Aeroelastic Optimization Study Based on X-56A Model

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Agenda

- ❑ Motivation, Objective & Approach
- ❑ X-56A model
- ❑ MDAO Tools and design environment
- ❑ First study: Aeroelastic tailoring optimization
- ❑ Second study: Mass balancing
- ❑ Conclusions

Two Optimization Studies

- 1st study - Aeroelastic Tailoring Optimization
  - Motivation
    - One of the research objectives of the Fixed Wing Project under NASA Fundamental Aeronautics Program is to explore and develop technologies to enable ultra flexible lightweight high aspect ratio wing
  - Objective
    - To demonstrate the use of aeroelastic tailoring concepts to minimize the structural weight while meeting the design requirements including strength, buckling, and flutter
  - Approach
    - Use X-56A high fidelity structural finite element model
    - Change wing skin lamination parameters including ply thickness and ply orientation angles
    - Use Hybrid optimization and discretization
- 2nd study - Mass Balancing Flutter Optimization
  - Motivation
    - To restrain the X-56A flutter speeds within a desired range so that during flight testing engineers can examine an active flutter suppression system within the flight envelope
  - Objective
    - To provide guidance to modify the wing design and alter the flutter speeds back into the flight envelope
  - Approach
    - Use X-56A high fidelity structural finite element model
    - Add wing mass ballast
    - Use Gradient-based optimization followed by sensitivity studies

X-56A Overview

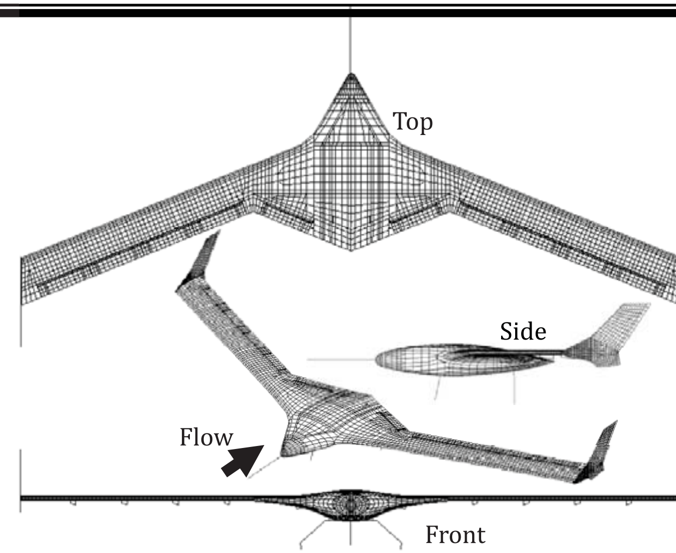
- ❑ Developed by the U.S. Air Force Research Laboratory (AFRL) to test the technologies for lightweight and extremely flexible aircraft.
- ❑ The aircraft is being built and will be flown by Lockheed Martin Skunk Works (LMSW) under contract with the AFRL.
- ❑ The initial purpose of the X-56A aircraft is to demonstrate the simultaneous active suppression of three flutter mechanism through the use of feedback controls.
  - ❖ first symmetric body-freedom flutter (SBFF)
  - ❖ first symmetric wing bending-torsion (SWBT) flutter
  - ❖ first anti-symmetric wing bending-torsion (AWBT) flutter
- ❑ Stay at NASA AFRC for future technology demonstrations.

Two reusable center bodies, one stiff wing, three flex wings, and ground control stations

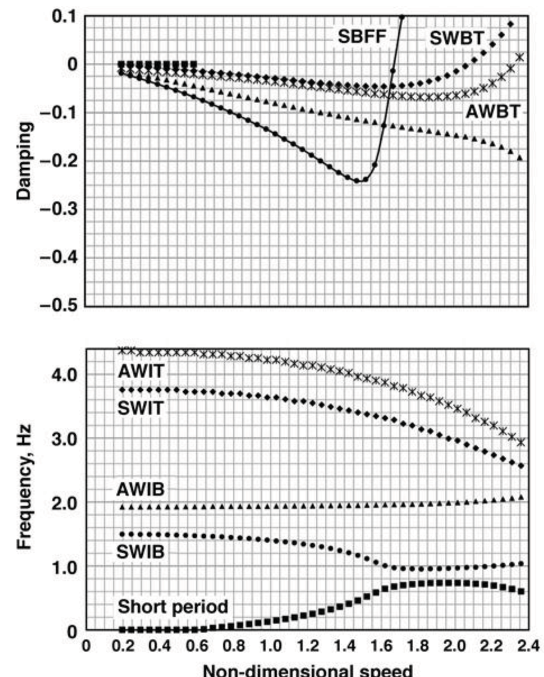
Dimension: 7.5 foot-long, 28-foot wing span, aspect ratio of 14
Powered by two JetCat turbojets
Weight: ~480 lbs

