Follow on Research for Multi-Utility Technology Test-bed Aircraft at NASA Dryden Flight Research Center

(FY13 Progress Report)

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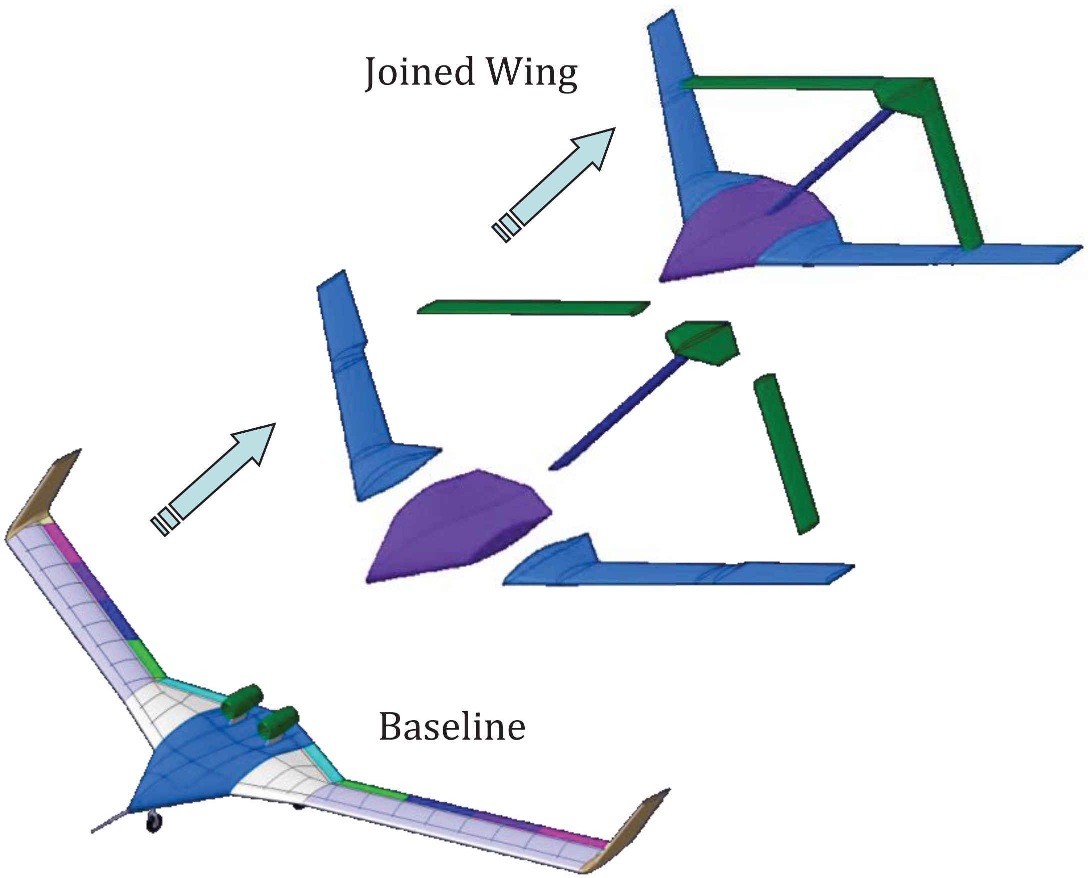
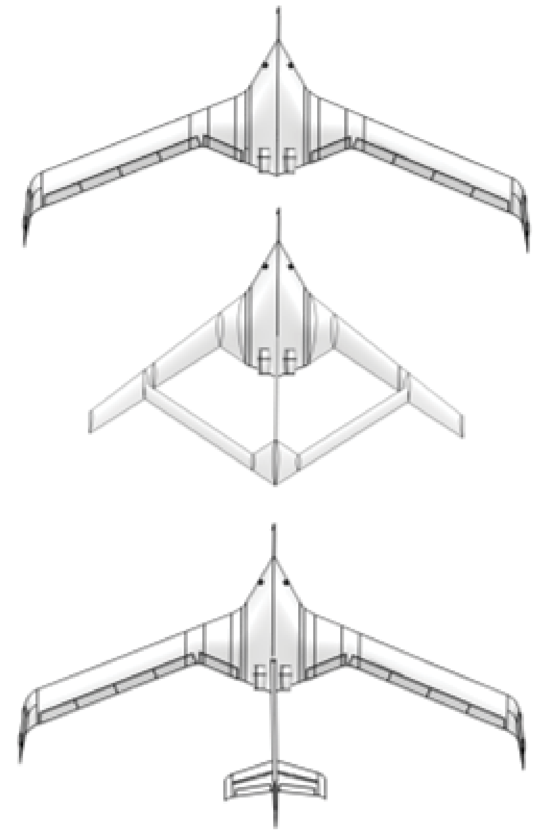
Follow on Research for MUTT Aircraft

