

Follow on Researches for X-56A Aircraft at NASA Dryden Flight Research Center (progress report)

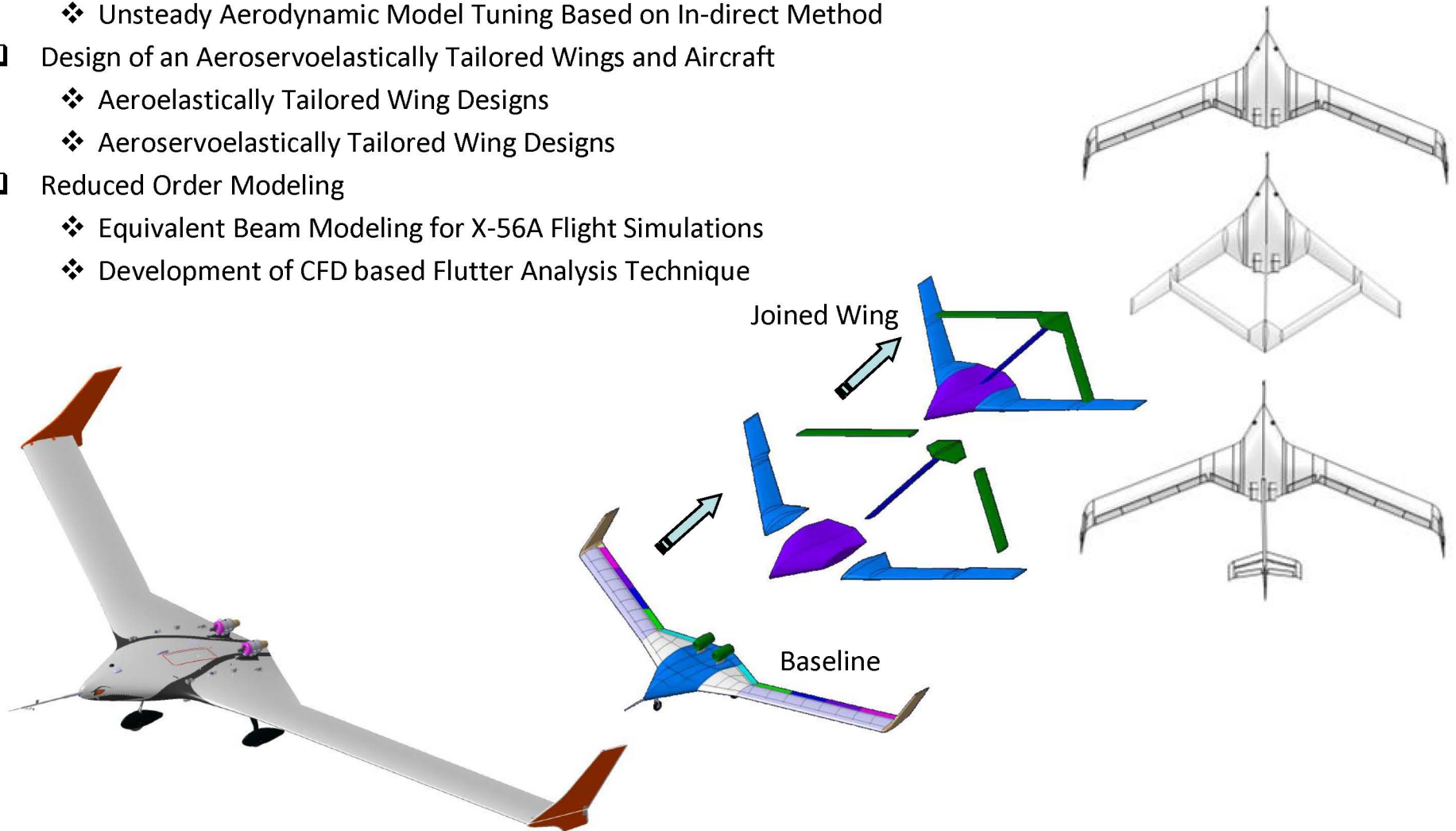
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NASA Dryden Flight Research Center



Follow on Researches for X-56A Aircraft

- ❑ Active/Adaptive Flexible Motion Controls with Aeroservoelastic System Uncertainties
 - ❖ Finite Element Model Tuning of X-56A Aircraft using Parallelized Big-Bang Big-Crunch Algorithm
 - ❖ Unsteady Aerodynamic Model Tuning Based on In-direct Method
- ❑ Design of an Aeroservoelastically Tailored Wings and Aircraft
 - ❖ Aeroelastically Tailored Wing Designs
 - ❖ Aeroservoelastically Tailored Wing Designs
- ❑ Reduced Order Modeling
 - ❖ Equivalent Beam Modeling for X-56A Flight Simulations
 - ❖ Development of CFD based Flutter Analysis Technique





Active/Adaptive Flexible Motion Controls with Aeroservoelastic System Uncertainties

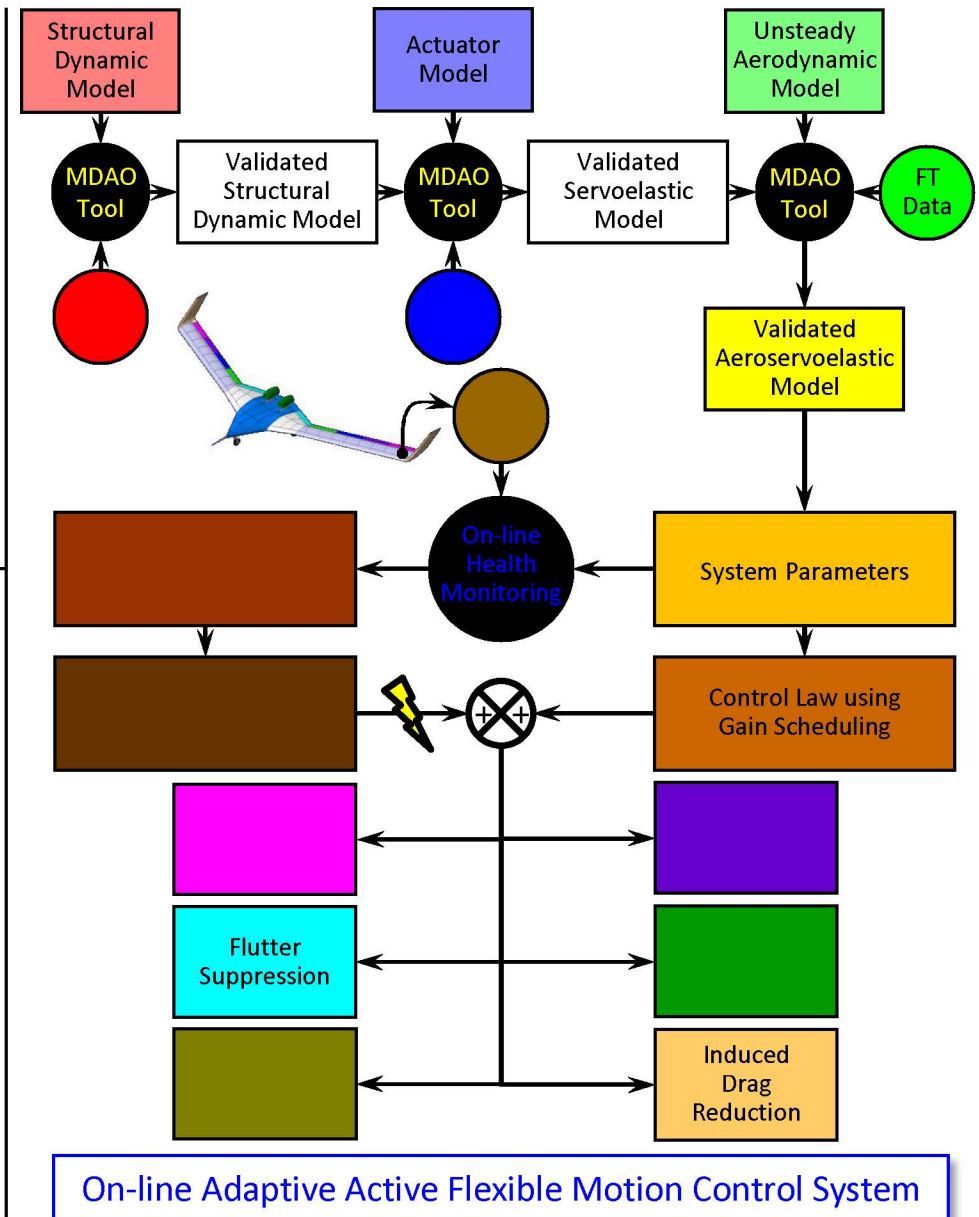
Research Goals/Objectives:

- ❑ Aeroservoelastic model validation is an essential procedure for the safety of flight.
- ❑ Uncertainties still exist in aeroservoelastic system even with the test validated aeroservoelastic model due to
 - ❖ time-varying uncertain flight conditions,
 - ❖ transient and nonlinear unsteady aerodynamics and aeroelastic dynamic environments.
- ❑ For a flexible motion control problems, we need a control law that adapts itself to such changing conditions.

Approach:

- ❑ Digital adaptive controller for a flexible motion control
 - ❖ On-line Parameter Estimation & Health Monitoring
 - ❖ On-line Control Law Design
 - Baseline Control Law Design will be based on the test validated aeroservoelastic model
 - On-line modification of control law will be based on the estimated "delta system model".
- ❑ Model Validation and Tuning
 - ❖ Minimizing uncertainties in an aeroservoelastic model
 - Structural Dynamic Model Tuning
 - Actuator Model Tuning
 - Unsteady Aerodynamic Model Tuning

Team: Chan-gi Pak, Marty Brenner, Roger Truax, & Alex Chin



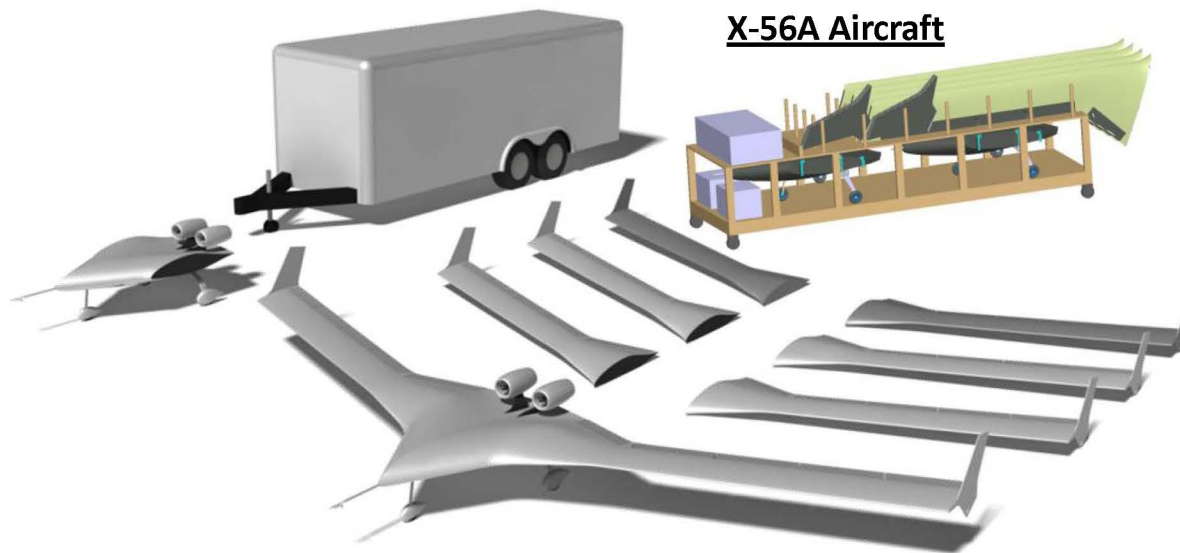
Finite Element Model Tuning of X-56A Aircraft using Parallelized Big-Bang Big-Crunch Algorithm





Objectives

- ❑ The primary objective of this study is to reduce uncertainties in the structural dynamic finite element model of an aircraft to increase the safety of flight.
- ❑ This model tuning technique is applied to improve the flutter prediction of the X-56A aircraft.
- ❑ This work is supported by the Aeronautics Research Mission Directorate (ARMD) Fixed Wing and High Speed projects under Fundamental Aeronautics (FA) program.



- ❑ Collaboration with AFRL & LMSW
 - ❖ Two Center Bodies
 - ❖ One Rigid Wing
 - ❖ Three Flexible Wings
 - ❖ Ground Control Station