X-56A Aeroelastic Model

- X-56A structural model
  - Modeled using the MSC Nastran code (8249 nodes).
  - The wing skin, spars (2), and ribs(16) are modeled using shell elements with composite material.
  - The fuel and ballast weights are modeled using concentrated mass elements connected to the ribs and spars by multiple point constraints elements.
  - The wing is connected to the center body by point spring elements.



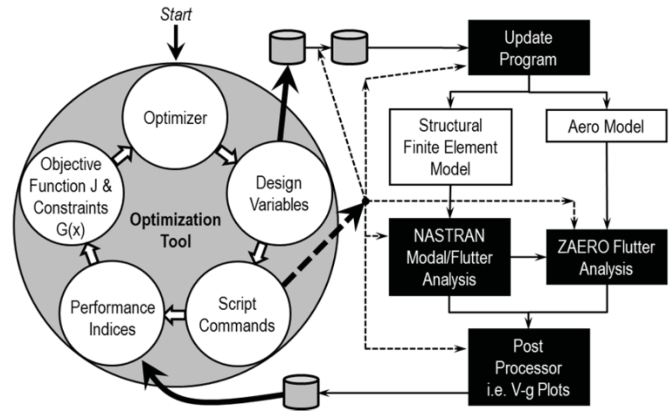
- Unsteady aerodynamics model
  - Generated using the MSC Nastran Doublet Lattice method.



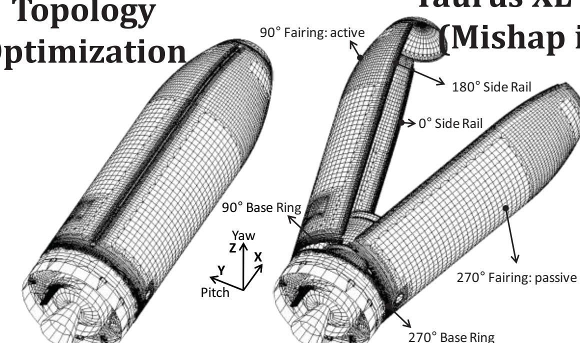
- Flutter analyses
  - Based on MSC Nastran's PK solution method
  - At Mach 0.16
  - Included 25 structural modes
  - Examined the flutter mechanism by V-g and V-f plots

AFRC MDAO Tools

- Object-oriented MDAO tools
  - Provide a computational environment. Optimizer can effectively receive objective and constraint function values from various disciplines through the interface variables.
  - Designed to handle the complex optimization problems (i.e. multi-point, multi-level and multi-fidelity modeling and analyses)
  - Optimization algorithms included
    - gradient-based algorithm: DOT
    - genetic algorithm
    - big-bang big-crunch algorithm
- Real-world applications
  - Structural dynamic model tuning
    - X-37 Drogue Chute Test Fixture
    - Quiet Spike Boom
  - Unsteady aerodynamic model tuning
    - Aerostructures Test Wing 2
  - Glory Mishap Investigation
    - Topology Optimization



Topology Optimization



Taurus XL Launch Vehicle (Mishap investigation)

