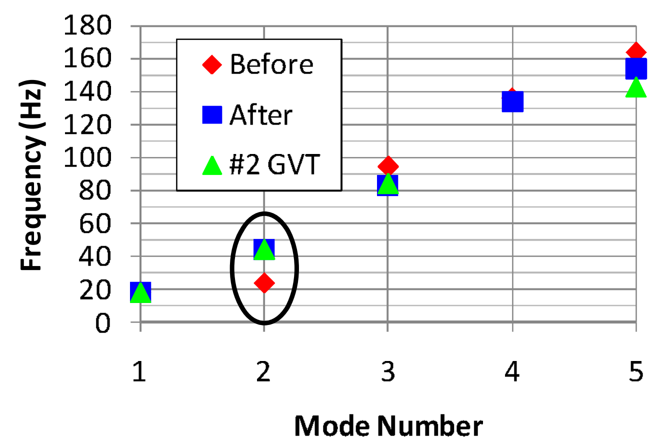
- Participation of the first three modes is a function of Mach number.
- In-plane modes do not participate for the first flutter mechanism at all.
  - Modes 4, 6, and 8
- Primary Modes: Modes 1, 2, and 3
  - Frequency error should be less than 3%.
- Secondary Modes: Modes 4 through 10 (higher)
  - Frequency error should be less than10%.

Results (Frequency Comparisons)

#2

Mode	GVT (Hz)			Before Tuning				After Tuning (Target #2 GVT data)				MIL-STD (%)
	#1: Strong Back	#2: FTF	#3: FTF & F15B	Freq (Hz)	Error (%)			Freq (Hz)	Error (%)			
					Wrt #1	Wrt #2	Wrt #3		Wrt #1	Wrt #2	Wrt #3	
1	17.24	17.45	17.42	17.60	2.09	0.86	1.03	17.45	1.22	0.00	0.17	3
2	**44.10**	**43.72**	**43.73**	**23.26**	**-47.3**	**-46.8**	**-46.8**	**43.48**	**-1.41**	**-0.55**	**-0.57**	**3**
3	84.00	83.66	84.14	93.99	11.9	12.4	11.7	82.98	-1.21	-0.81	-1.38	3
4	N/A	N/A	N/A	135.4	N/A	N/A	N/A	133.6	N/A	N/A	N/A	
5	N/A	142.3	143.0	163.1	N/A	14.6	14.1	153.8	N/A	8.08	7.55	10





Results (Total Weight, Orthogonality, & MAC)

#2

		Measured	Before Tuning			After Tuning		
Total Weight		2.66 lb	1.76 lb (error 34%)			2.85 lb (error 7.1%)		
Orthonormalized Mass Matrix			1	2	3	1	2	3
	1		1	-24.9%	38.0%	1	-1.92%	-4.46%
	2		-.249	1	-66.1%	-.0192	1	6.16%
	3		.380	-.661	1	-.0446	.0616	1
MAC	Mode 1		.97			.99		
	Mode 2		.70			.99		
	Mode 3		.75			.98		