- ❑ Adaptive/Active Flexible Motion Control with Aeroservoelastic Uncertainties
  - ❖ Structural Dynamic Finite Element Model Tuning for Flexible Wing Configuration
  - ❖ Unsteady Aerodynamic Model Tuning
  - ❖ Computation of Wing Shape (deflection and slope) from Measured Strain





- ❑ Multidisciplinary Design Optimization
  - ❖ Flutter Optimization Study for MUTT Aircraft with Flexible Wing Configuration
  - ❖ Aeroelastically Tailored Wing Designs

Adaptive/Active Flexible Motion Controls with Aeroservoelastic System Uncertainties

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Adaptive/Active Flexible Motion Controls with Aeroservoelastic System Uncertainties

Problem

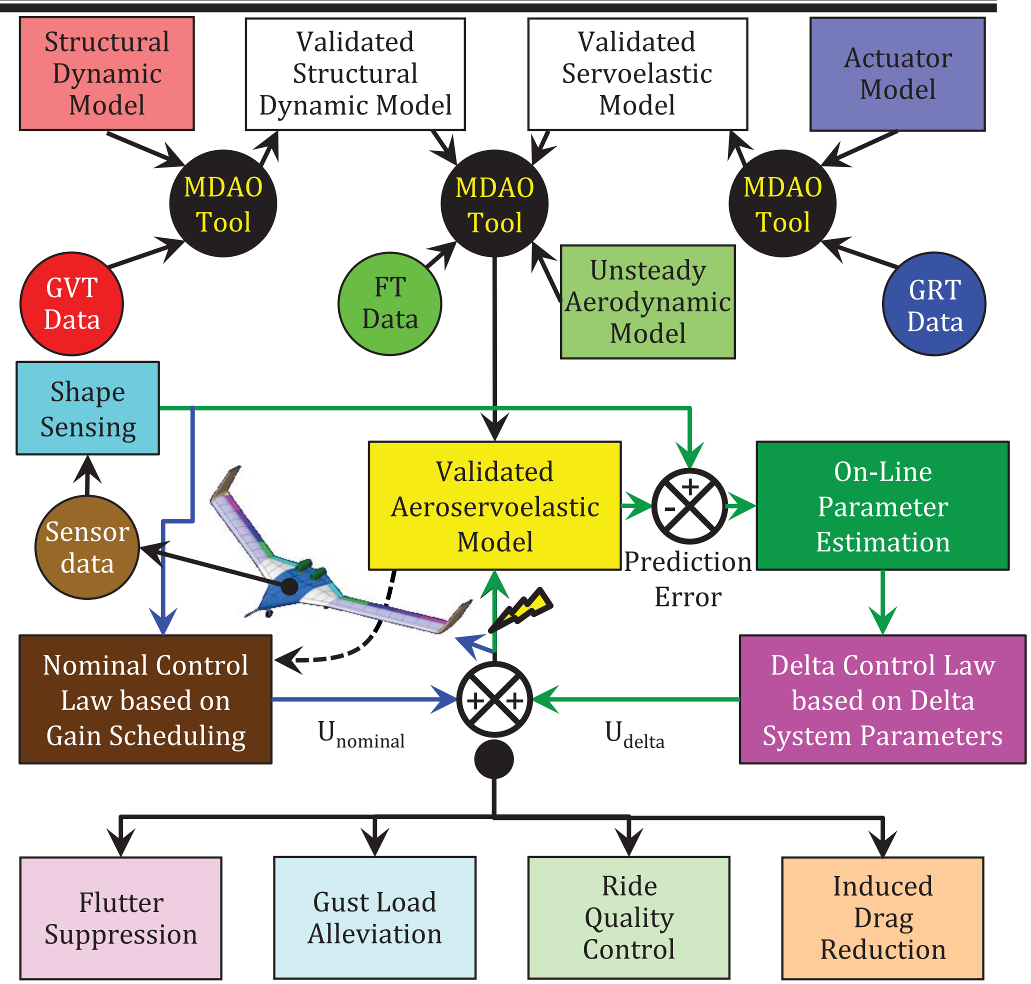
- The increased flexibility, due to weight reduction, creates an aircraft that is more susceptible to aeroelastic phenomena such as flutter, divergence, buzz, buffet, and gust response.
- Uncertainties are existed in aeroservoelastic system even with the test validated aeroservoelastic model due to
  - time-varying uncertain flight conditions,
  - transient and nonlinear unsteady aerodynamics and aeroelastic dynamic environments.