Study 1

AEROELASTIC TAILORING

Aeroelastic Tailoring Optimization

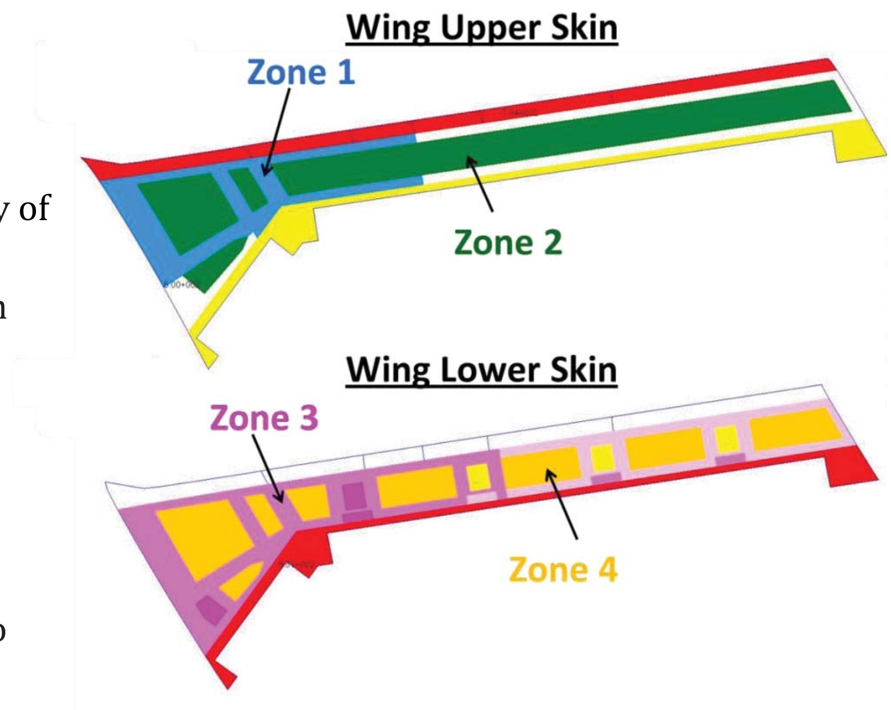
- Objective
  - To demonstrate the use of aeroelastic tailoring concepts to minimize the structural weight while meeting the design requirements including strength, buckling, and flutter.

- Find design variables $\mathbf{X} = \begin{Bmatrix} x_1 \\ x_2 \\ \vdots \\ x_N \end{Bmatrix}$ which minimizes
  - Objective function $f(\mathbf{X})$ = total structural weight
  - Side constraints
    - $x_{Lj} \leq x_j \leq x_{Uj}$
  - Inequality constraints
    - Design requirements

Design Requirements	Value	Comments
Composite Failure Index 1	< 1.0	Based on 2.5g loads. Factor of safety of 1.5.
Composite Failure Index 2	< 1.0	Based on -1.0 g loads. Factor of safety of 1.5.
Buckling load factor	> 1.0	Applied loads are based on 2.5g loads. Factor of safety of 1.5.
Normalized critical Flutter speed	> 1.62	At Mach 0.16

Design Process

- Based on X-56A aircraft with flex wings FEM (EFEW)
  - With strengthened wing upper and lower skin thicknesses
  - To guarantee the optimization starts from a feasible region.
- A hybrid optimization approach
  - To improve accuracy and computation efficiency of a global optimization algorithm.
  - Step 1: Use a global optimizer; genetic algorithm
    - with discrete design variables
    - population size of 200 and 30 generations
  - Step 2: Use a gradient based optimizer; DOT
    - with continuous design variables
- Discretization
  - Round up or round down the design variables to the predefined value for manufacturing



- Design cases

Case	Design Variable Set	Number of design variables	Step	Optimization Descriptions
1	Thickness	12	1	GA + DDV
			2	DOT + CDV
2	Thickness + Orientation	24	1	GA + DDV
			2	DOT + CDV

Starting Configuration

	Case 1 (thickness)		Case 2 (thickness + angle)	
Normalized Weight	1.0		1.0	
Failure Index 1	0.26		0.26	
Failure Index 2	0.17		0.087	
Buckling load factor	1.05		1.05	
Normalized critical flutter	Speed	Frequency	Speed	Frequency
	1.69	0.97	1.92	0.83

- The skin thickness upper limit was used for all the thickness design variables to guarantee that the optimization starts from a feasible region.
- Ply thickness and orientation angle
  - Case 1 & 2 have the same ply thicknesses
  - Case 1 has orientation angles of 0° and 90°
  - Case 2 has orientation angles of 45° and 90°

Case 1: Results (Thickness only)

	Starting		Step 1 (Genetic +DDV)		Step 2 (DOT + CDV)		Round Down		Round Up	
Number of function calls	N/A		1406		77		N/A		N/A	
Weight Reduction	1.0		0.88		0.87		0.86		0.89	
Composite FI 1	0.26		0.28		0.30		0.30		0.29	
Composite FI 2	0.17		0.19		0.20		0.20		0.20	
Buckling load factor	1.05		1.14		1.16		1.18		1.14	
Normalized critical Flutter	Speed	Freq.	Speed	Freq.	Speed	Freq.	Speed	Freq.	Speed	Freq.
	1.69	0.97	1.62	0.97	1.61	0.96	1.60	0.96	1.64	0.97

Too low

- The skin thickness upper limit was used for all the thickness design variables to guarantee that the optimization starts from a feasible region.