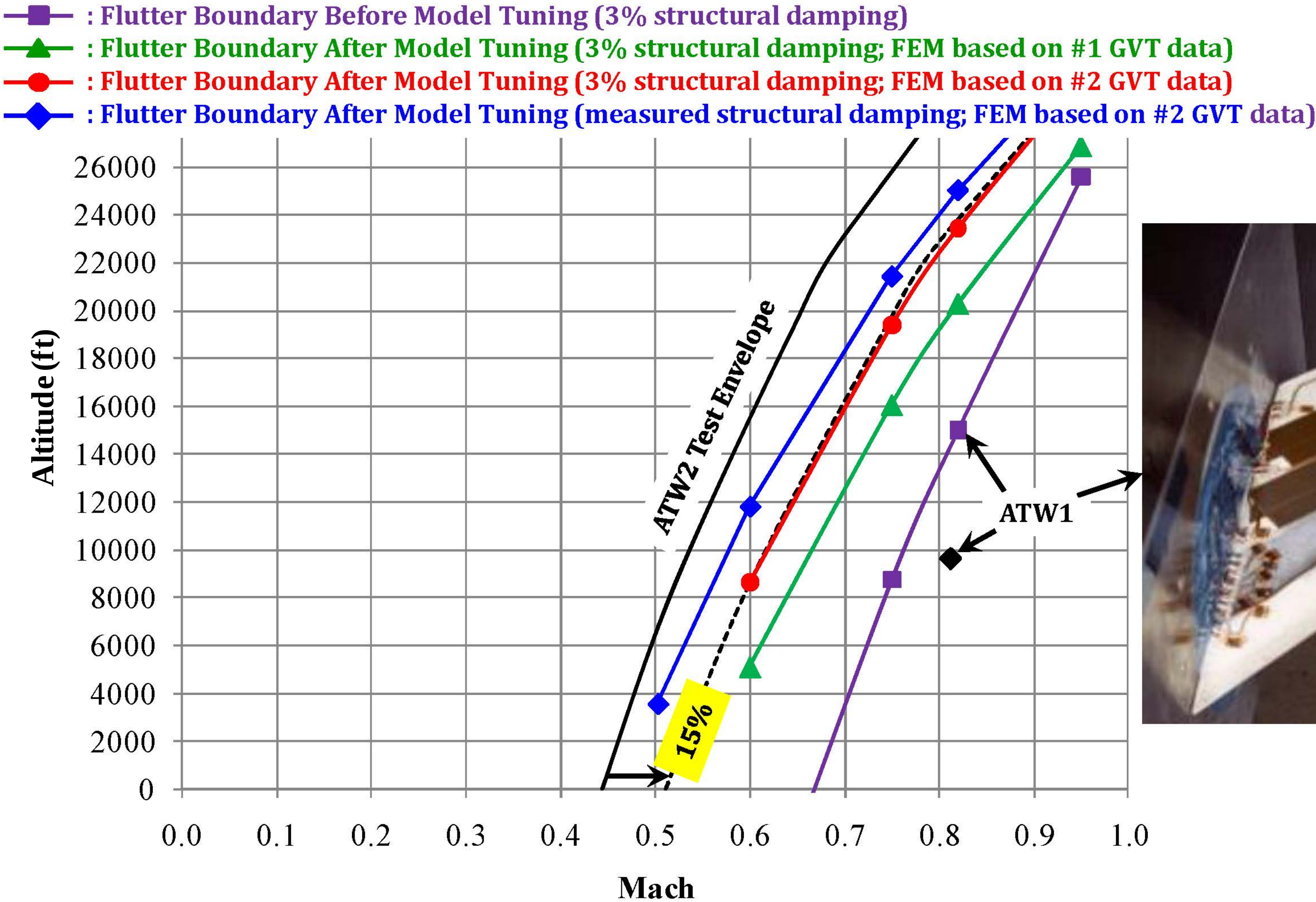
Violate

Satisfy

MIL-STD & AFFTC-TIH-90-001 Requirements: 10%

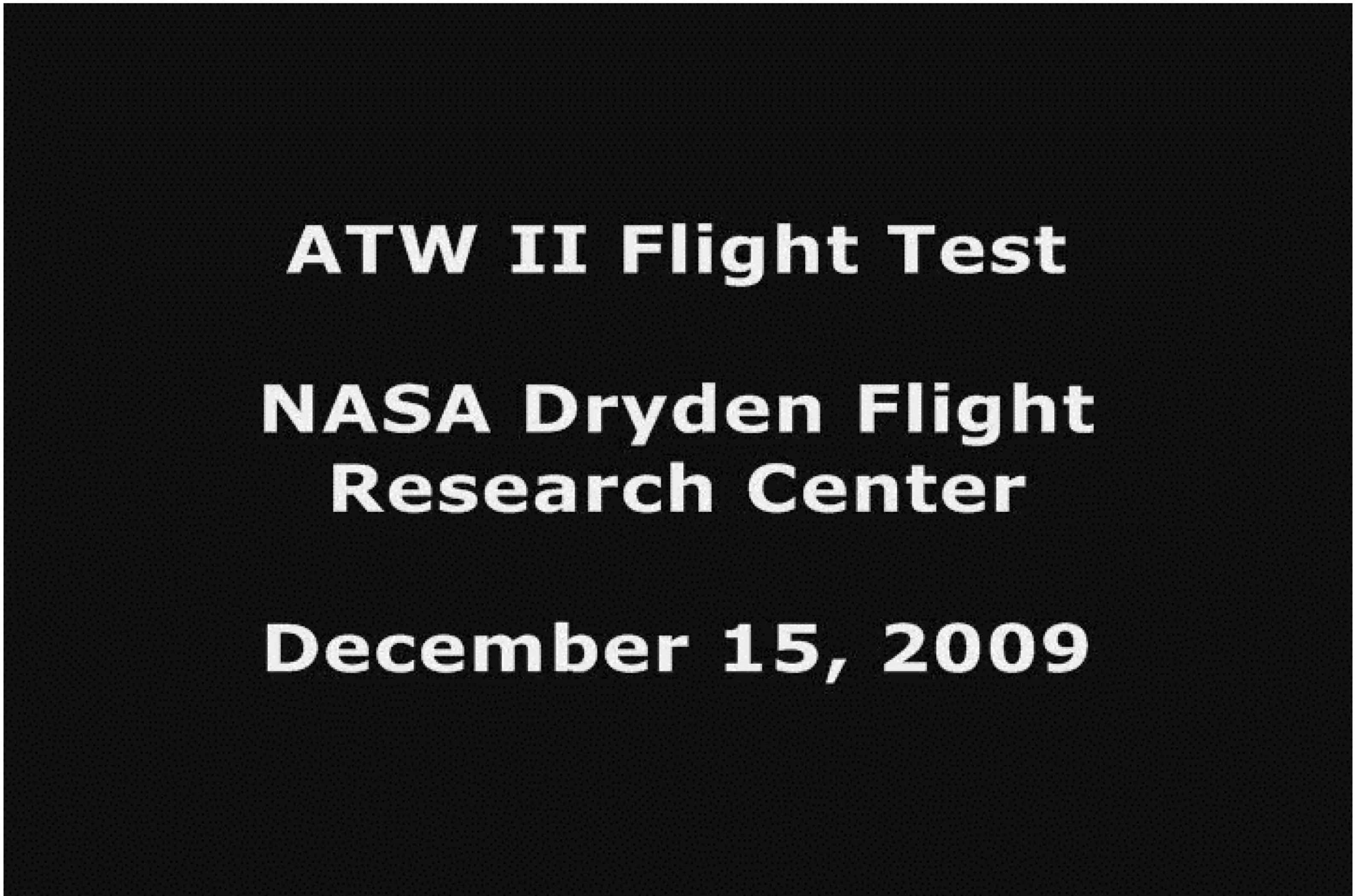
Flight Test & Summary of Flutter Margins