Objective

Implementation of an adaptive delta control methodology during real flight test.

Approach

- An adaptive "delta control" methodology is proposed.
  - On-line parameter estimation will be applied to the prediction error, uncertainties in the validated aeroservoelastic model.
- The online update for the delta control gain is determined on the basis of a test-validated aircraft model whose predicted output response is compared with the actual aircraft measurements.
- The delta control scheme will act in addition to a nominal control law developed solely from the test-validated model so has to help offset some of the model's inaccuracies and uncertainties.



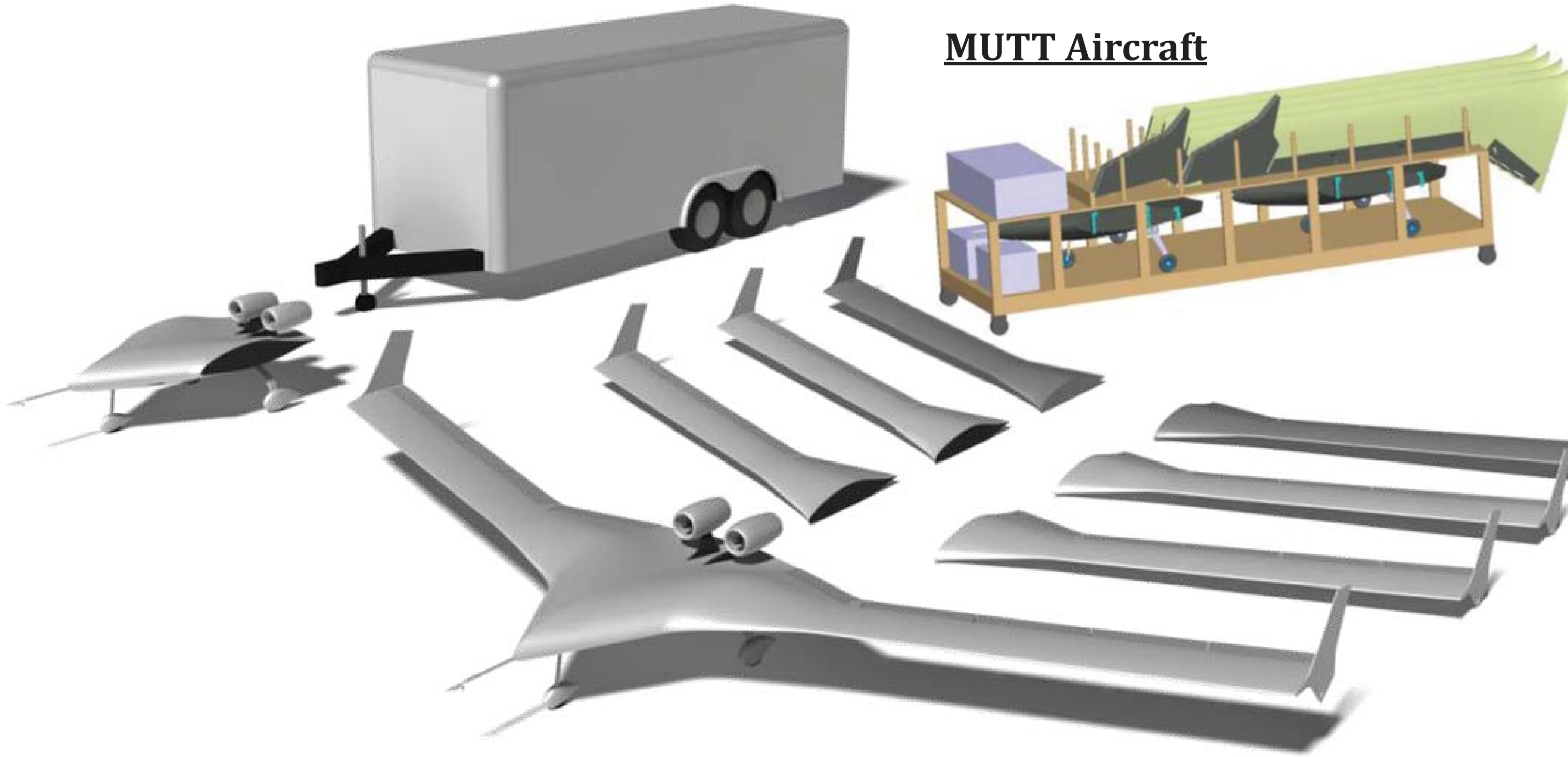
On-line Adaptive Active Flexible Motion Control System