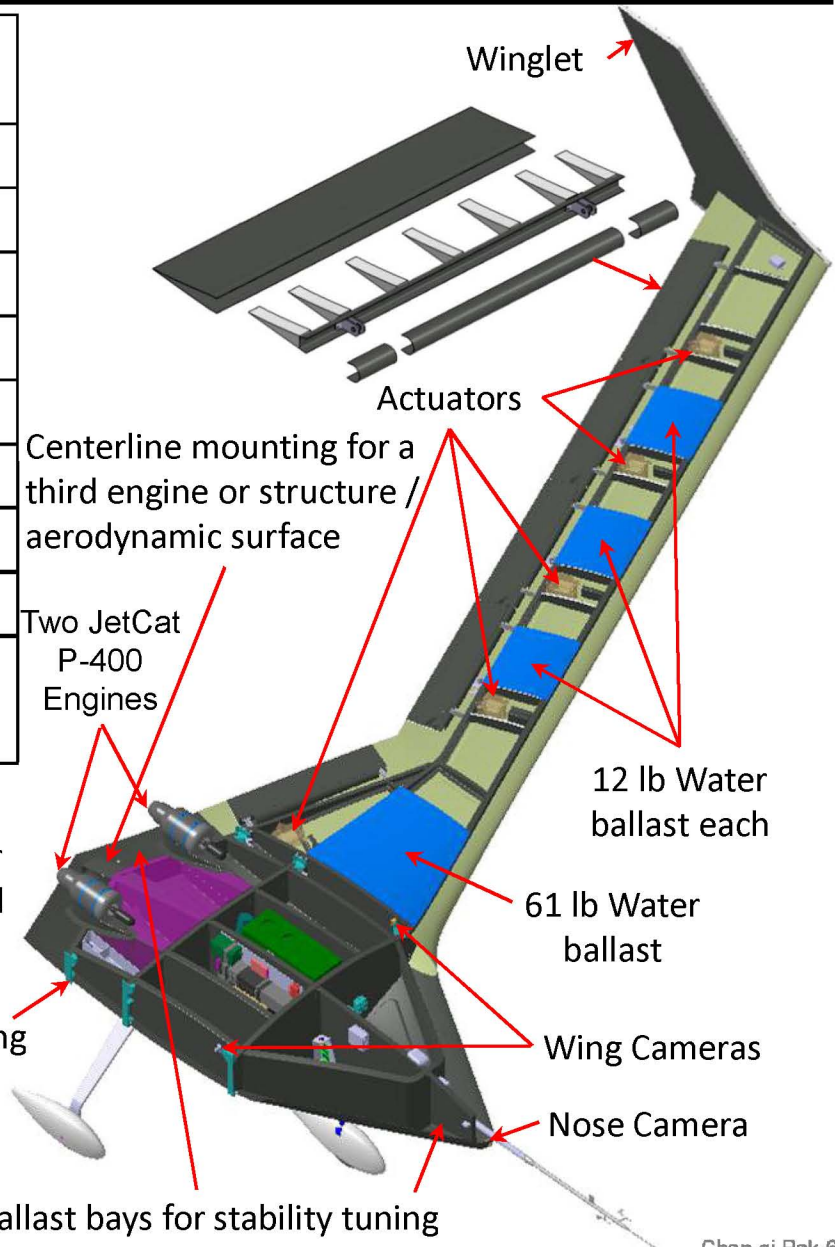
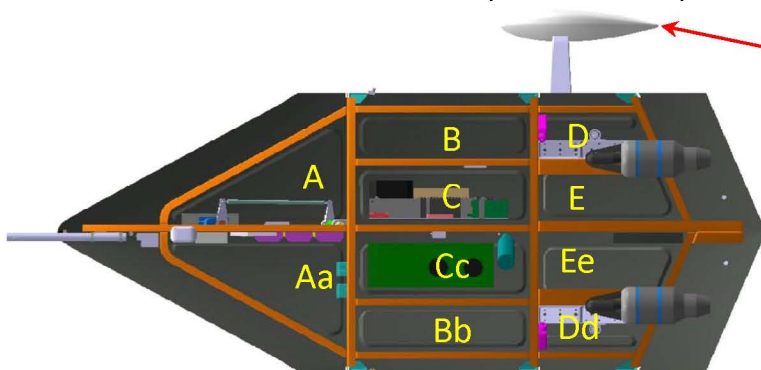




X-56A Aircraft: Exploded View of X-56A

Bay	Volume (ft ³)	% Occupied	Comment
A	1.90	10%	Nose Wheel System Bay
Aa		20%	Power System Bay
B	1.10	0%	
Bb		0%	
C	2.00	70%	Electronics Bay
Cc		90%	Ballistic Recovery System
D	0.46	30%	Fuel System
Dd		30%	Fuel System
E	0.94	100%	Fuel Wet Bays
Ee		100%	

6.9 ft³ Useable volume (54% of total)

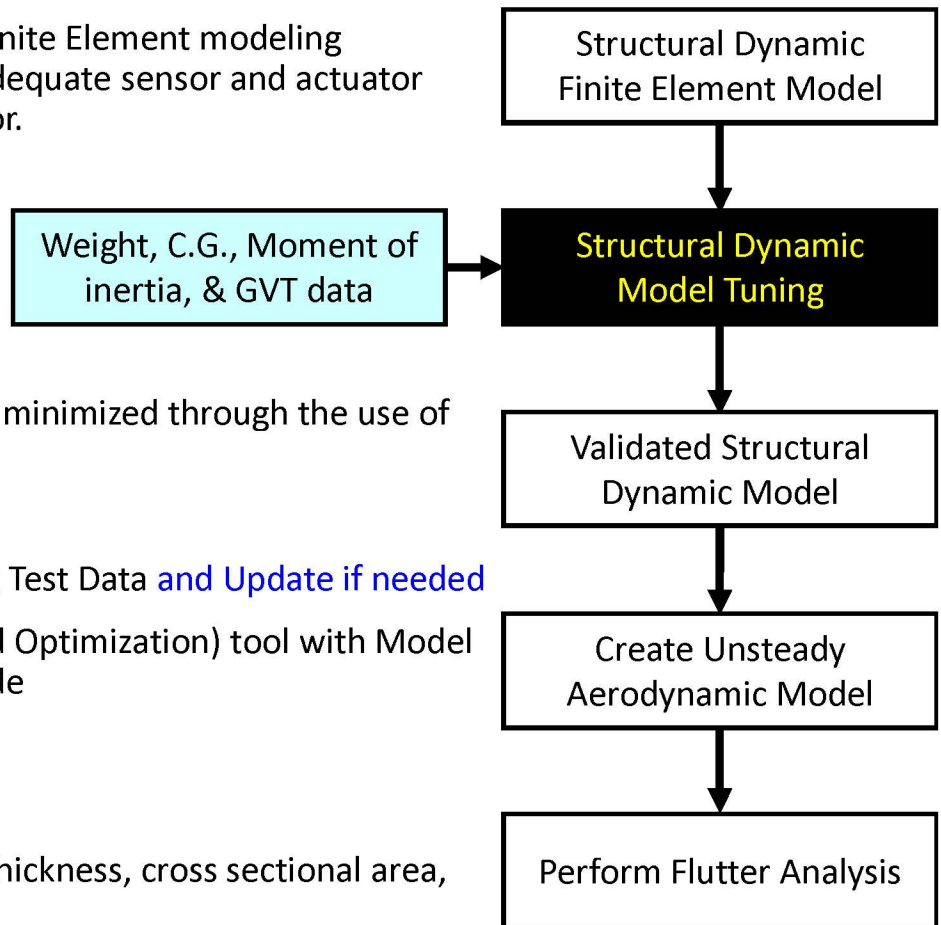




Flutter Analysis Procedure @ NASA Dryden

- ❑ Everyone believes the test data except for the experimentalist, and no one believes the finite element model except for the analyst.

- ❖ Some of the discrepancies come from analytical Finite Element modeling uncertainties, noise in the test results, and/or inadequate sensor and actuator locations. Not the same orientation for each sensor.



- ❑ Flutter Analysis

- ❖ Uncertainties in the structural dynamic model are minimized through the use of “model tuning technique”
- ❖ Based on analytical modes

- ❑ Validate Structural Dynamic Finite Element Model using Test Data and Update if needed

- ❖ Use MDAO (Multidisciplinary Design, Analysis, and Optimization) tool with Model Tuning Capability or Standalone Model Tuning Code

- Model tuning is based on optimization.

- ✓ Design Variables

- Structural sizing information: Thickness, cross sectional area, area moment of inertia, etc.
- Point properties: lumped mass, spring constant, etc.
- Material properties: density, Young’s modulus, etc.

- ✓ Constraints



Structural Dynamic Model Tuning using Object Oriented Optimization Tool

□ Approach

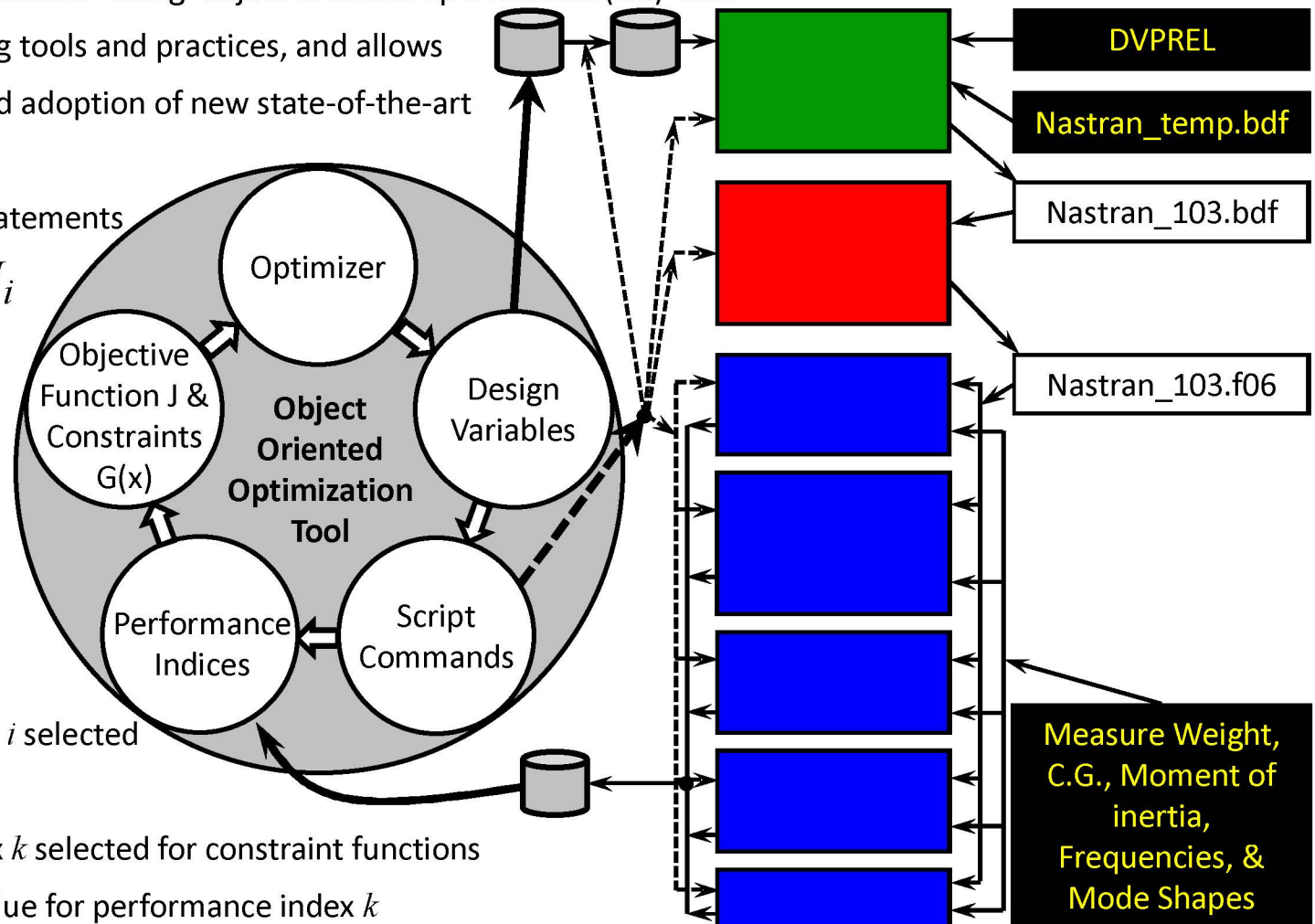
- ❖ Minimize “objective functions” using object oriented optimization (O3) tool which leverages existing tools and practices, and allows the easy integration and adoption of new state-of-the-art software.

□ Optimization Problem Statements

- ❖ Minimize $J = \sum_i w_i J_i$

Such that $J_k \leq \varepsilon_k$

- J : Objective function
- w_i : Weighting factor for the performance index i
- J_i : Performance index i selected for objective function
- J_k : Performance index k selected for constraint functions
- ε_k : Small tolerance value for performance index k



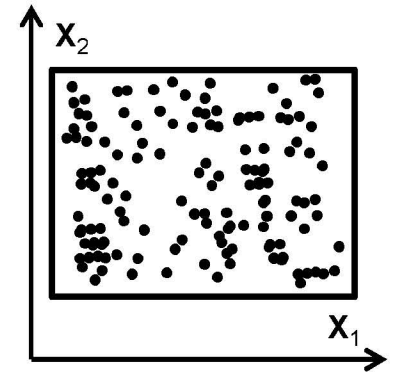


Parallelized Big Bang Big Crunch Algorithm

□ A global optimizer

❖ First step: Big Bang step

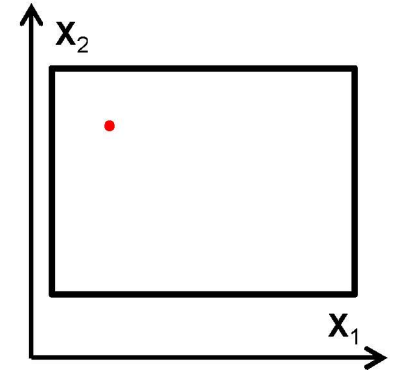
- Selection of the N (number of population) random design variable vectors $\mathbf{X}_i$ ($i=2,3,\dots,N$) using uniform random number generator such that
 - ✓ $\mathbf{X}_L \leq \mathbf{X}_i \leq \mathbf{X}_U$
- Current design configuration is saved in the design variable vector $\mathbf{X}_1$.
- Create M ($N = M \times \text{integer}$) number of design variable vectors simultaneously.
- M number of objective functions will be computed simultaneously.
 - ✓ Needs M number of NASTRAN licenses



❖ Second step: Big Crunch step

- Shrink design variable vectors to a single representative design point via a center of gravity (CG)

$$\mathbf{X}_{CG} = \frac{\sum_{i=1}^N \frac{\mathbf{X}_i}{J_i}}{\sum_{i=1}^N \frac{1}{J_i}}$$

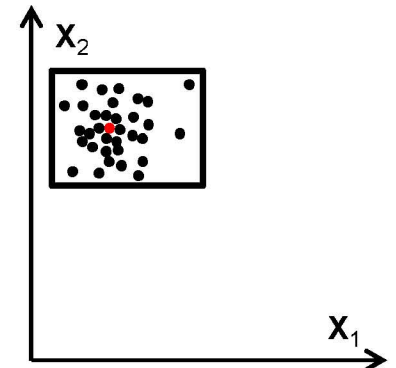


❖ Third step: Big Bang step

- Compute new candidate design variable vectors around the CG location using the standard normal random number generator

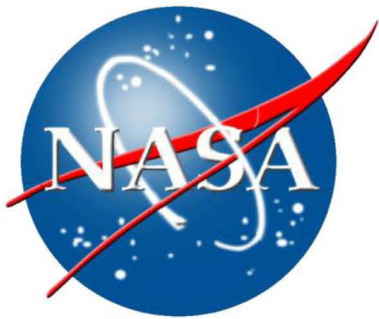
$$\mathbf{X}_i^n = \beta \mathbf{X}_{CG} + (1 - \beta) \mathbf{X}_{GO} + \frac{r\alpha(\mathbf{X}_U - \mathbf{X}_L)}{NBB}$$

- ✓ where, r is the standard normal random number; α is the parameter limiting the size of the design space; NBB is the number of current big bang iteration; and β is the parameter controlling the influence of the global optimum solution $\mathbf{X}_{GO}$.
- ✓ Parameters α and β for the best performance was $\alpha=1$ and $\beta=0.2$ for the truss design problems and $\alpha=1$ and $\beta=0.7$ for the parameter estimation problems.