Flutter Boundaries vs. Flight Envelope

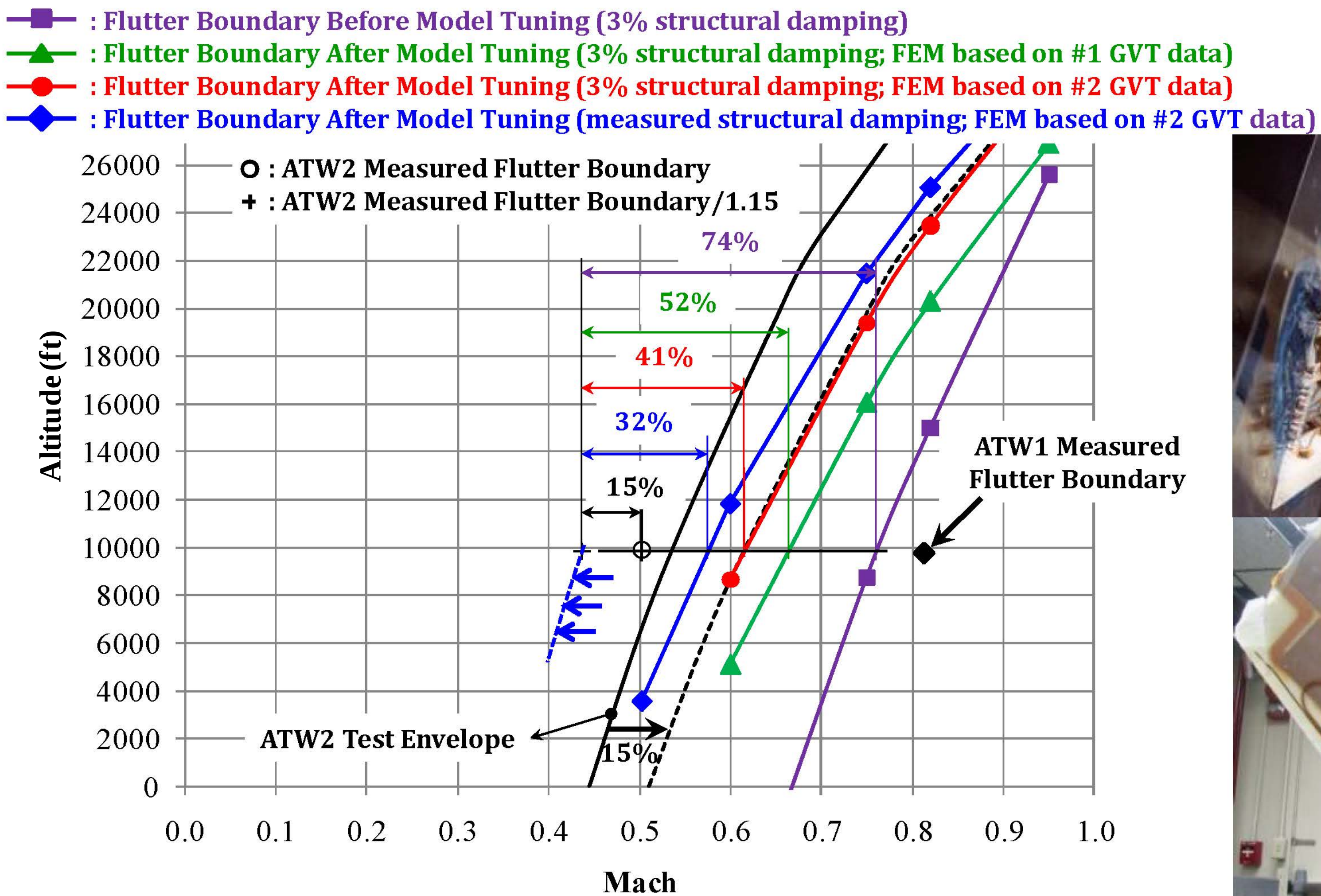


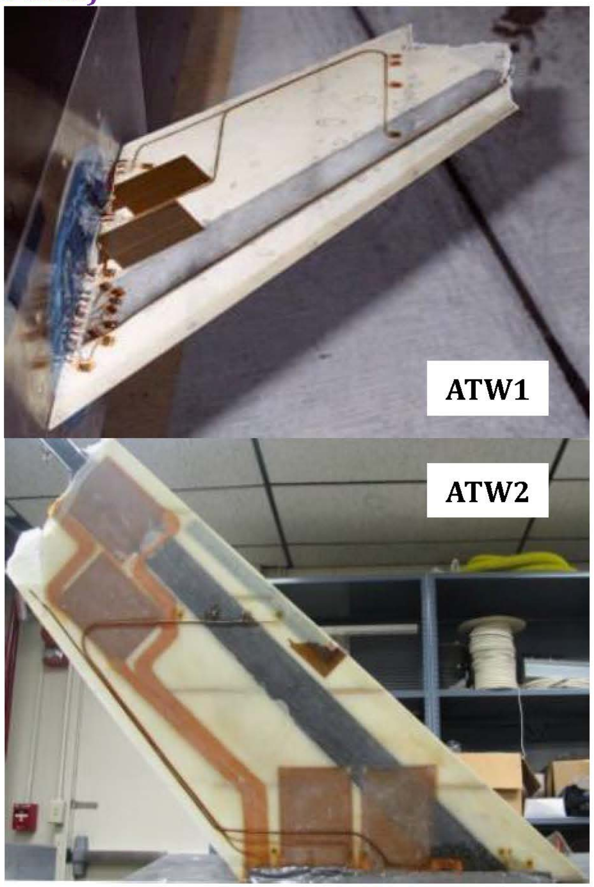
ATW2 Flight Test

#2



Summary of Flutter Margins





Summary of Flutter Margins (continued)

#2

Flutter Boundaries	Flutter Speed Differences
Measured/1.15 = V_d	0 %
Measured = 1.15 V_d	15 %
Test validated FEM; using #2 GVT data; with measured damping	32%