- Assumptions and Limitations:
  - Dynamically linear assumption will be used for the prediction error model.
  - On-board computer should be powerful enough to perform on-line estimation and control law updates.

Creating a Test Validated Structural Dynamic Finite Element Model of Multi Utility Technology Test-bed Aircraft

Objectives

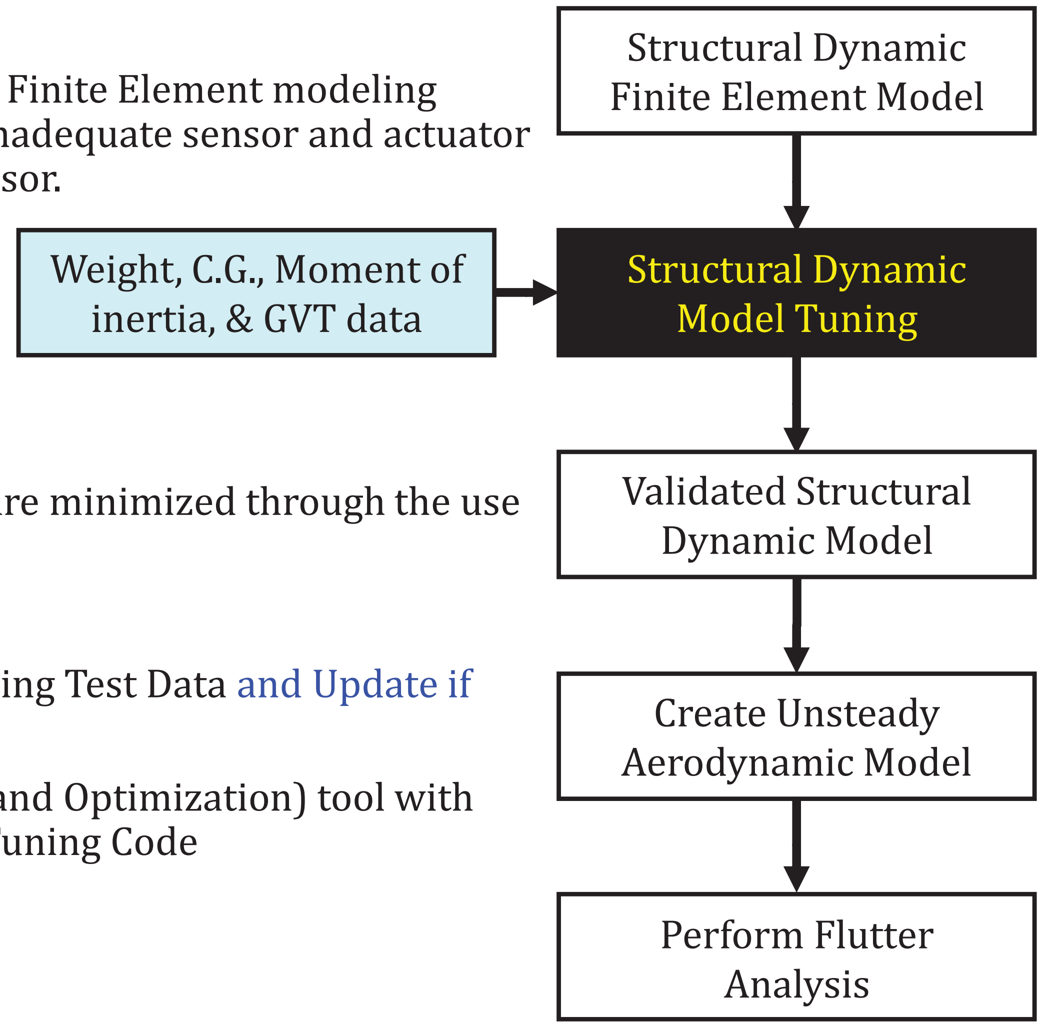
- ❑ The primary objective of this study is to reduce uncertainties in the structural dynamic finite element model of an aircraft to increase the safety of flight.
- ❑ This model tuning technique is applied to improve the flutter prediction of the MUTT aircraft.
- ❑ This work is supported by the Aeronautics Research Mission Directorate (ARMD) Aero-Science Project (ASP) under Fundamental Aeronautics (FA) program.