❖ Go to the second step until converge

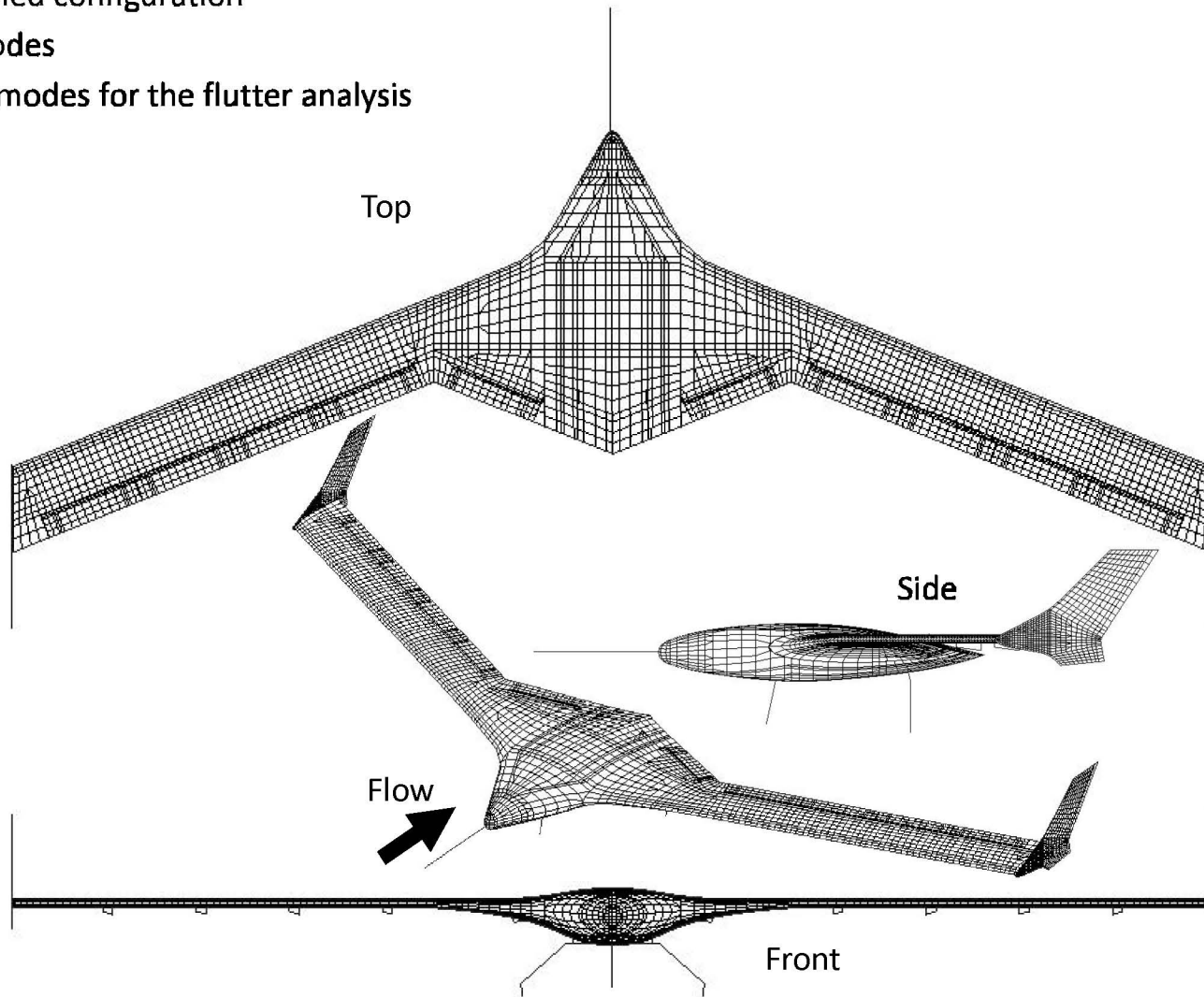
Pre-GVT Modal Analysis of X-56A





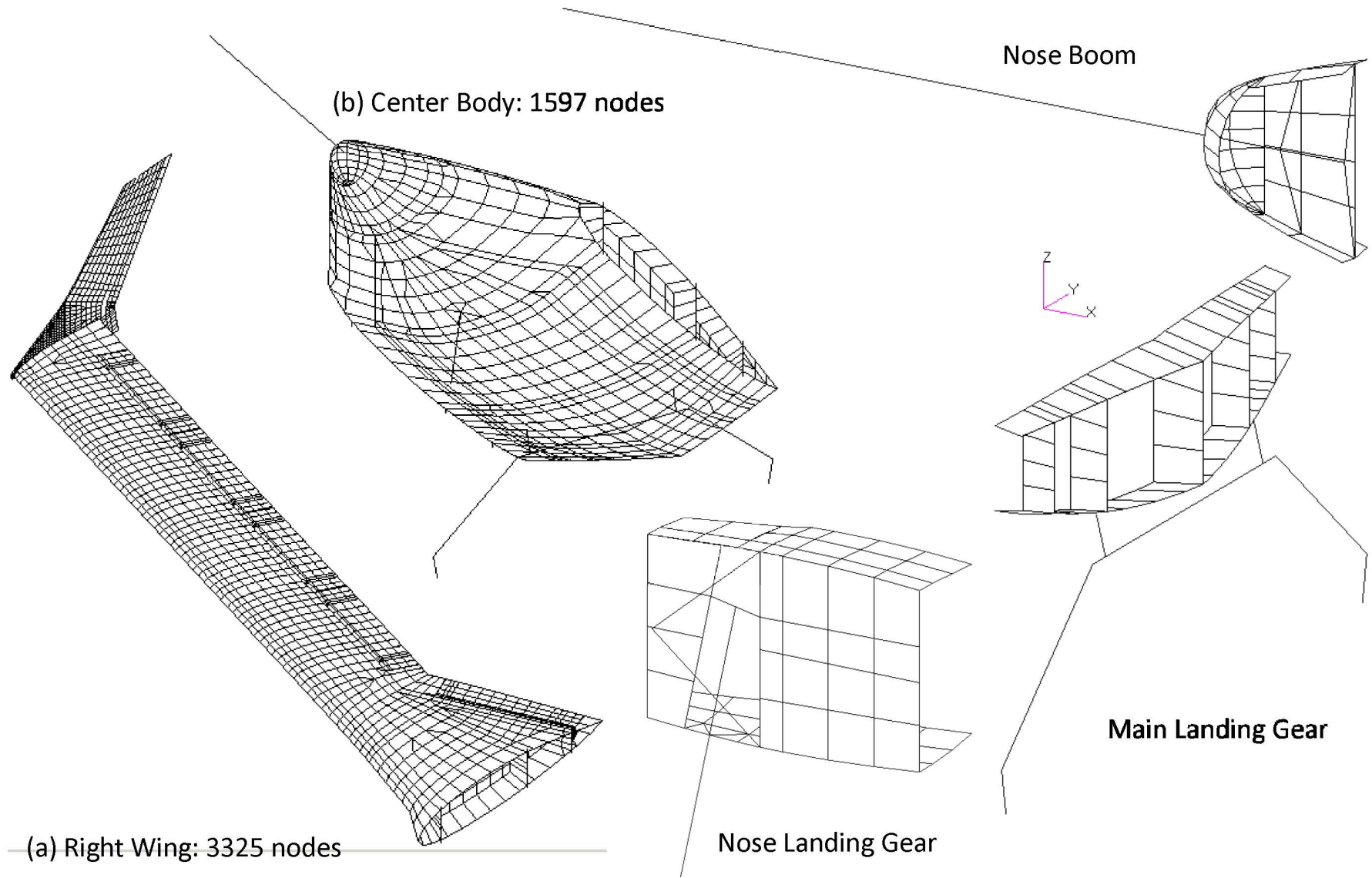
Structural Dynamic Finite Element Model

- ❑ Based on MSC/NASTRAN code
 - ❖ Assembled configuration
 - ❖ 8249 nodes
 - ❖ Use 40 modes for the flutter analysis



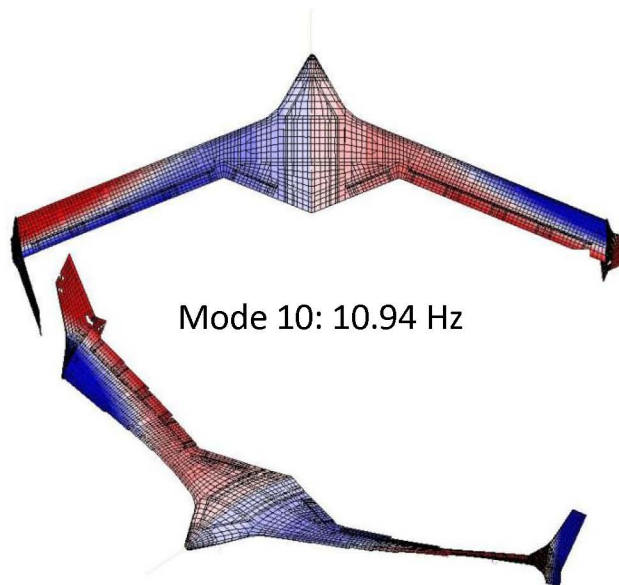
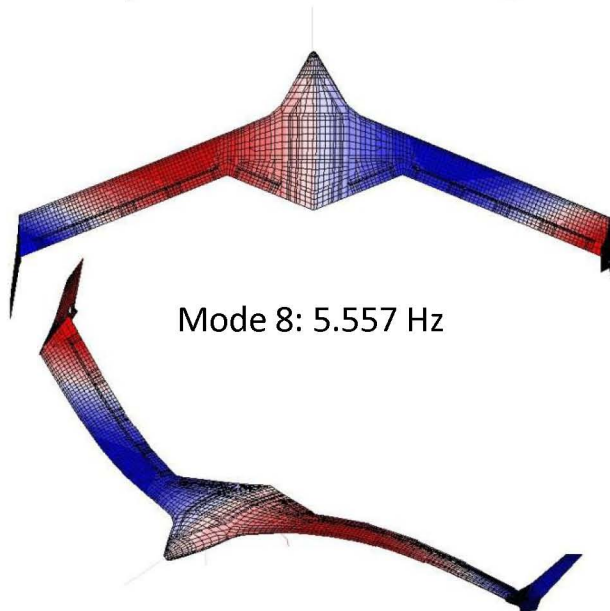
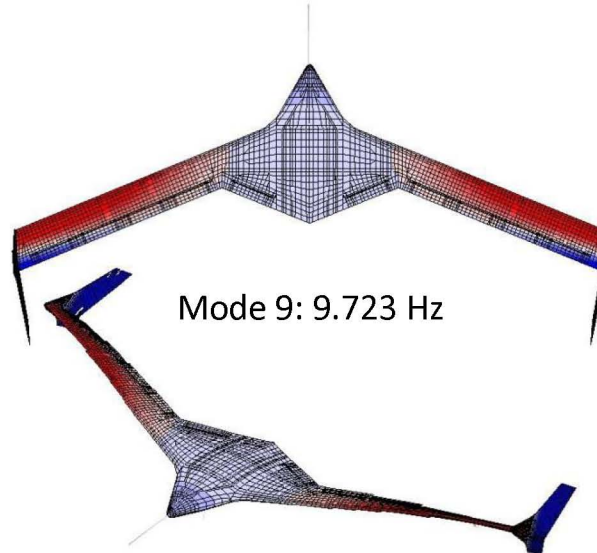
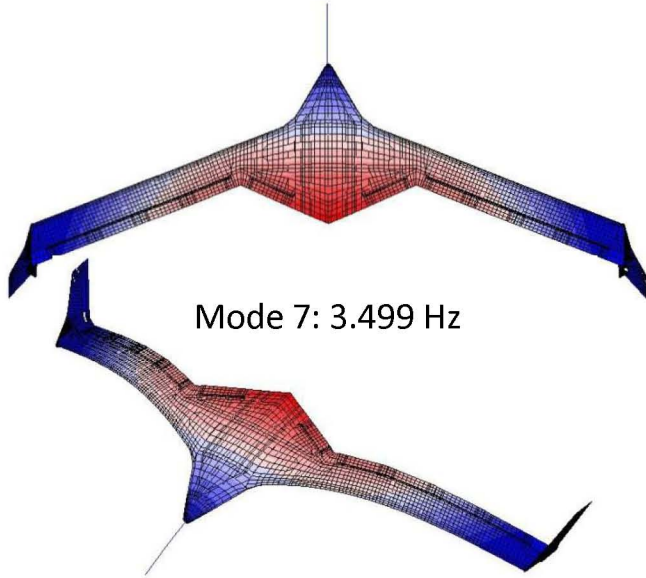


Modal Analyses of Each Structural Component

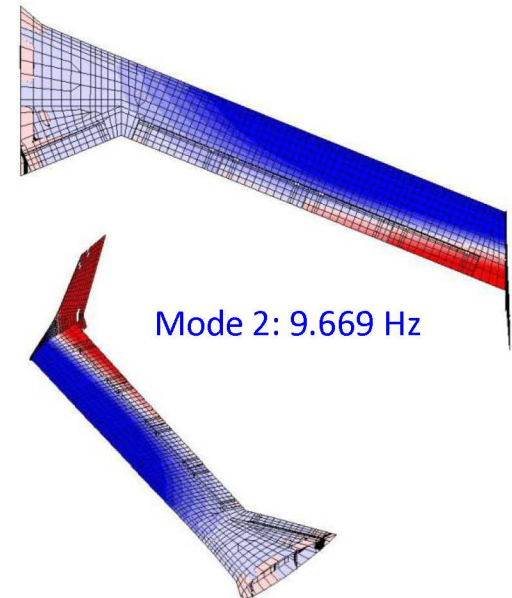
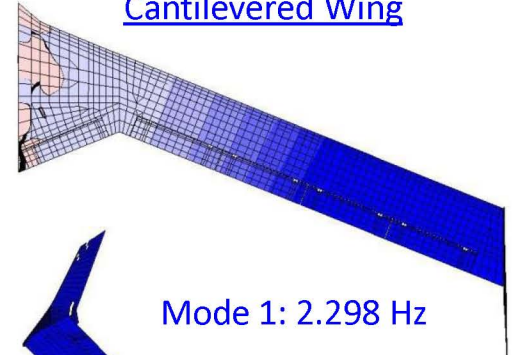