Test validated FEM; using #2 GVT data; with 3% structural damping	41%
Test validated FEM; using #1 GVT data; with 3% structural damping	52%
FEM; before model tuning; with 3% structural damping	74%

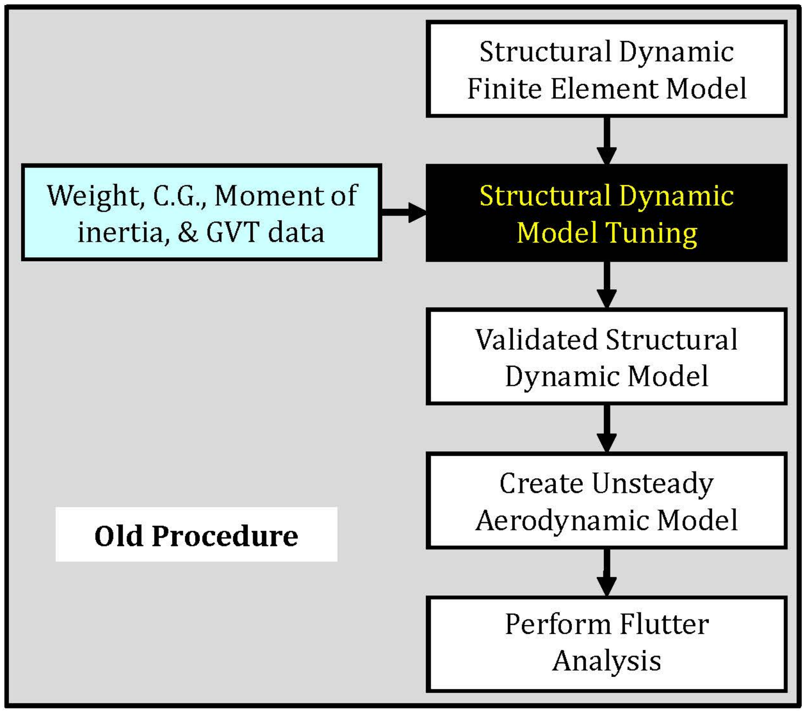
***: DOD's *JSSG-2006 Guidelines for Flutter Speed Clearance*; Faustino Zapata, AFDC May 22-23, 2008**
JSSG(Joint Service Specification Guide)