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

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.



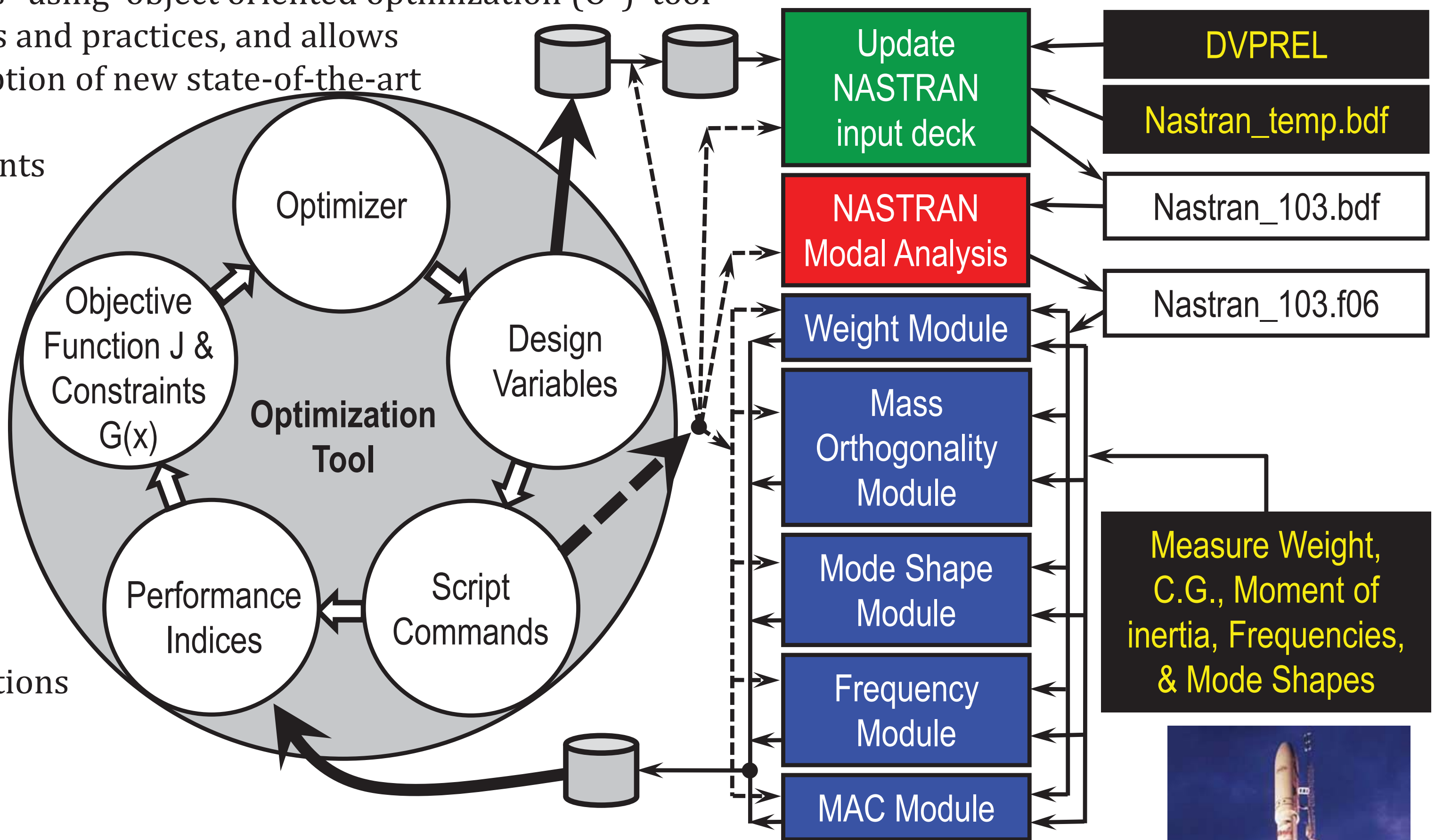
- ❑ Flutter Analysis
  - ❖ Uncertainties in the structural dynamic model are minimized through the use of "model tuning technique"
  - ❖ Based on analytical modes
- ❑ Validate Structural Dynamic Finite Element Model using Test Data and Update if needed
  - ❖ Use MDAO (Multidisciplinary Design, Analysis, 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 (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 Statements
  - Minimize $J = \sum_i w_i J_i$