- Flutter speed constraint ≥ 1.62
  - Genetic algorithm+ exterior penalty function: $\frac{1.62-V}{1.62} \leq 0.002; \quad V \geq 1.617$
  - DOT: $\frac{1.62-V}{1.62} \leq (0.002 + 0.003)\ (\text{CTMIN})\ ; \quad V \geq 1.612$

Case 2: Results (Thickness + Orientation Angle)

	Starting		Step 1 (Genetic +DDV)		Step 2 (DOT + CDV)		Round Down		Round Up	
Number of function calls	N/A		3416		297		N/A		N/A	
Weight Reduction	1.0		0.78		0.72		0.70		0.73	
Composite FI 1	0.26		0.43		0.40		0.43		0.39	
Composite FI 2	0.087		0.28		0.27		0.27		0.26	
Buckling load factor	1.05		1.24		1.26		1.27		1.25	
Normalized critical Flutter	Speed	Freq.	Speed	Freq.	Speed	Freq.	Speed	Freq.	Speed	Freq.
	1.92	0.83	1.62	0.57	1.61	0.56	1.42	0.64	1.62	0.63

Too low

- The skin thickness upper limit was used for all the thickness design variables to guarantee that the optimization starts from a feasible region.
- Ply thickness and orientation angle
  - Case 1 & 2 have the same ply thicknesses
  - Case 1 has orientation angles of 0° and 90°
  - Case 2 has orientation angles of 45° and 90°

Summary of Aeroelastic Tailoring Study

	Thickness only				Thickness + orientation angle			
	Step 1 (Genetic +DDV)		Step 2 & Round Up		Step 1 (Genetic +DDV)		Step 2 & Round Up	
Number of function calls	1406		77		3416 →		297	
Weight Reduction	0.88		0.89		0.78 →		0.73	
Composite FI 1	0.28		0.29		0.43		0.39	
Composite FI 2	0.19		0.20		0.28		0.26	
Buckling load factor	1.14		1.14		1.24		1.25	
Normalized critical Flutter	Speed	Freq.	Speed	Freq.	Speed	Freq.	Speed	Freq.
	164.7	3.29	167.3	3.31	164.7	1.94	164.5	2.16

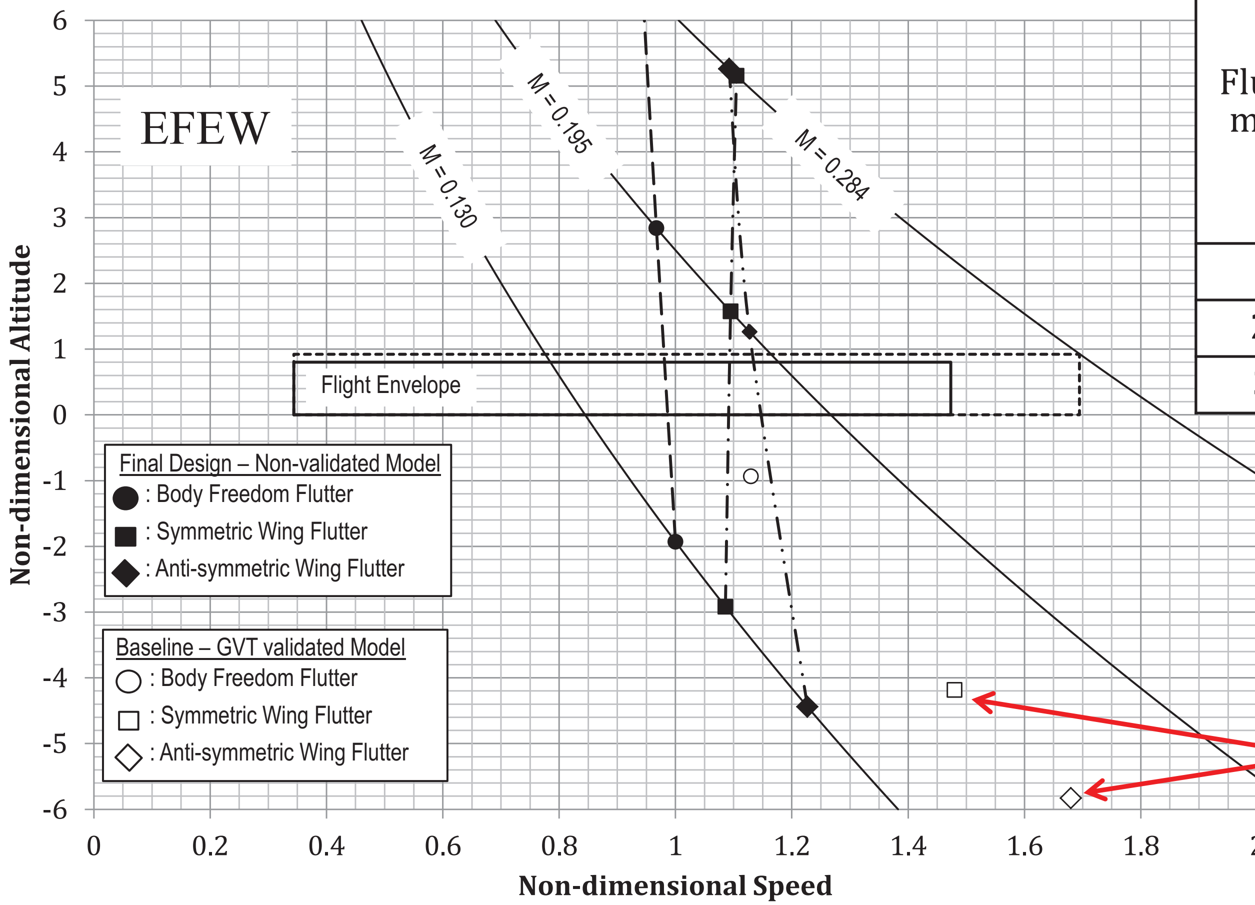
- ❑ Effect of Aeroelastic Tailoring: 0.88 vs. 0.73 (**15%** more reduction by **aeroelastic tailoring**)
- ❑ Effect of Hybrid optimization + Discretization: genetic algorithm is slow near the global optimum solution; accelerate global optimizer; further improve design with additional 10% of function calls