Mode Shapes

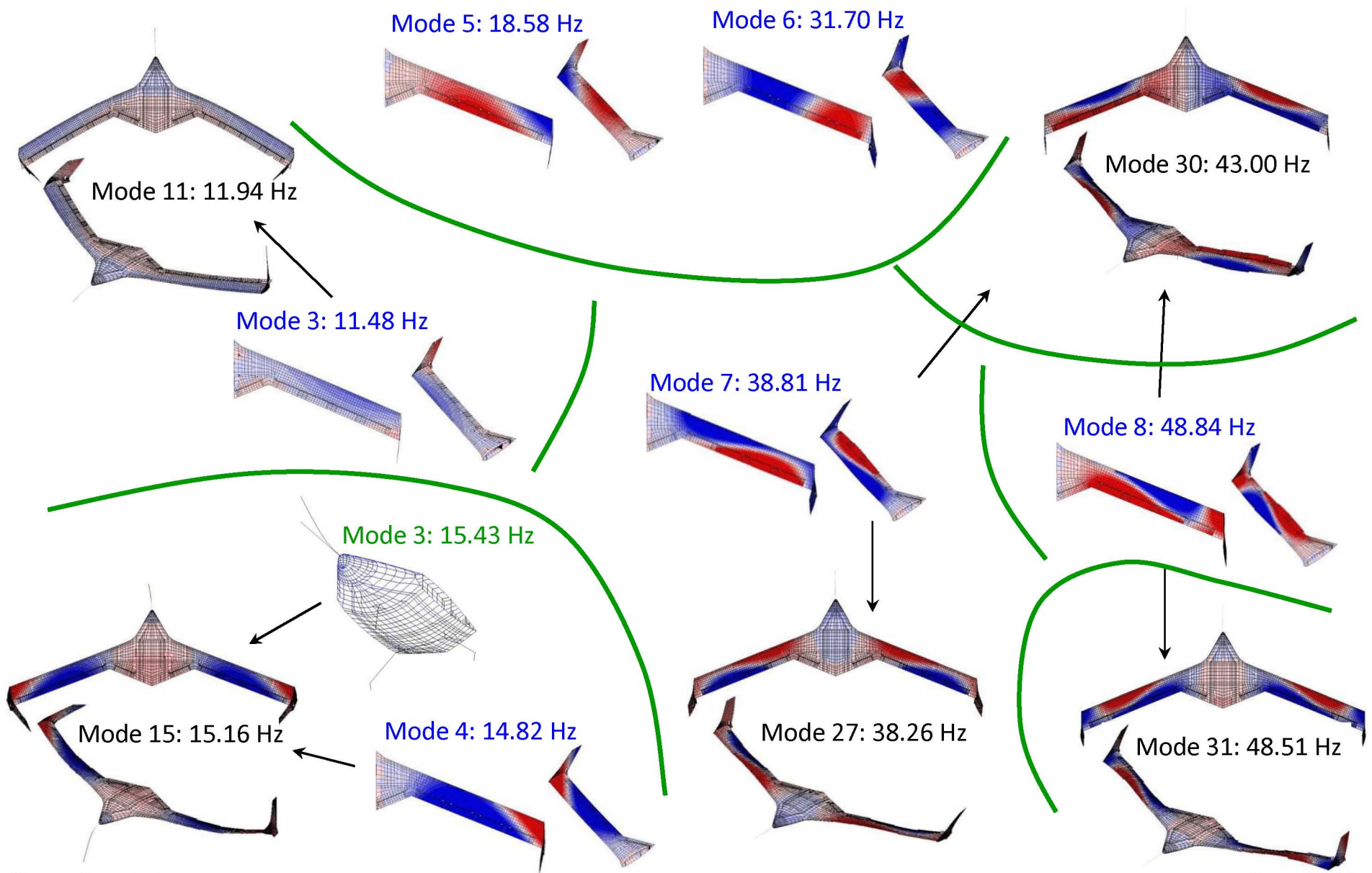


Cantilevered Wing





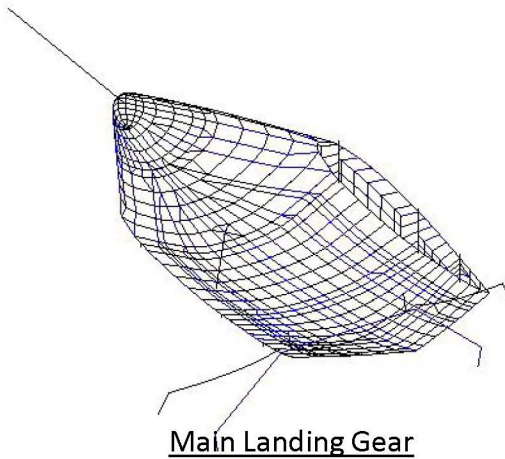
Mode Shapes (continued)



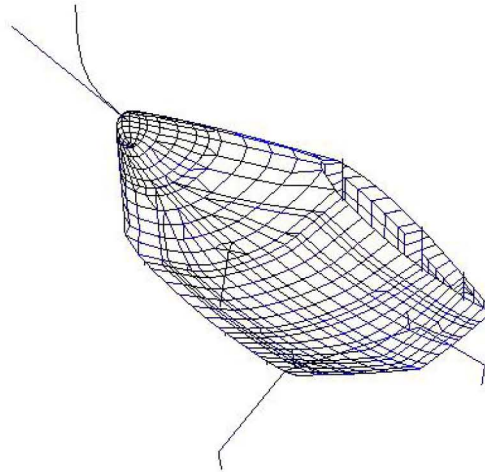


Mode Shapes: Boom & Landing Gears

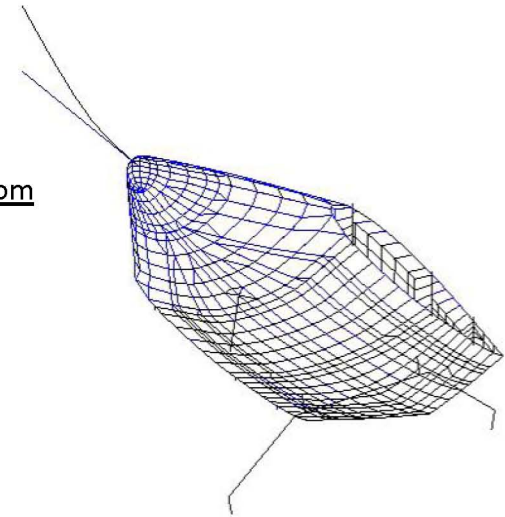
Mode 1: 13.51 Hz



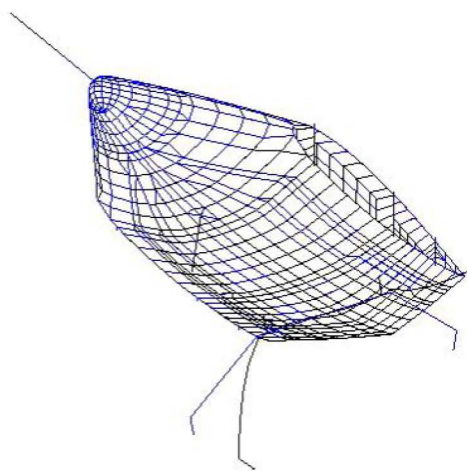
Mode 2: 15.36 Hz



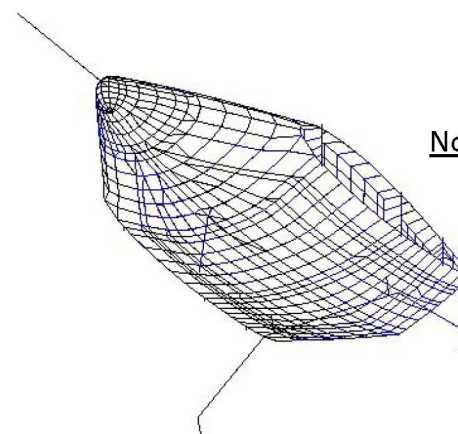
Mode 3: 15.43 Hz



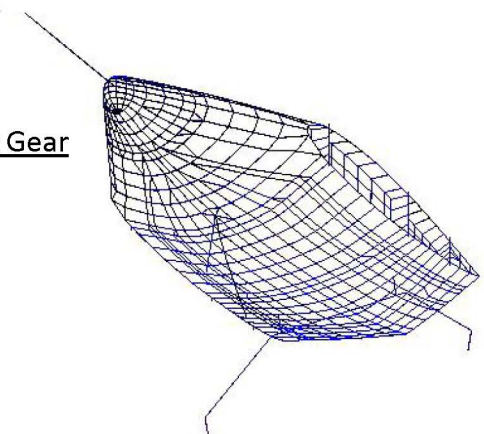
Mode 4: 16.75 Hz



Mode 5: 33.03 Hz



Mode 6: 33.08 Hz



Pre-GVT Flutter Analysis of X-56A

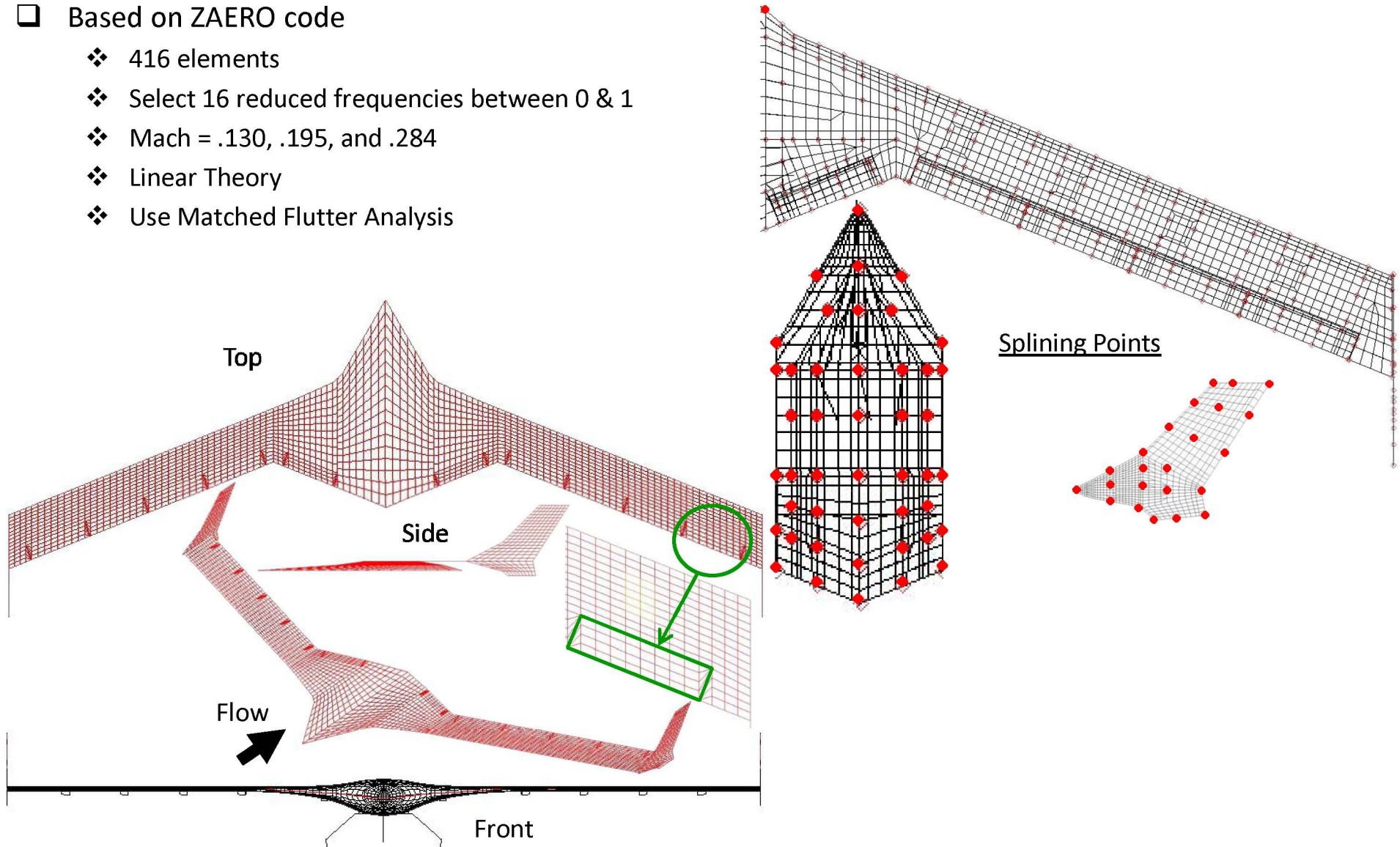




Unsteady Aerodynamic Model

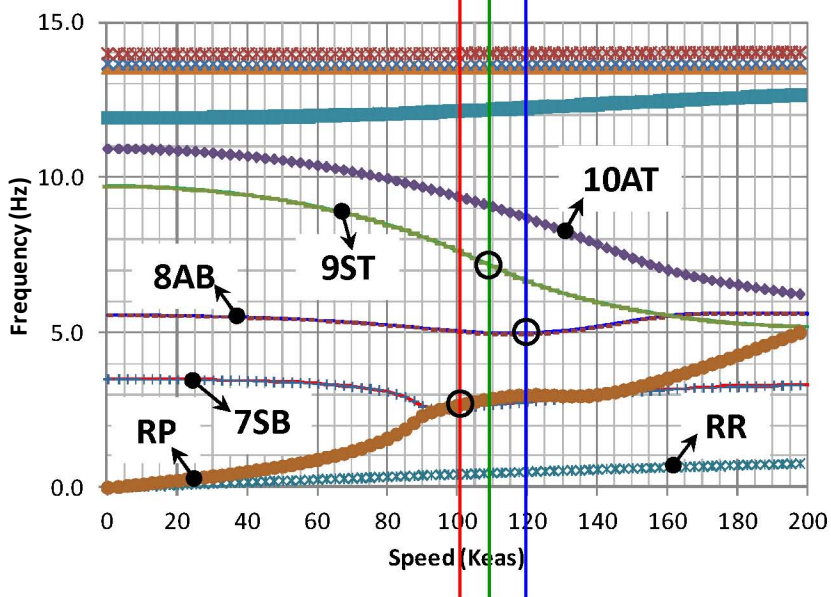
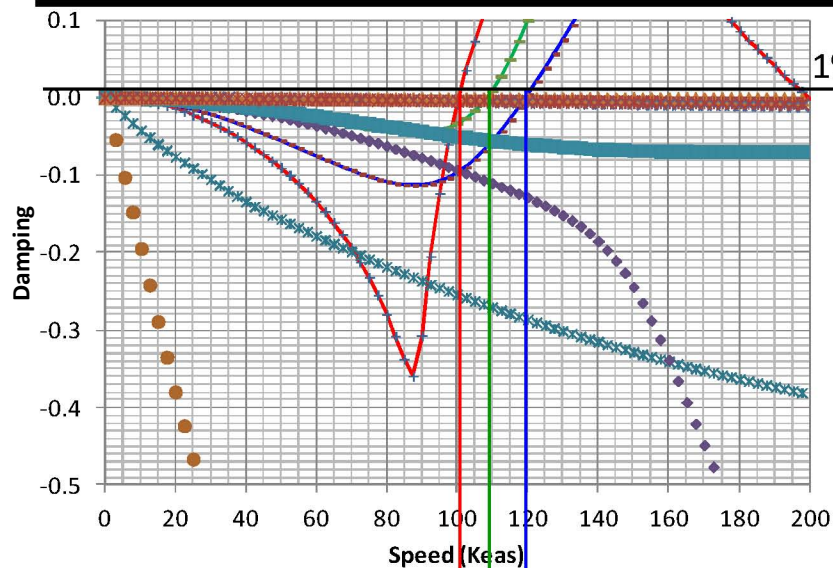
❑ Based on ZAERO code