    Such that $J_k \le \varepsilon_k$

    - 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
    - e_k: Small tolerance value for performance index k
- Previous applications
  - X-37 Drogue Chute Test Fixture
  - Quiet Spike Boom
  - Aerostructures Test Wing 2
  - Glory Mishap Investigation: Use "Topology Optimization"




ATW 2

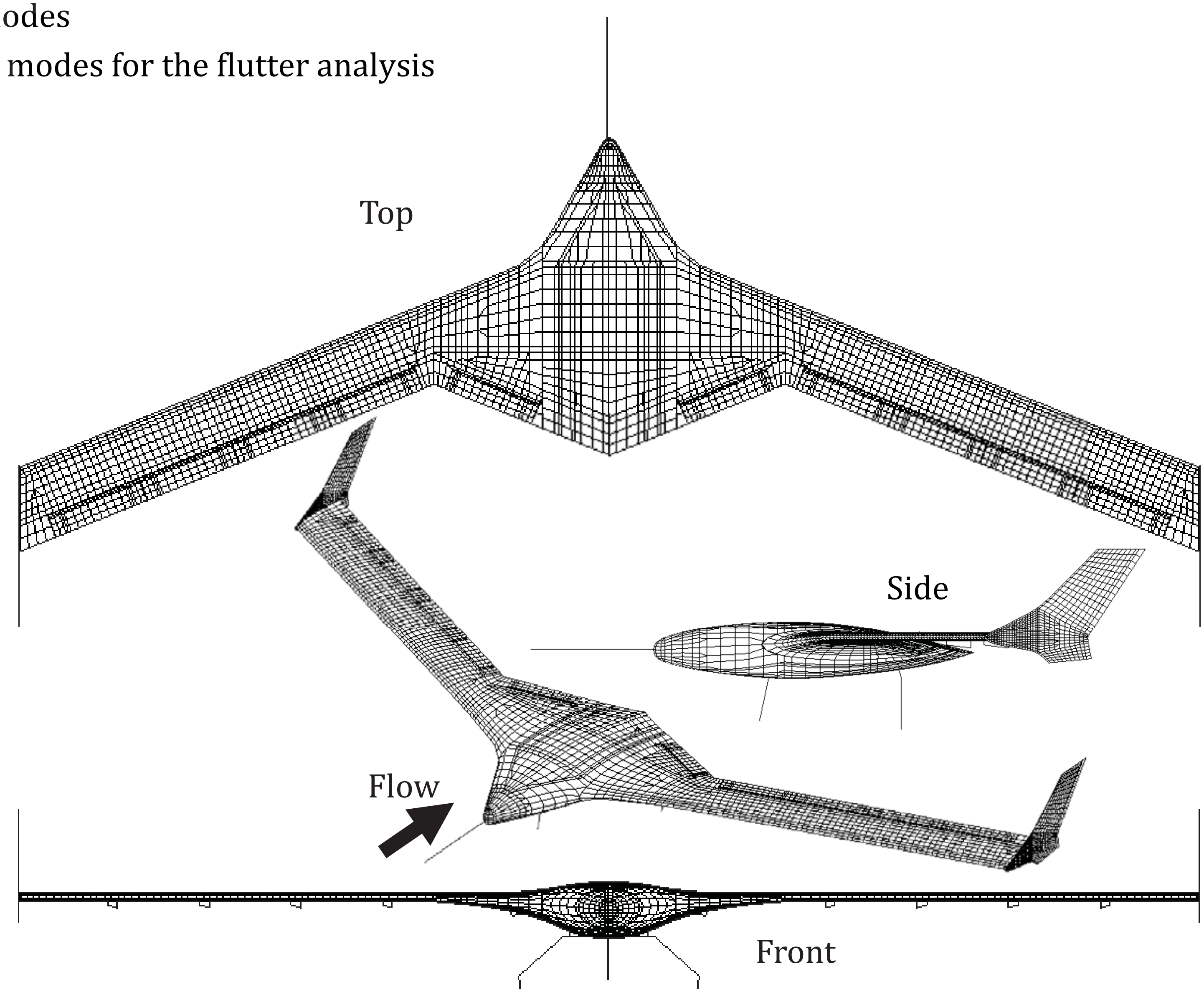

Quiet Spike Boom

X-37 DCTF


Taurus XL Launch Vehicle

Structural Dynamic Finite Element Model

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



Frequencies of MUTT Aircraft: EFEW case

Table 1. The first 24 flexible modes of the MUTT aircraft with empty fuel empty water before model tuning

GVT data			NASTRAN Results					Target error (%)
			Final Design		Baseline			
Mode Number	Mode Shape	Frequency	Frequency	Error (%)	Mode Number	Frequency	Error (%)	
7	SW1B	1.067	1.035	-3.0	7	1.090	2.1	3
8	AW1B	1.543	1.534	-0.5	8	1.540	-0.2	3