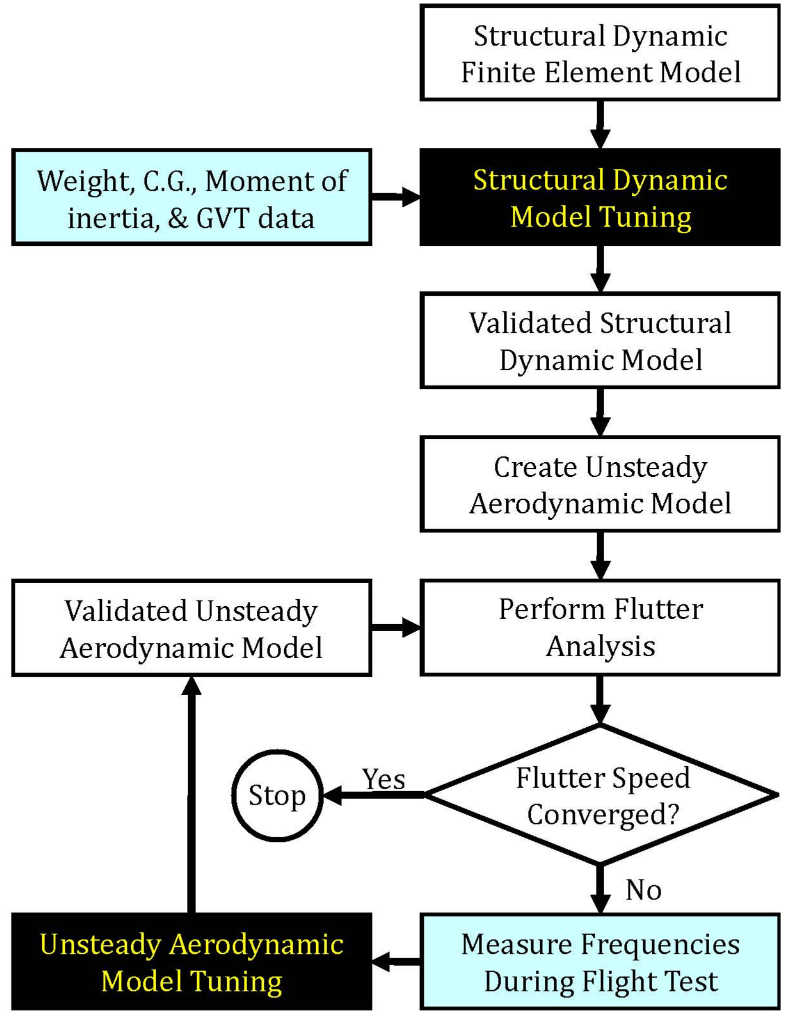
Validated Structural Dynamic Model	Validated Unsteady Aerodynamic Model	Recommended* Flutter Margins	ATW2 Case
Yes	Yes	15%	
Yes	No	49%	32 – 52 %
No	No	54%	74%

Unsteady Aerodynamic Model Tuning

New Flutter Analysis Procedure @ NASA Armstrong

#2





Unsteady Aerodynamic Model Tuning

- Optimization Problem Statement
  - Objective Function:

    Minimize J = measured aeroelastic frequency – computed aeroelastic frequency
  - Design Variables: e_{ij} & f_{ij}

$$\begin{bmatrix} e_{11}a_{11} & e_{12}a_{12} & \cdots & e_{1n}a_{1n} \\ e_{21}a_{21} & e_{22}a_{22} & \cdots & e_{2n}a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ e_{m1}a_{m1} & e_{m2}a_{m2} & \cdots & e_{mn}a_{mn} \end{bmatrix} + i \begin{bmatrix} f_{11}b_{11} & f_{12}b_{12} & \cdots & f_{1n}b_{1n} \\ f_{21}b_{21} & f_{22}b_{22} & \cdots & f_{2n}b_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ f_{m1}b_{m1} & f_{m2}b_{m2} & \cdots & f_{mn}b_{mn} \end{bmatrix} \qquad \mathbf{A} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix} + i \begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1n} \\ b_{21} & b_{22} & \cdots & b_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ b_{m1} & b_{m2} & \cdots & b_{mn} \end{bmatrix}$$

  - Design Variable Linking
    - Option 1: single design variable

      $d=e_{11}=e_{12}=\ldots=e_{mn}=f_{11}=f_{12}=\ldots=f_{mn}$
    - Option 2: two design variables

      $d_1=e_{11}=e_{12}=\ldots=e_{mn}$; real part $d_2=f_{11}=f_{12}=\ldots=f_{mn}$; imaginary part
    - Option 3: columnwise the same design variables (total n design variables)

      $d_1=e_{11}=e_{21}=\ldots=e_{m1}= f_{11}=f_{21}=\ldots=f_{m1}$ $d_2=e_{12}=e_{22}=\ldots=e_{m2}= f_{12}=f_{22}=\ldots=f_{m2}$

      … $d_n=e_{1n}=e_{2n}=\ldots=e_{mn}=f_{1n}=f_{2n}=\ldots=f_{mn}$;
    - Option 4: columnwise the same design variables (total 2n design variables)