- ❖ 416 elements
- ❖ Select 16 reduced frequencies between 0 & 1
- ❖ Mach = .130, .195, and .284
- ❖ Linear Theory
- ❖ Use Matched Flutter Analysis





V-g and V-f Curves at Mach = 0.130 Before Model Tuning



Modal Participation Factors

Mode	Freq. (Hz)	1 st Flutter			2 nd Flutter			3 rd Flutter		
1-6	0.000	2	30.3	73.3	2	25.9	87.1	1	40.9	40.9
7	3.499	3	15.8	89.1	3	7.6	94.7		0.0	
8	5.557		0.0			0.0		2	26.1	67.0
9	9.723	1	43.0	43.0	1	61.2	61.2		0.0	
10	10.94		0.0			0.0		3	26.1	93.1
11	11.94	8	1.0	97.7	5	1.1	97.2		0.0	
15	15.16	5	2.3	94.4	4	1.4	96.1		0.0	
20	19.01	7	1.1	96.7		0.1			0.0	
27	38.26	4	3.0	92.1	7	1.0	99.2		0.0	
30	43.00		0.0			0.0		4	2.3	95.4
31	48.51	6	1.2	95.6	6	1.0	98.2		0.0	

Flutter Mode	Speed	Frequency	Altitude
1	101.0 Keas	2.597 Hz	-9204.3 ft
2	110.1 Keas	7.134 Hz	-14330. ft
3	121.0 Keas	4.971 Hz	-20169. ft

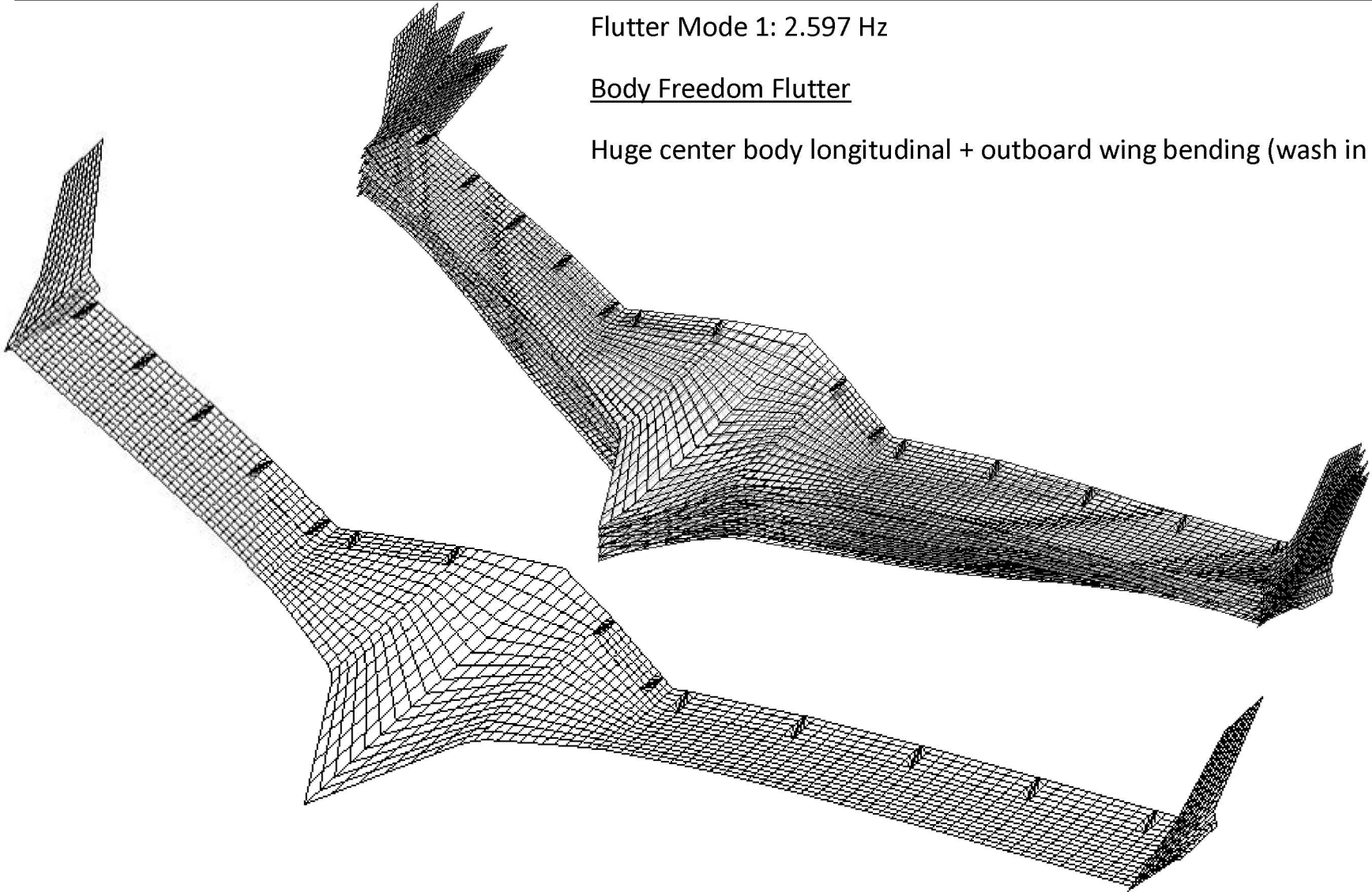


First Flutter Mode Shapes of X-56A Aircraft

Flutter Mode 1: 2.597 Hz

Body Freedom Flutter

Huge center body longitudinal + outboard wing bending (wash in motion)



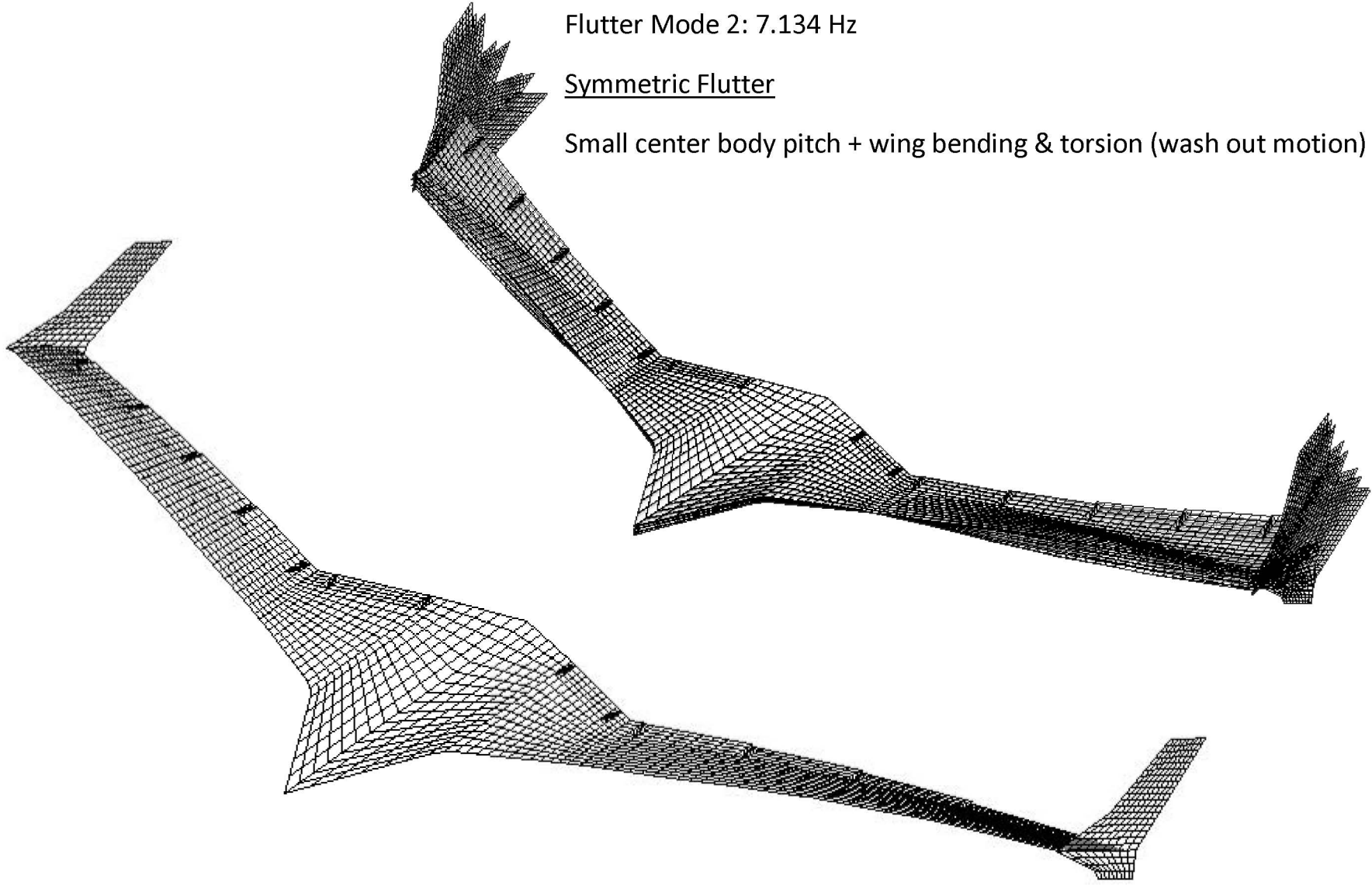


Second Flutter Mode Shapes of X-56A Aircraft

Flutter Mode 2: 7.134 Hz

Symmetric Flutter

Small center body pitch + wing bending & torsion (wash out motion)



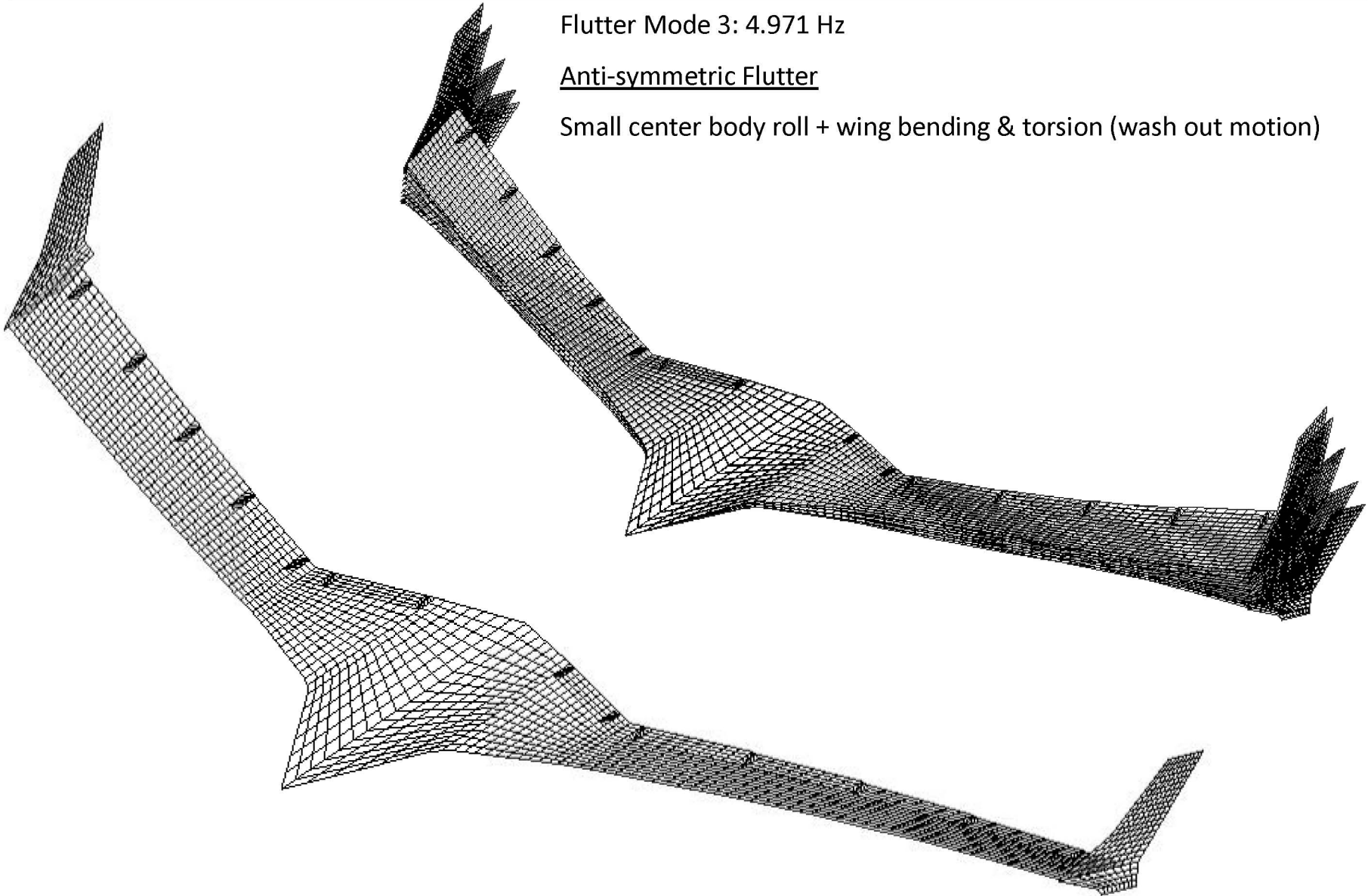


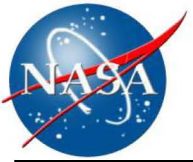
Third Flutter Mode Shapes of X-56A Aircraft