Study 2

MASS BALANCING

Mass Balancing Study

- X-56A Research objective: to demonstrate the simultaneous active suppression of three flutter mechanisms through the use of feedback controls.
- Study goal: to provide guidance to modify the wing design and move flutter speeds back into the flight envelope.



Flutter mode	Baseline flutter points at Mach = 0.16		
	Speed		
	Lower Bounds	EFEW	Upper Bounds
1st	0.79	1.13*	0.98
2nd	0.98	1.48	1.18
3rd	0.98	1.68	1.30

**Note: Baseline flutter speeds violate flutter speed constraints*

Unfortunately, after GVT and correlation, the 2nd and 3rd predicted flutter speeds were too high or outside the flight envelope

Note: Final design flutter results are based on LMSW's final design model and ZAERO g-method.

Mass Balancing Optimization

- Find design variables $\mathbf{X} = \begin{Bmatrix} x_1 \\ x_2 \\ \vdots \\ x_N \end{Bmatrix}$ which minimizes (or maximizes)

  - $Objective\ function\ f(\mathbf{X}) = total\ structural\ weight$
  - $Objective\ function\ f(\mathbf{X}) = flutter\ speed$ & frequency

    - such that:
      - Flutter speed constraints:
        $V_{Lj} \leq V_{EFEWj}(\mathbf{X}) \leq V_{Uj}\ \ \&\ \ V_{Lj} \leq V_{FFFWj}(\mathbf{X}) \leq V_{Uj} \quad j = 1, 2, \& 3$
      - Flutter frequency constraints:
        $f_{Lj} \leq f_{EFEWj}(\mathbf{X}) \leq f_{Uj}\ \ \&\ \ f_{Lj} \leq f_{FFFWj}(\mathbf{X}) \leq f_{Uj} \quad j = 1, 2, \& 3$
      - Side constraints: (ballast weight)
        $0 \leq x_j \leq x_{Uj}$

- Based on DOT, a gradient-based optimization.
- Two weight configurations included in a single optimization run.

Flutter Speed and Frequency

- Design requirement (Constraints)
  - 1st flutter (body freedom): ~0.78 to 0.93
  - 2nd and 3rd flutter: ~0.98 to 1.18

Flutter mode	Flutter Constraints*			
	Speed		Frequency	
	Lower Bounds	Upper Bounds	Lower Bounds	Upper Bounds
1st	0.79	0.98	0.53	1.76
2nd	0.98	1.18	1.17	2.35
3rd	0.98	1.30	1.50	3.52

**Note: optimization constraints for trailing wing tip boom optimization*

- Baseline flutter model
  - Based on GVT correlated flexible wing model from Lockheed Martin
  - Two weight configuration were used: EFEW and FFFW