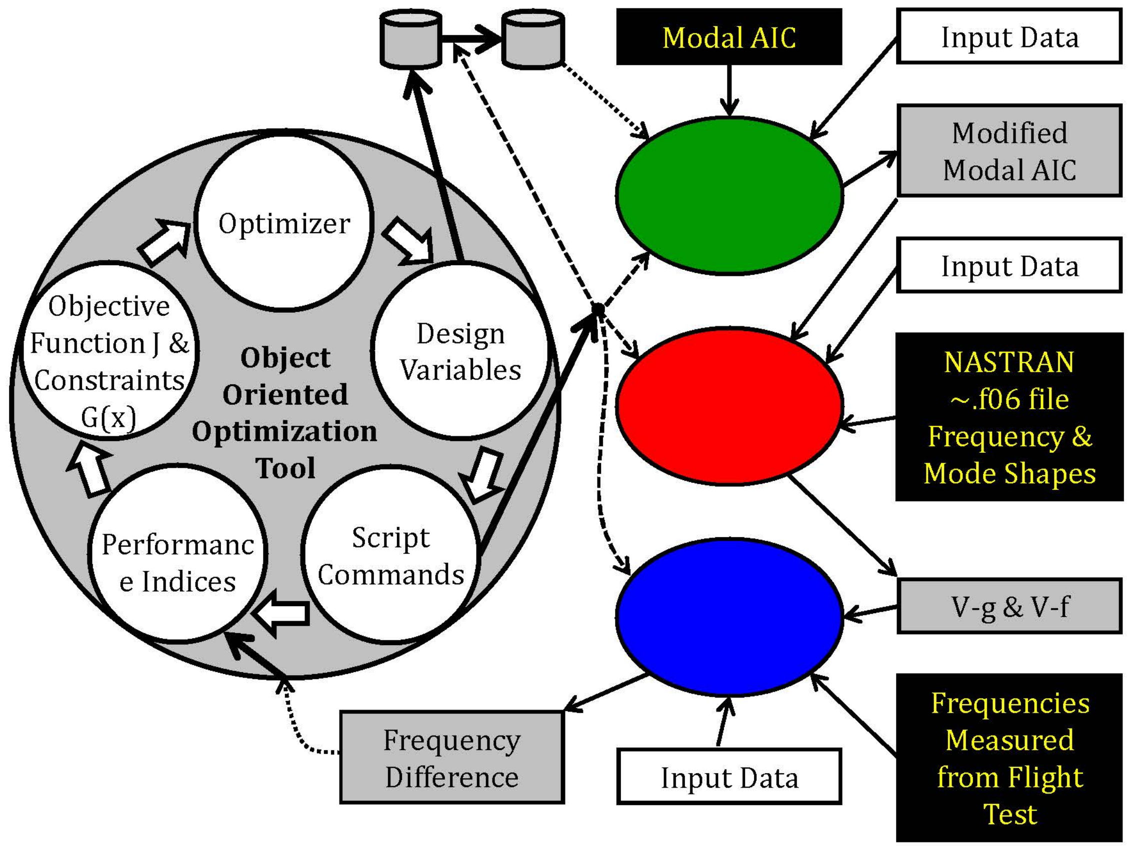
      $d_1=e_{11}=e_{21}=\ldots=e_{m1}$ $d_2=e_{12}=e_{22}=\ldots=e_{m2}$ … $d_n=e_{1n}=e_{2n}=\ldots=e_{mn}$; real parts

      $d_{n+1}=f_{11}=f_{21}=\ldots=f_{m1}$ $d_{n+2}=f_{12}=f_{22}=\ldots=f_{m2}$ … $d_{2n}=f_{1n}=f_{2n}=\ldots=f_{mn}$; imaginary parts
    - Option 5: No design variable linking; total 2mn design variables.

Unsteady Aerodynamic Model Tuning using Object-Oriented Optimization Tool

#2

- The NASA Amstrong has developed an Object-Oriented Optimization (O^3) tool.
  - The O^3 tool leverages existing tools and practices, and allows the easy integration and adoption of new state-of-the-art software.
  - Local gradient based optimizer as well as global optimizers are available. Hybrid methods are also available.
    - Optimizers:
      ADS/DOT (local), Genetic Algorithm (GA), &
      Big Bang-Big Crunch (BBBC) algorithm
    - Hybrid optimizers:
      GA+ADS/DOT & BBBC+ADS/DOT
  - Applications
    - MDAO tool
    - Structural Dynamic Model Tuning
    - Failure mode identification (mishap investigation)
      - ✓ Topology and sizing optimizations
    - Actuator Model Tuning



Pak, C.-g., "Unsteady Aerodynamic Model Tuning for Precise Flutter Prediction," *AIAA Journal of Aircraft,* Vol. 48, No. 6, 2011, pp. 2178-2184.