Flutter Mode 3: 4.971 Hz

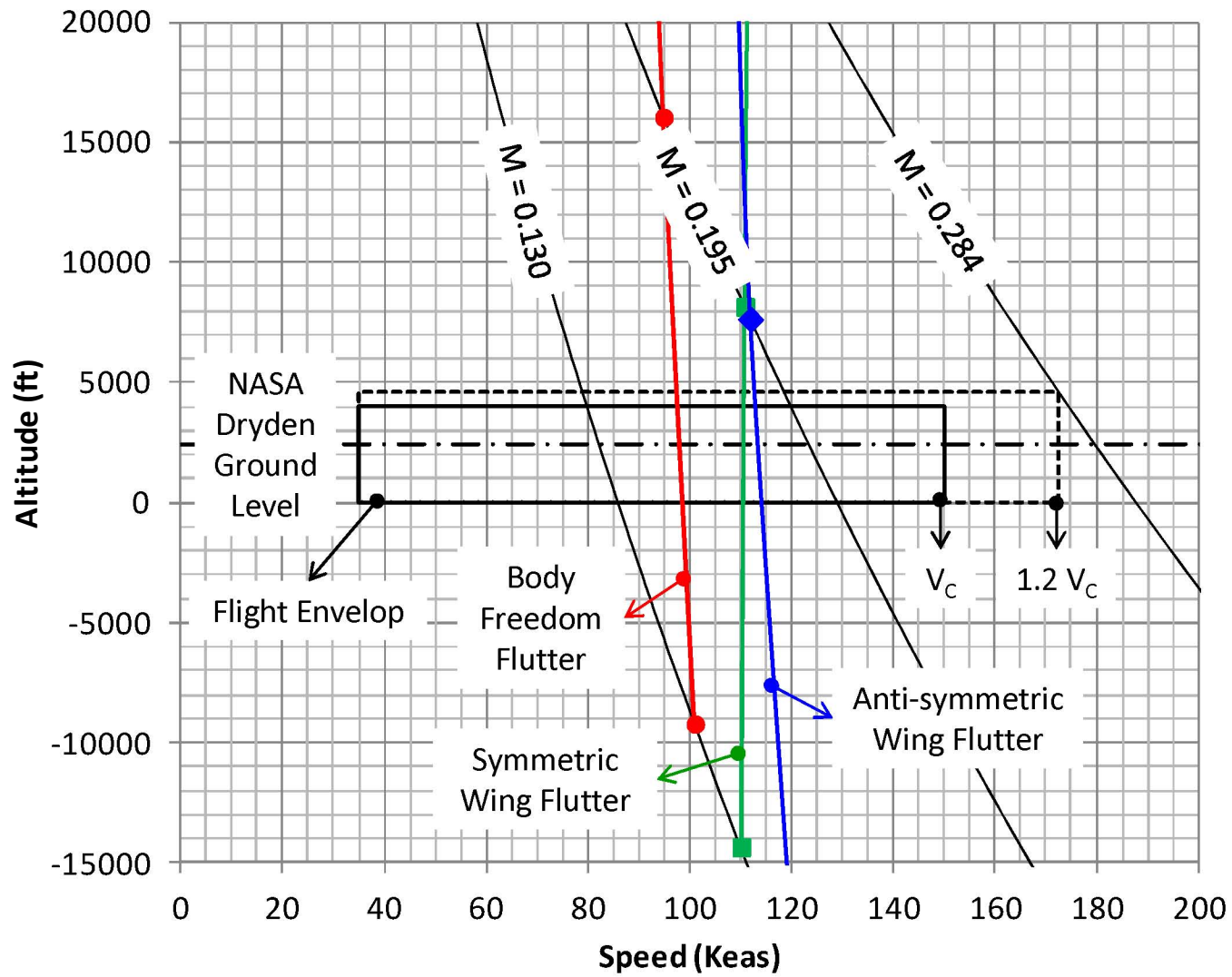
Anti-symmetric Flutter

Small center body roll + wing bending & torsion (wash out motion)





Flutter Boundaries



Updating the Finite Element Model of the X-56A Using Ground Vibration Test Data





Structural Dynamic Model Tuning using GVT Data

❑ NASA Standard: NASA-STD-5002 Section 4.2.6.d

- ❖ NASA Technical Load Analysis of Spacecraft and Payloads
- ❖ Agreement between test and analysis natural frequencies shall, as a goal, be within [5%](#) for the significant modes.
- ❖ Accurate mass representation of the test article shall be demonstrated with orthogonality checks using the analytical mass matrix $\mathbf{M}$ and the test mode shapes Φ_G . The orthogonality matrix is computed as $\Phi_G^T \mathbf{M} \Phi_G$. As a goal, the off-diagonal terms of the orthogonality matrix should be less than [0.1](#) for significant modes based on the diagonal terms normalized to 1.0.

❑ Military Standard: MIL-STD-1540C Section 6.2.10

- ❖ Test Requirements for Launch, Upper-Stage, & Space Vehicles
- ❖ Analytical model frequencies are to be within [3%](#) of test frequencies.
- ❖ Using a cross-orthogonality matrix formed from the analytical mass matrix and the analytical and test modes, corresponding modes are to exhibit at least 95% correlation and dissimilar modes are to be orthogonal to within [10%](#).

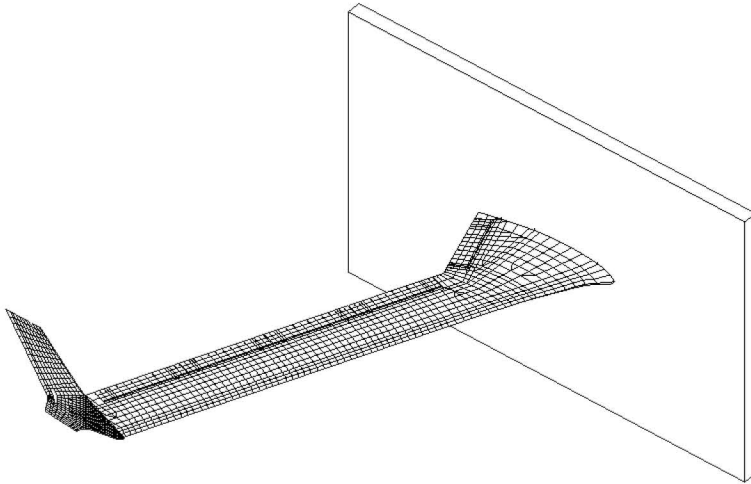
❑ AFFTC-TIH-90-001 (Structures Flight Test Handbook)

- ❖ If measured mode shapes are going to be associated with a finite element model of the structure, *it will probably [need to be adjusted](#) to match the lumped mass modeling of the analysis.*
- ❖ Based on the measured mode shape matrix Φ_G and the analytical mass matrix $\mathbf{M}$, the following operation is performed: $\Phi_G^T \mathbf{M} \Phi_G$
- ❖ The results is near diagonalization of the resulting matrix with values close to 1 on the diagonal and values close to zero in the off-diagonal terms. Experimental reality dictates that the data will not produce exact unity or null values, so [10 percent of these targets are accepted as good orthogonality](#) and the data can be confidently correlated with the finite element model.

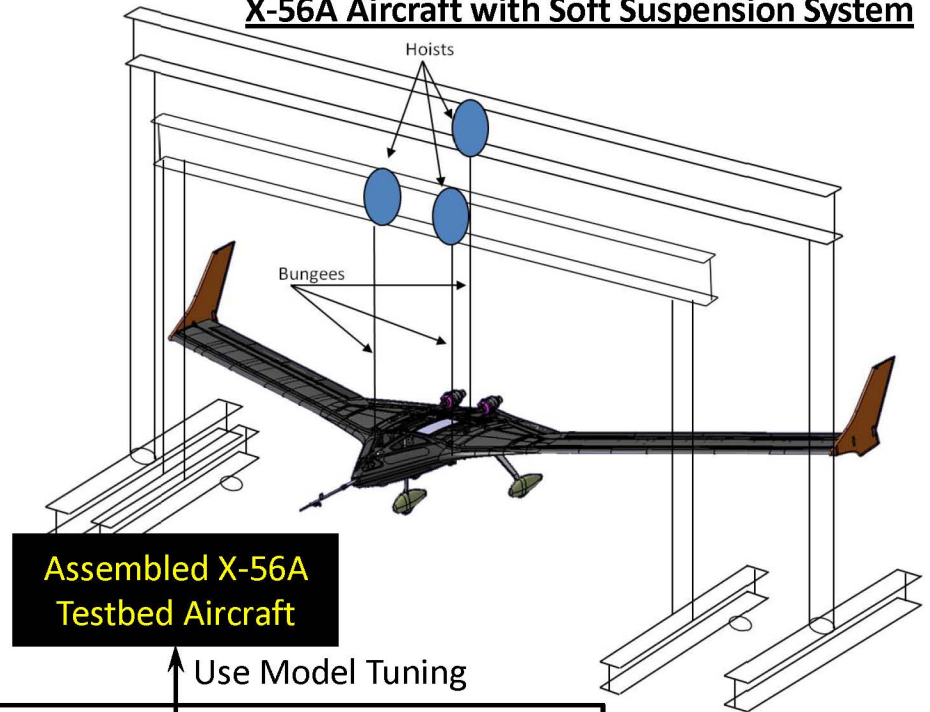


Bottom-Up Approach for Structural Dynamic Model Tuning

Cantilevered or Free-Free Right Wing with Winglet

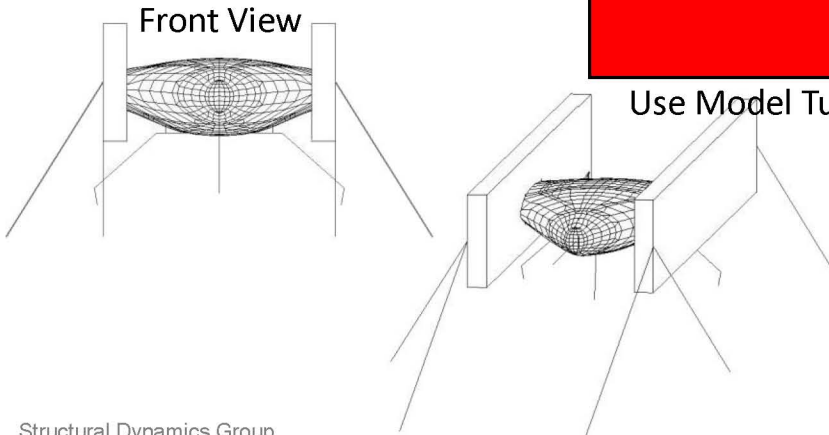


X-56A Aircraft with Soft Suspension System



Constrained Center-Body

Front View



Use Model Tuning

Use Mirror Image

Use Model Tuning

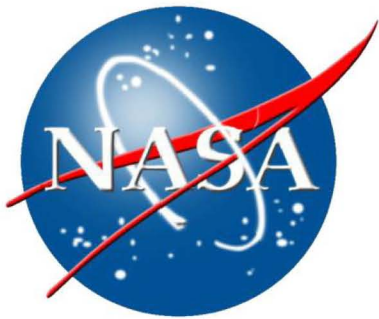
Center Body Model



Structural Dynamic Model Tuning

- ☐ Nose boom
 - ❖ Beam elements
 - ❖ Match first two modes, 15.36 Hz and 15.43 Hz; improve CG; and mass matrix
- ☐ Main landing gear
 - ❖ Beam elements
 - ❖ Match first two modes, 13.51 Hz and 16.75 Hz ; improve CG; and mass matrix
- ☐ Nose landing gear
 - ❖ Beam elements
 - ❖ Match first two modes, 33.03 Hz and 33.08 Hz ; improve CG; and mass matrix
- ☐ Center body
 - ❖ Improve CG and mass matrix
- ☐ Wing with winglet
 - ❖ Match first eight modes
 - Use different weighting factors
 - ✓ Modes 1 & 2 : 1.0
 - ✓ Modes 4, 7, & 8 : 0.5
 - ✓ Modes 3, 5, & 6 : 0.01
 - ❖ Most time consuming part
- ☐ Assembled configuration
 - ❖ Use superelement
 - ❖ Match 6DOF springs between wings and center body