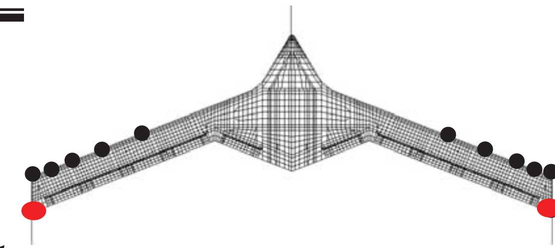
Flutter mode	Baseline flutter points at Mach = 0.16							
	Speed				Frequency			
	Lower Bounds	EFEW	FFFW	Upper Bounds	Lower Bounds	EFEW	FFFW	Upper Bounds
1st	0.79	1.13*	1.16	0.98	0.53	0.68	0.53	1.76
2nd	0.98	1.48	1.48	1.18	1.17	2.34	2.25	2.35
3rd	0.98	1.68	1.68	1.30	1.50	1.52	2.43	3.52

**Note: Baseline flutter speeds violate flutter speed constraints*

Configuration # 1 & 2

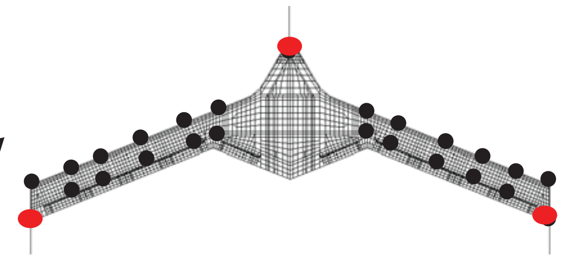
- Objective: Min 1st flutter speed ($0.79<f_1<1.18$)
- Constraints: 2nd and 3rd flutter speed ($0.98<f_2<1.18$, $0.98<f_3<1.3$)
- Design Variables
  - Based on the mode shapes
  - Center body nose ballast (0 to 20.0 lbs.)
  - Wing lumped mass ballast design variables (0 to 5 lbs. each)
  - Use design variable linking for wing symmetric masses
- Configuration 1
  - Wing leading edge (6 design variables)
  - Results: two 5 lbs. ballast were added at aft wing tip location.
- Configuration 2
  - Nose, wing leading and trailing edge (13 design variables)
  - Results: 20 lbs. nose ballast and two 5 lbs.. ballast at aft wing tip location.
- Observation
  - Nose ballast: Primarily to reduce body freedom flutter speed
  - Wing tip ballast: reduce 2nd and 3rd flutter speeds

Configuration 1



- Optimization ballast location
- Final design ballast location

Configuration 2



Normalized flutter speeds				
Flutter mode	Configuration 1		Configuration 2 (Nose ballast)	
	EFEW	FFFW	EFEW	FFFW
SBFF	1.16	1.18	1.12	1.12
SWBT	1.49	1.67	1.49	1.67
AWBT	1.59	1.57	1.56	1.55
Normalized flutter frequency				
Flutter mode	Configuration 1		Configuration 2 (Nose ballast)	
	EFEW	FFFW	EFEW	FFFW
SBFF	0.66	0.52	0.71	0.58
SWBT	1.28	1.25	1.28	1.25
AWBT	2.09	2.02	2.07	2.01