Time-Invariant Flight Conditions

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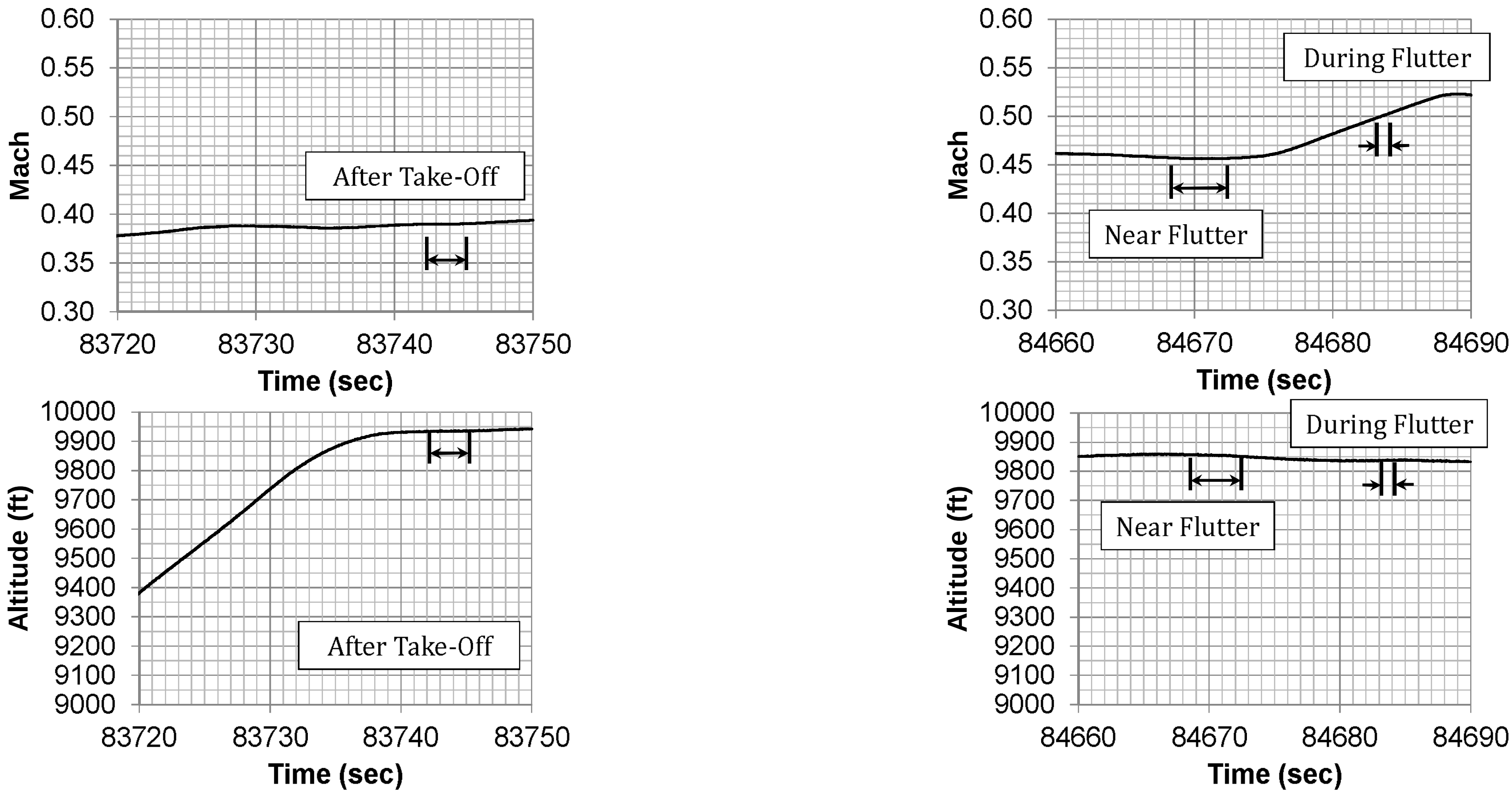


- First selection: Mach = 0.390 Altitude = 9934 ft
- Second selection: Mach = 0.456 Altitude = 9858 ft
- Flutter condition: Mach = 0.502 Altitude = 9837 ft (time varying)

Results

Numerical and measured frequencies (Hz) of the ATW2 during flight test

Mode	Natural Frequencies (Hz)		Measured Aeroelastic Frequencies (Hz)		
	Test Validated FEM	GVT	After take off M = 0.390	Near flutter M = 0.456	During flutter M = 0.502
1	17.45	17.45(0.623%)			
2	43.48	43.72(0.610%)	40.45	38.99	37.69
3	82.98	83.66(0.778%)			
4	133.6	N/A			
5	153.8	142.3(0.674%)			

The second aeroelastic frequency before and after unsteady aerodynamic model tuning and corresponding scaling factors

Mach Number	Measured (Hz)	Altitude (ft)	Before Tuning (Hz)	Scaling Factor (design variable)	After Tuning (Hz)
0.390	40.45	9934	41.12	1.2579	40.45
0.456	38.99	9858	40.10	1.2719	38.99