Flutter Analysis Using Validated Structural Dynamic Finite Element Model





Unsteady Aerodynamic Model Tuning Based on In-direct Method

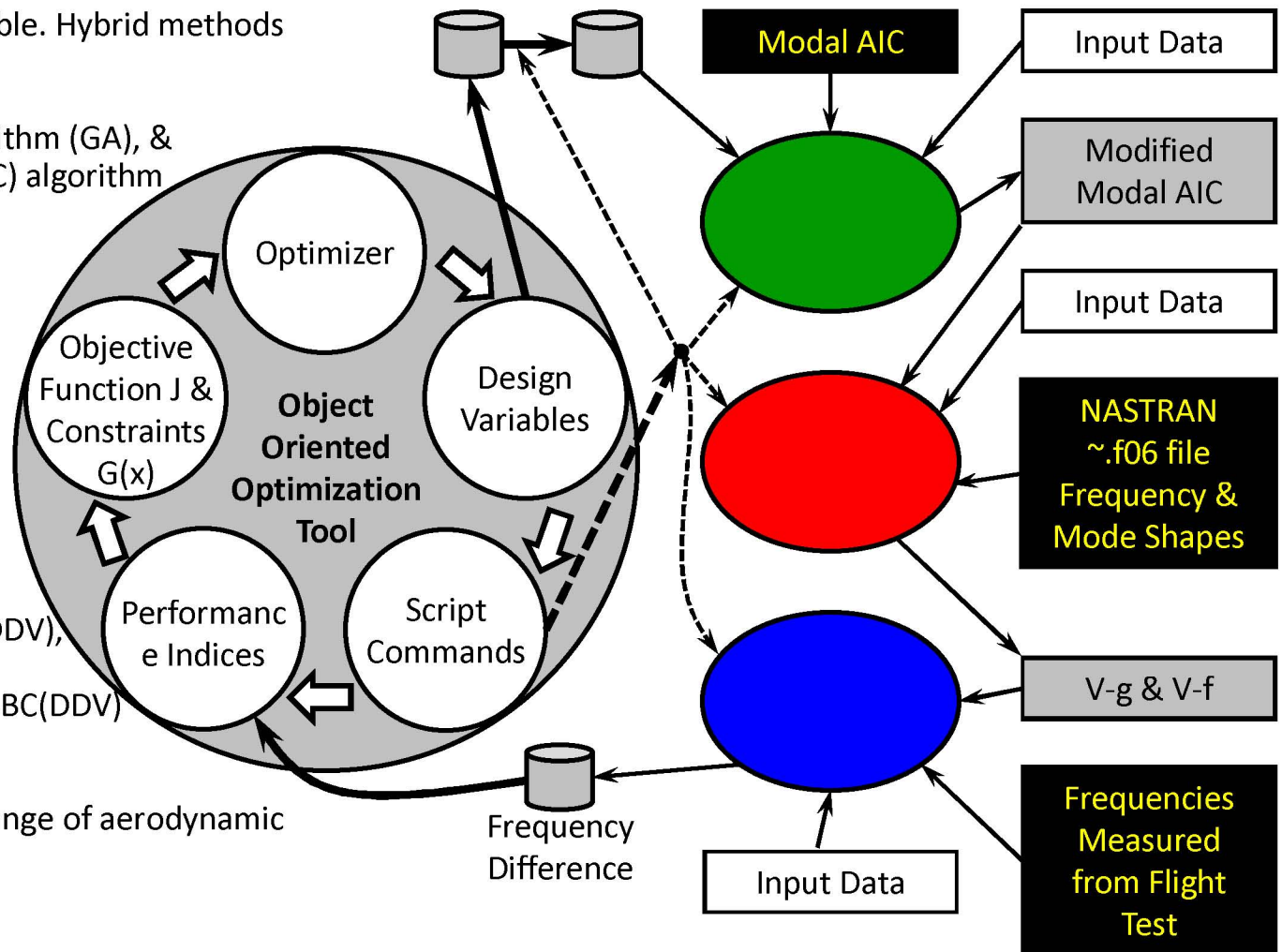
❑ Unsteady Aerodynamic Model Tuning based on Direct Method

- ❖ The NASA Dryden 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:
DOT (local), Genetic Algorithm (GA), & Big Bang-Big Crunch (BBBC) algorithm

- Hybrid optimizers:
GA(CDV)+DOT(CDV),
GA(CDV)+DOT(CDV)+GA(DDV),
BBBC(CDV)+DOT(CDV), &
BBBC(CDV)+DOT(CDV)+BBBC(DDV)

❑ In-direct Method

- ❖ Change AIC through the change of aerodynamic panel geometry

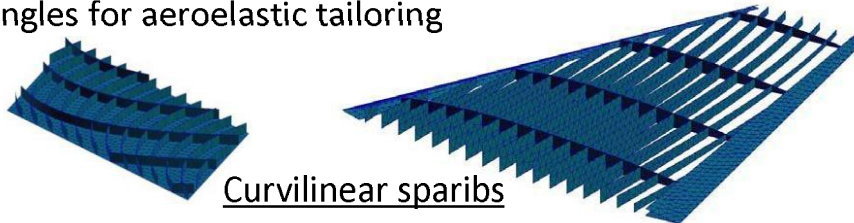




Design of an Aeroservoelastically Tailored Wings and Aircraft

Research Goals/Objectives:

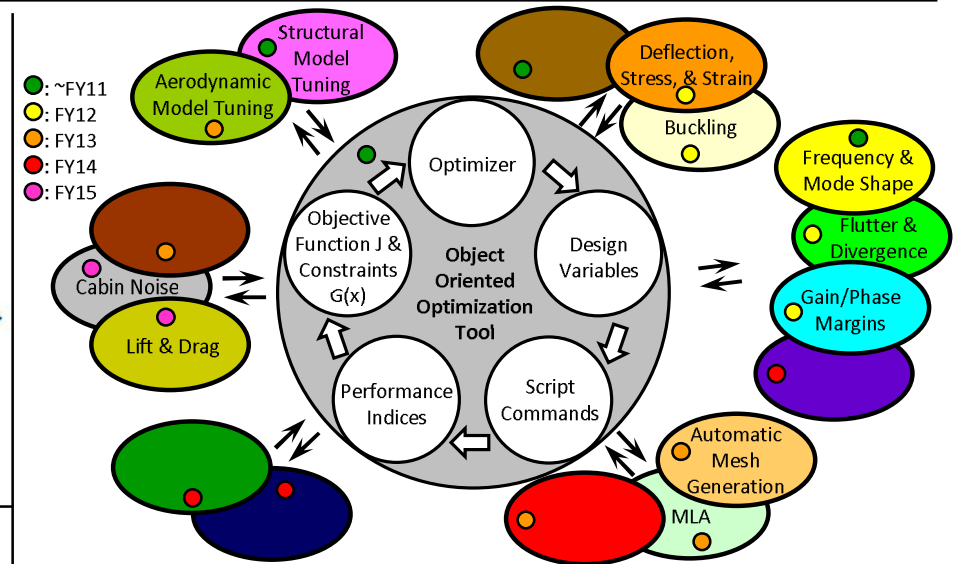
- ❑ Use aeroelastic tailoring theory and active flexible motion control technique to satisfy the overall strain and aeroelastic and aeroservoelastic instability requirements within given flight envelopes
- ❑ Use curvilinear sparrib concept as well as composite ply angles for aeroelastic tailoring



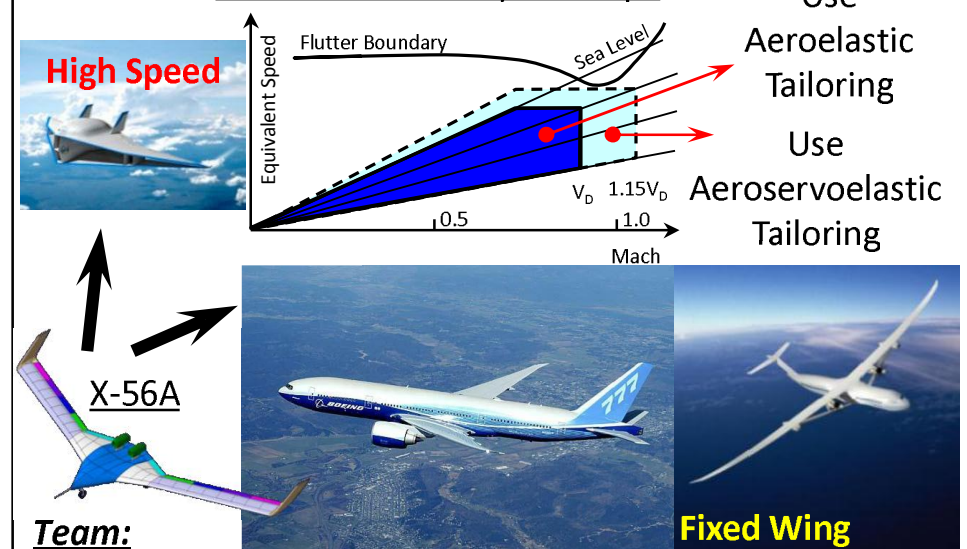
Approach:

- ❑ Simultaneously update structural as well as control design variables during early design phase
 - ❖ Perform topology optimization with curvilinear sparibs
 - ❖ Use aeroelastic tailoring up to V_d line
 - ❖ Use aeroservoelastic tailoring between V_d and $1.15 V_d$
- ❑ During MDAO code development use X-56A as a sample case
- ❑ Design AR10 Wing using object-oriented MDAO tool
 - ❖ Design scaled AR10 wing using structural model tuning tool
 - ❖ Candidate aircraft: B-777 or B-747 (SOFIA)
- ❑ Design AR14 Wing using Object-Oriented MDAO tool
 - ❖ Design scaled AR14 wing using structural model tuning tool
 - ❖ Candidate aircraft: Truss Braced Wing, etc.
- ❑ Design Supersonic Biplane

Structural Dynamics Group



Aeroelastic stability envelope



Team:

- ❑ Chan-gi Pak, Wesley Li, Alex Chin, Roger Truax, & Paul Yoo

Chan-gi Pak-29



Equivalent Beam Modeling for X-56A Flight Simulations

Research Goals/Objectives:

- ❑ Create accurate and affordable model for aeroservoelastic simulations

Approach:

- ❑ Create a wing equivalent beam or plate model using structural dynamic model tuning tool
 - ❖ Use equivalent beam model for high aspect ratio wing
 - ❖ Use equivalent plate model for low aspect ratio wing

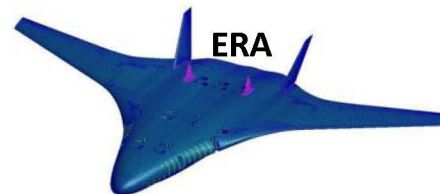
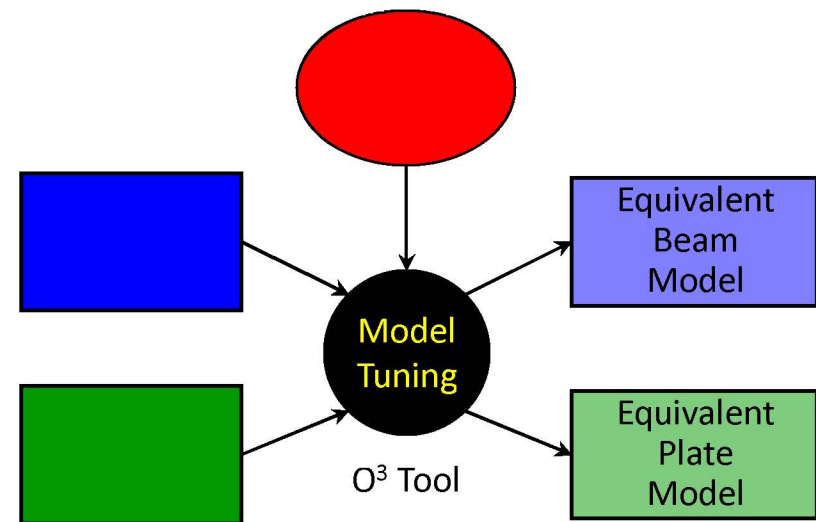
Applications:

- ❑ Wing equivalent beam modeling
 - ❖ High aspect ratio wings
 - X-56A
 - AR10 Wing
 - AR14 Wing
- ❑ Wing equivalent plate modeling
 - ❖ Low aspect ratio wings



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Reduced Order Structural Dynamic Modeling



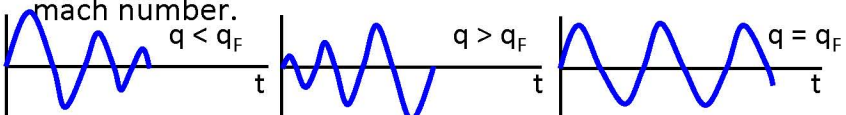
Team:

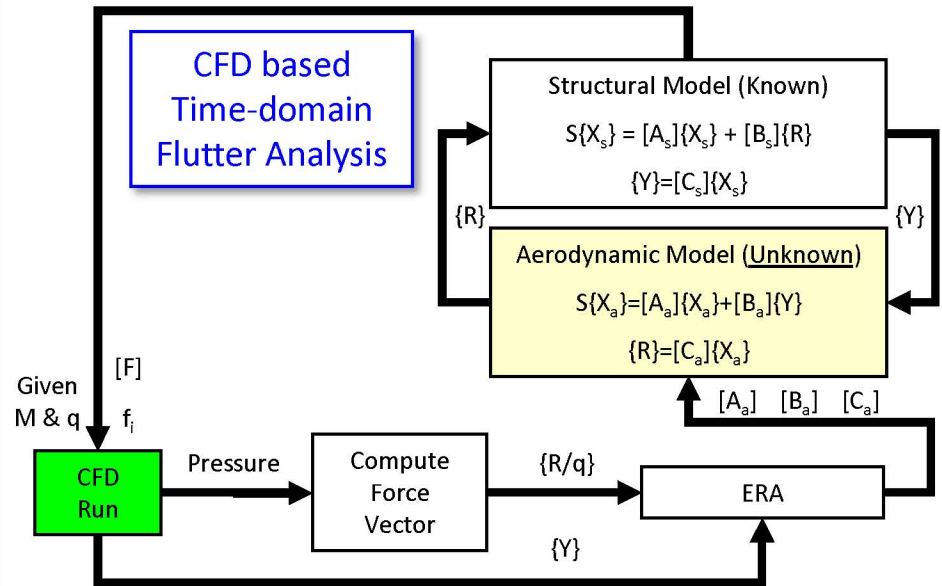
- ❑ Chan-gi Pak & Peter Suh (Ph.D. Student @ Georgia Tech)



Development of CFD based Flutter Analysis Technique

Research Goals/Objectives:

- ❑ A flutter analysis technique in the transonic flight regime. The technique uses an iterative approach to determine the critical dynamic pressure, i.e. flutter boundary, for a given mach number.
- 
- ❑ Unlike other CFD-based flutter analysis methods, each iteration solves for the critical dynamic pressure and uses this value in subsequent iterations until the value converges. This process reduces the iterations required to determine the critical dynamic pressure. To improve the accuracy of the analysis, the technique employs a known structural model, leaving only the aerodynamic model as the unknown.