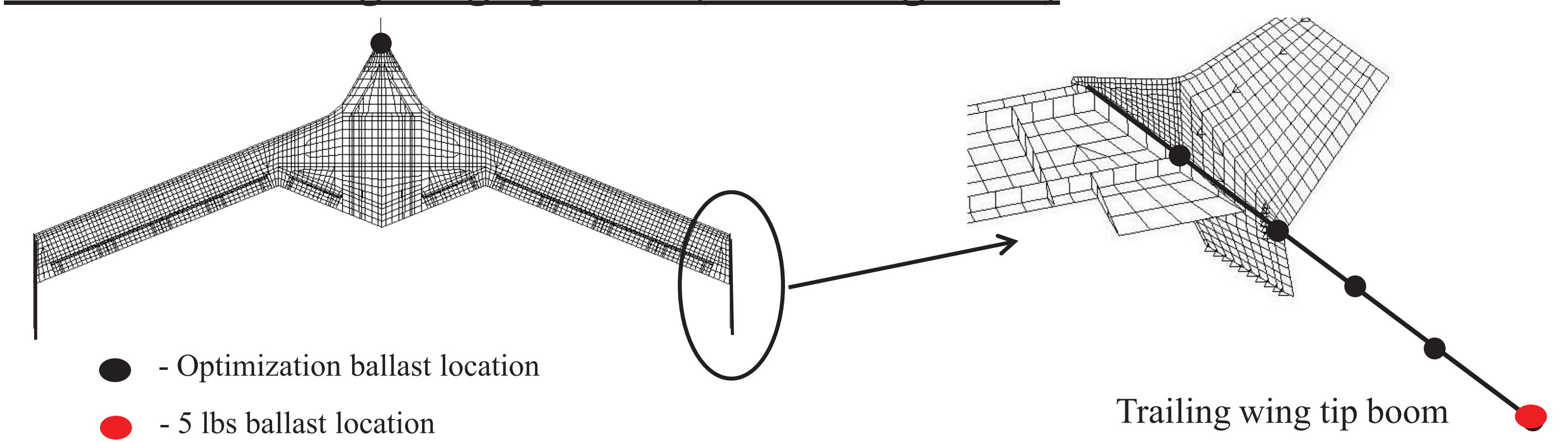
Configuration # 3

- Based on configuration 1 and 2 results
- Add a 25 inch long Trailing Wing Tip Boom and ballast to increase mass effectiveness / efficiency.
- Design variables
  - Total 11 design variables
  - One Center body nose ballast (0 to 20 lbs.)
  - Five wing tip boom ballasts and corresponding locations
    - 0 to 5 lbs. each
    - 5 inch per segment

Final Design Variables			
Design variable	**Run 1**	**Run 2**	**Run 3**
Nose Ballast (lb)			
1	20.0	20.0	20.0
Wing Tip Boom Ballast (lb)			
2	0.00	0.00	0.00
3	0.00	0.00	0.04
4	0.00	0.00	0.04
5	0.00	0.34	2.44
6	**5.00**	**4.74**	**5.00**
Wing Tip Ballast X Location (inch)			
7	216.0	212.0	215.0
8	221.0	221.0	221.0
9	226.0	226.0	226.0
10	231.0	231.0	231.0
11	**236.0**	**236.0**	**236.0**

Configuration 3

With a 25" trailing wing tip boom (Five 5" segments)



Mass Balancing Results

Optimization:

Normalized flutter speeds						
Flutter mode	Configuration					
	1		2		3 (Run 1)	
	EFEW	FFFW	EFEW	FFFW	EFEW	FFFW
SBFF	1.16	1.18	1.12	1.12	1.13	1.14
SWBT	1.49	1.67	1.49	1.67	1.11	1.18
AWBT	1.59	1.57	1.56	1.55	1.29	1.26
Normalized flutter frequency						
Flutter mode	Configuration					
	1		2		3 – Run 1	
	EFEW	FFFW	EFEW	FFFW	EFEW	FFFW
SBFF	0.66	0.52	0.71	0.58	0.72	0.58
SWBT	1.28	1.25	1.28	1.25	1.07	1.03
AWBT	2.09	2.02	2.07	2.01	1.57	1.55

Flutter happens before SBFF.