Measured and computed flutter boundaries at Mach = 0.502

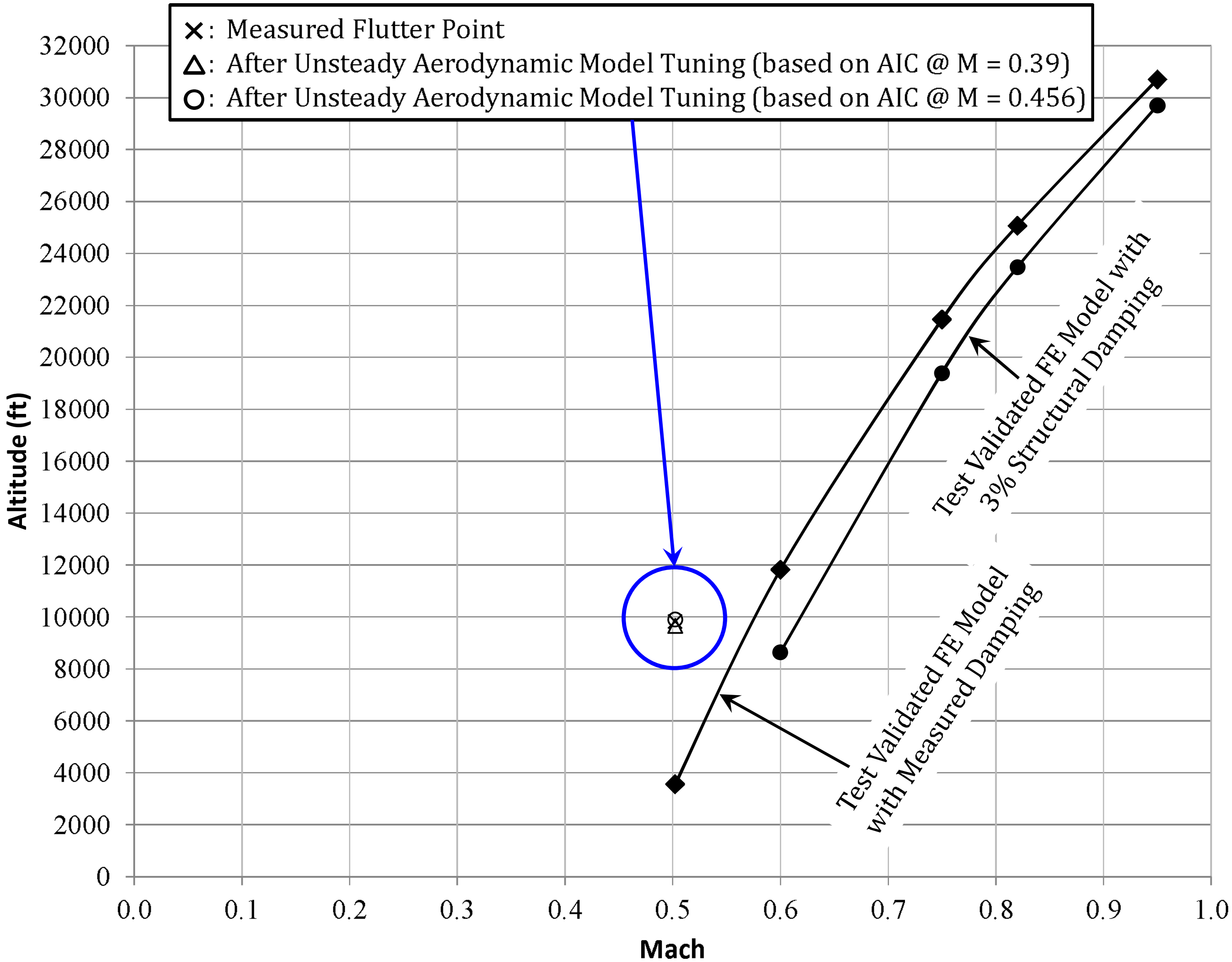
#2

Comment	Scaling Factor (design variable)	Flutter Speed		Altitude ft	Flutter Frequency	
		Keas	% difference		Hz	% difference
Measured	N/A	276.4	0.00	9836.9	37.69	0.00
Before tuning @ M=0.502	1.0	311.3	13.0	3561.5	37.67	-0.05
Use AIC @ M=0.390	1.2579	277.3	0.33	9670.0	37.69	0.00
Use AIC @ M=0.456	1.2719	276.0	-0.14	9912.5	37.68	-0.03

M=0.502

Flutter boundaries before and after unsteady aerodynamic model tuning

#2



Conclusions

- After model tuning (for ATW 2 case)
  - Maximum of 13%, 0.13=(311.3-276.4)/276.4, flutter speed error becomes -0.14 %.

Flutter Boundaries	Flutter Mach Number Altitude = 9836.9 ft	Flutter Speed Differences
Measured/1.15 = V_d	0.437	0 %
Measured = 1.15 V_d	0.502	15 %
Test validated FEM & unsteady aerodynamics; use M=0.456 aerodynamics	0.5015	14.8%
Test validated FEM & unsteady aerodynamics; use M=0.390 aerodynamics	0.5039	15.4%
Test validated FEM; using #2 GVT data; with measured damping	0.576	32%
Test validated FEM; using #2 GVT data; with 3% structural damping	0.616	41%
Test validated FEM; using #1 GVT data; with 3% structural damping	0.665	52%
FEM; before model tuning; with 3% structural damping	0.762	74%

- Model tuning based on ground vibration test and flight test data are needed to minimize uncertainties in the structural dynamics as well as unsteady aerodynamic models and to increase the safety of flight.
- Once both models are validated then we can use 15% margin for the flutter safety.

Validated Structural Dynamic Model	Validated Unsteady Aerodynamic Model	Recommended Flutter Margins	ATW2 Case
Yes	Yes	15%	14.8 – 15.4 %
Yes	No	49%	32 – 52 %
No	No	54%	74%

Questions ?