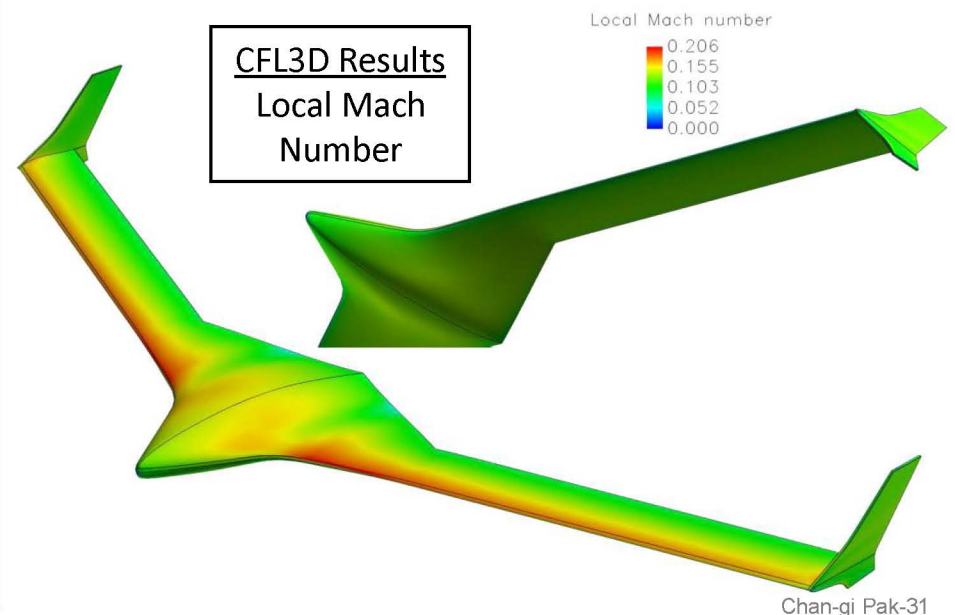
Approach:

- ❑ The known structural model is represented as a FEM.
- ❑ The unsteady CFD analysis is performed. The output time history of the surface pressure is converted to a nodal aerodynamic force vector. The forces are then normalized by the given dynamic pressure.
- ❑ A multi-input multi-output parameter estimation software, Eigenvalue Realization Algorithm, estimates the aerodynamic model.
- ❑ The critical dynamic pressure is then calculated using the known structural model and the estimated aerodynamic model.
- ❑ This output is used as the dynamic pressure in subsequent iterations until the critical dynamic pressure is determined.

Team:

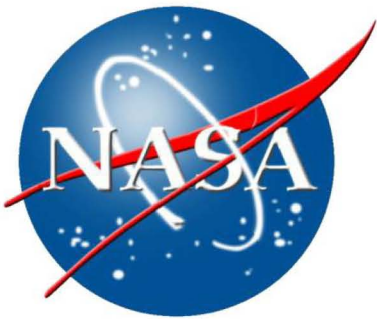
- ❑ Chan-gi Pak & Paul Yoo (Ph.D. Student @ USC)

Structural Dynamics Group



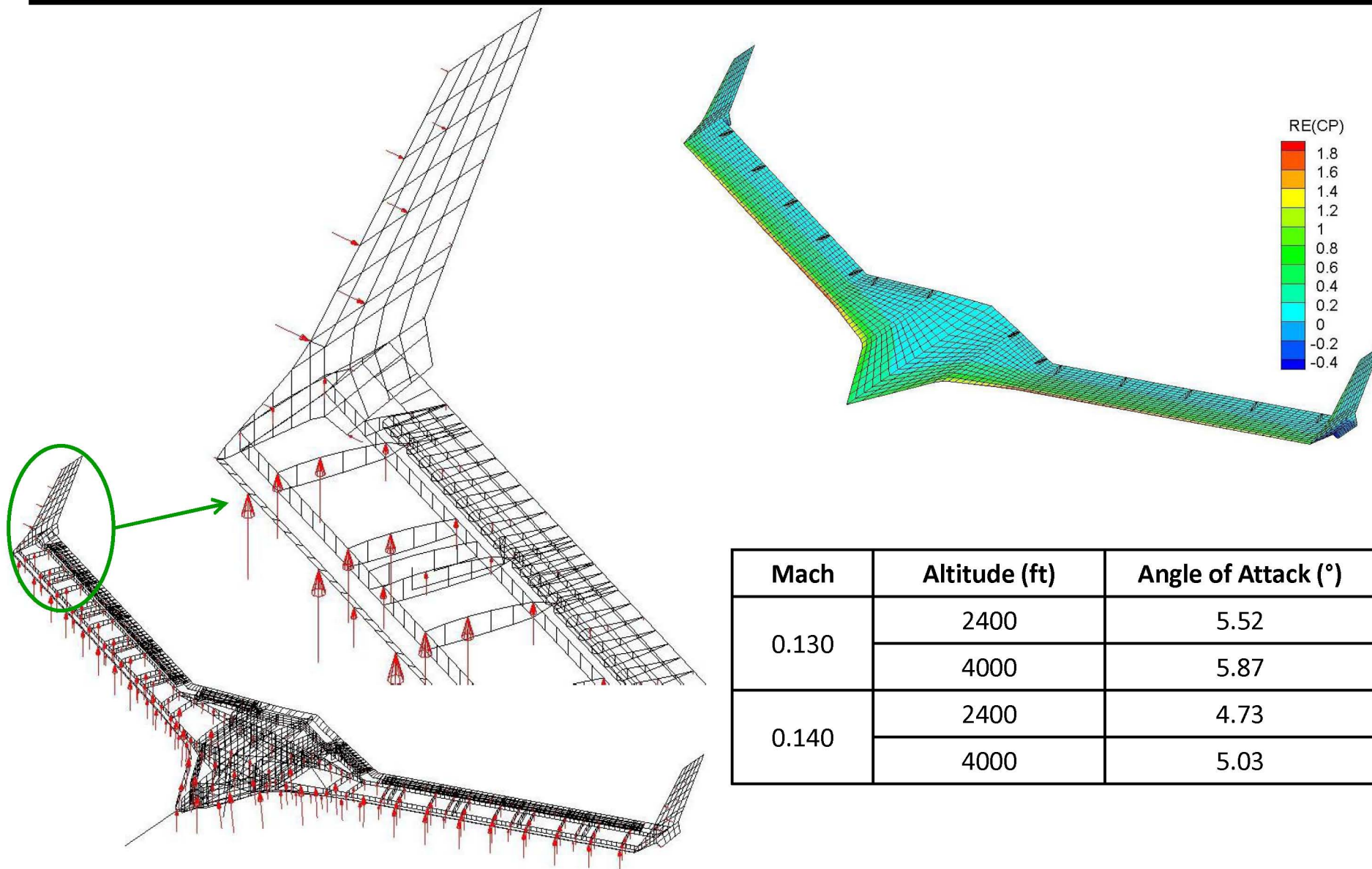
Chan-gi Pak-31

Questions?



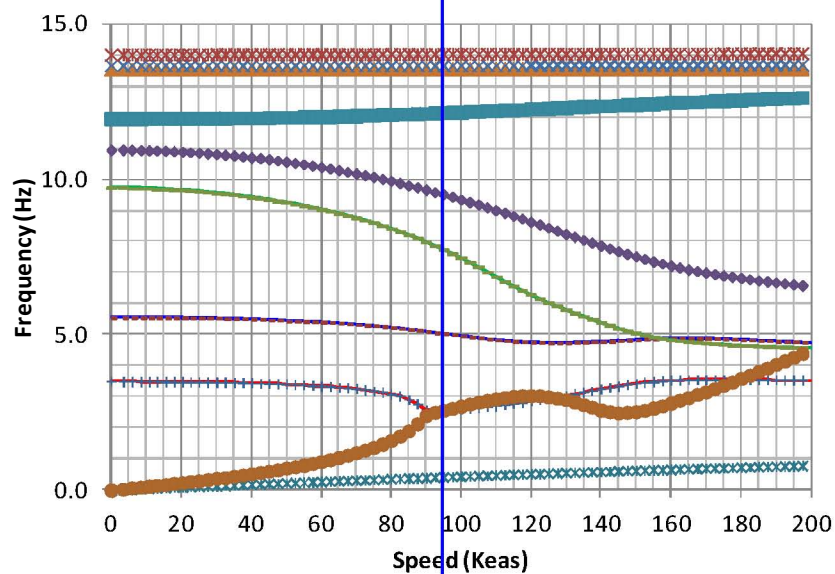
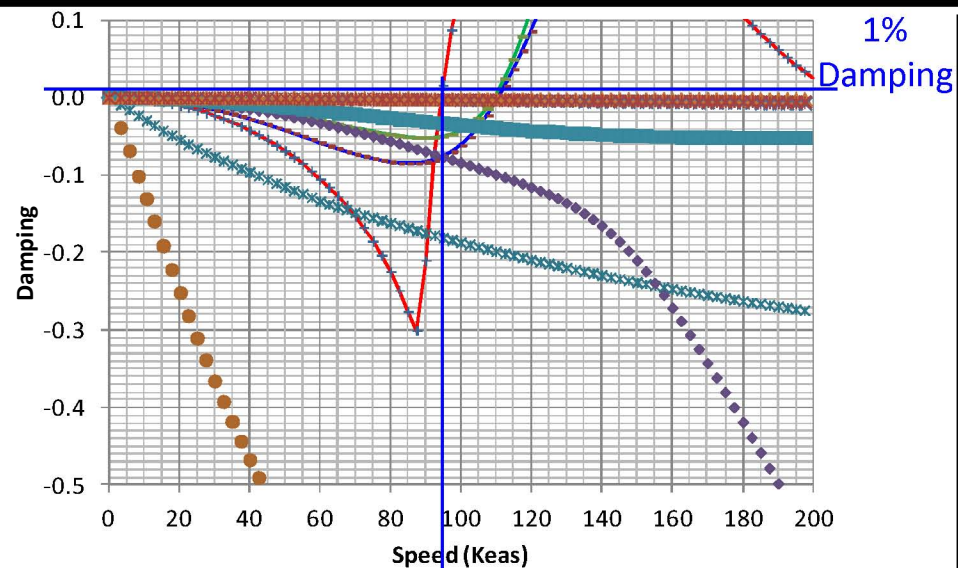


1G Trim Analysis





V-g and V-f Curves at Mach = 0.195 Before Model Tuning

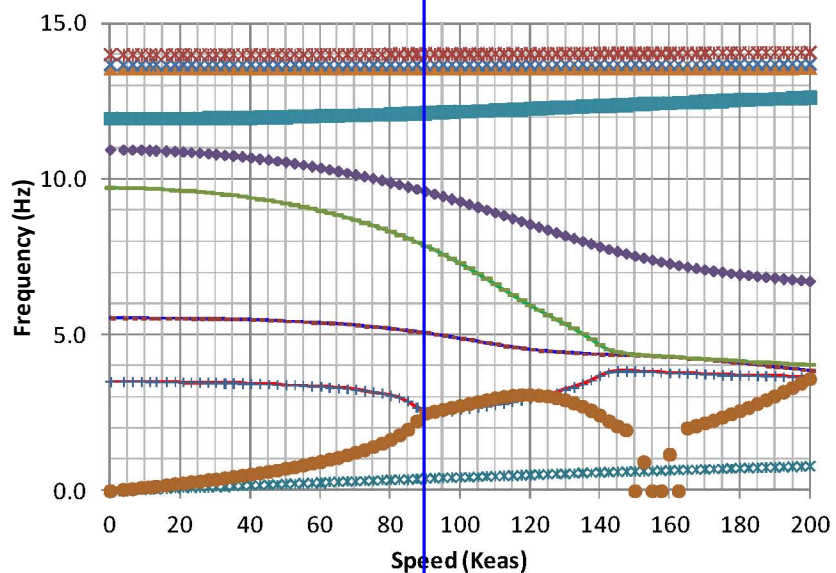
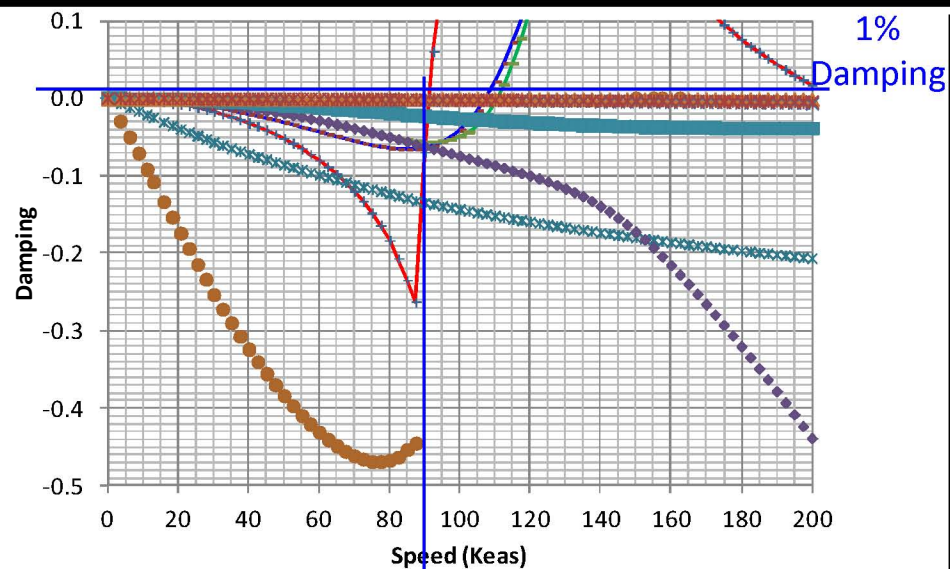


Mode	Frequency	1st		2nd		3rd	
1-6	0.000 Hz	2	28.5	2	27.1	1	31.6
7	3.499	3	13.4	3	6.8		0.0
8	5.557		0.0		0.0	2	31.3
9	9.723	1	49.4	1	61.7		0.0
10	10.94		0.0		0.0	3	31.3
11	11.94	8	0.8	6	0.9		0.0
15	15.16	5	1.7	5	0.9		0.0
20	19.01	7	0.9		0.0		0.0
27	38.26	4	2.4	7	0.8		0.0
30	43.00		0.0		0.0	4	2.2
31	48.51	6	1.0	4	1.0		0.0

Flutter Mode	Speed	Frequency	Altitude
1	94.87 Keas	2.553 Hz	16045. ft
2	110.8 Keas	6.814 Hz	8153.8 ft
3	111.9 Keas	4.807 Hz	7636.9 ft



V-g and V-f Curves at Mach = 0.284 Before Model Tuning



Mode	Frequency	1st		2nd		3rd	
1-6	0.000 Hz	2	27.8	2	28.3	3	24.7
7	3.499	3	11.4	3	6.1		0.0
8	5.557		0.0		0.0	1	34.9
9	9.723	1	53.2	1	62.0		0.0
10	10.94		0.0		0.0	2	34.9
11	11.94	8	0.7	5	0.7		0.0
15	15.16	5	1.4	7	0.7		0.0
20	19.01	7	0.8		0.0		0.0
27	38.26	4	2.1	6	0.7		0.0
30	43.00		0.0		0.0	4	2.3
31	48.51	6	0.9	4	0.9		0.0

Flutter Mode	Speed	Frequency	Altitude
1	91.67 Keas	2.516 Hz	34749. ft
2	111.7 Keas	6.519 Hz	26092. Ft
3	108.7 Keas	4.725 Hz	27354. ft