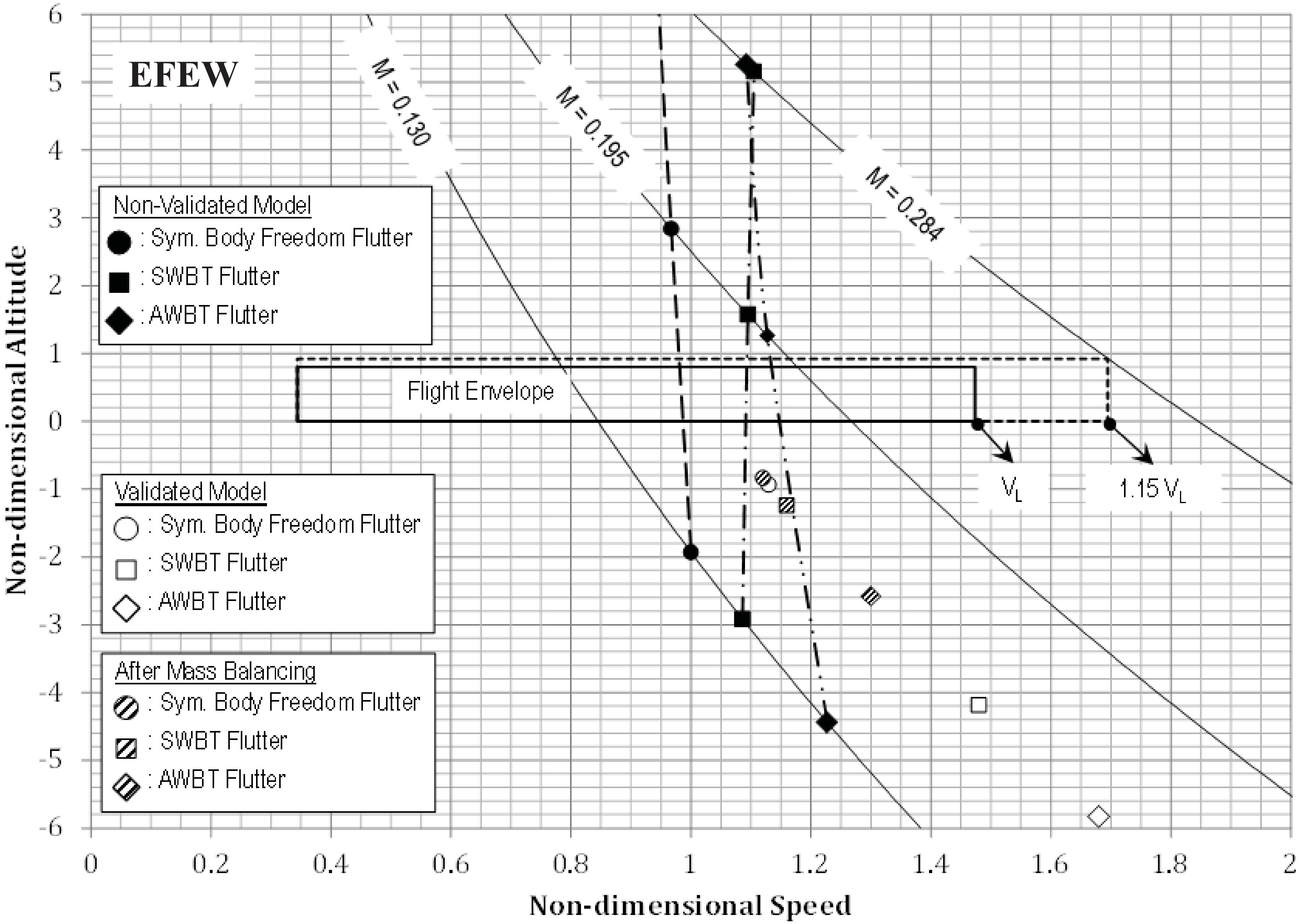
Wing Tip Boom Sensitivity Study:

Configuration	**1st EFEW**		**2nd EFEW**		**3rd EFEW**		**1st FFFW**		**2nd FFFW**		**3rd FFFW**	
	Speed	Freq.	Speed	Freq.	Speed	Freq.	Speed	Freq.	Speed	Freq.	Speed	Freq.
Baseline	1.13	0.68	1.48	2.34	1.68	1.52	1.16	0.53	1.48	2.25	1.68	2.43
20* & 1**	1.11	0.73	1.39	1.30	1.38	2.02	1.12	0.59	1.60	1.29	1.37	1.96
20 & 2	1.12	0.73	1.28	1.23	1.34	1.87	1.13	0.59	1.43	1.19	1.32	1.82
20 & 3	1.12	0.72	1.21	1.17	1.31	1.75	1.13	0.58	1.32	1.12	1.29	1.72
20 & 4	1.12	0.72	1.16	1.11	1.30	1.65	1.13	0.58	1.24	1.07	1.28	1.62
20 & 5	1.13	0.72	1.11	1.07	1.29	1.57	1.14	0.58	1.18	1.03	1.26	1.55
0 & 5	1.17	0.65	1.11	1.07	1.32	0.65	1.20	0.51	1.18	1.03	1.28	1.56

*: Nose ballast (lb) **: Wing tip ballast (lb)

Too low

Flight envelope (EFEW)



Conclusions

- An object-oriented MDAO tool that integrates aeroelastic effects has been developed and demonstrated using X-56A model.

- Aeroelastic Tailoring Study
  - Demonstrated a genetic algorithm with discrete design variables is a beneficial approach for optimizing composite laminates and solving aeroelastic tailoring problems
    - Able to handle all types of design variables, i.e. realistic constraint sets in a finite element model, different material types, and manufacturing ability/ constraints.
  - A hybrid and discretization optimization approach can be used to improve accuracy and computational efficiency of a global optimization algorithm.
    - With the use of additional DOT optimization and discretization approaches (i.e. 5% to 8% of the total computational cost) following the genetic algorithm, the final design can be fine-tuned.
  - **15%** more reduction by **aeroelastic tailoring**

- Mass Balancing Study
  - Provided guidance to modify the wing design and move the flutter speeds back into the flight envelope, so that the original objective of X-56A flight test can be accomplished successfully.
  - Demonstrated the object-oriented MDAO tool can handle multiple analytical configurations in a single optimization run.

THANK YOU !!
&
QUESTIONS?