9	SW1T	3.223	2.781	-13.7	9	3.159	-2.0	3
10	SWFA	3.607	3.068	-14.9	10	3.607	0.0	5~10
11	AW1T	3.839	3.522	-8.3	11	3.636	**-5.3**	3
12	SW2B	4.440	4.127	-7.1	12	4.514	1.7	3
13	AMLGL	4.466	4.262	-4.6	13	4.567	2.3	3
14	SMLGL	4.666	4.467	-4.3	14	4.961	**6.3**	3
15	BoomH	5.273	4.530	-14.1	15	5.223	-0.9	5~10
16	AWL	5.305	4.569	-13.9	16	5.294	-0.2	10
17	BoomV	5.399	5.159	-4.4	17	5.349	-0.9	10
18	AW2B	6.026	5.404	-10.3	18	6.061	0.6	5~10
19	SWL	6.264	5.815	-7.2	19	6.189	-1.2	5~10
20	SEngL	7.067	N/A	N/A	20	7.283	3.0	10
21	AEngL	7.238	N/A	N/A	21	7.381	2.0	10
22	AWFA	8.484	8.133	-4.1	22	8.574	1.1	10
23	NLGL	8.490	8.812	3.8	23	8.085	-4.8	10
24	NLGFA	9.217	9.433	2.3	24	9.205	-0.1	10
25	SW3B	9.346	9.798	4.8	25	9.416	0.8	5~10
26	AW3B	10.598	9.889	-6.7	27	11.048	4.2	10
27	SW2T	11.370	10.186	-10.4	28	11.462	0.8	5~10
28	AMLGFA	11.930	10.969	-8.1	26	10.035	**-15.9**	5~10
29	SMLGFA	12.235	11.355	-7.2	29	11.835	-3.3	10
30	AW2T	12.405	11.986	-3.4	30	12.811	3.3	5~10

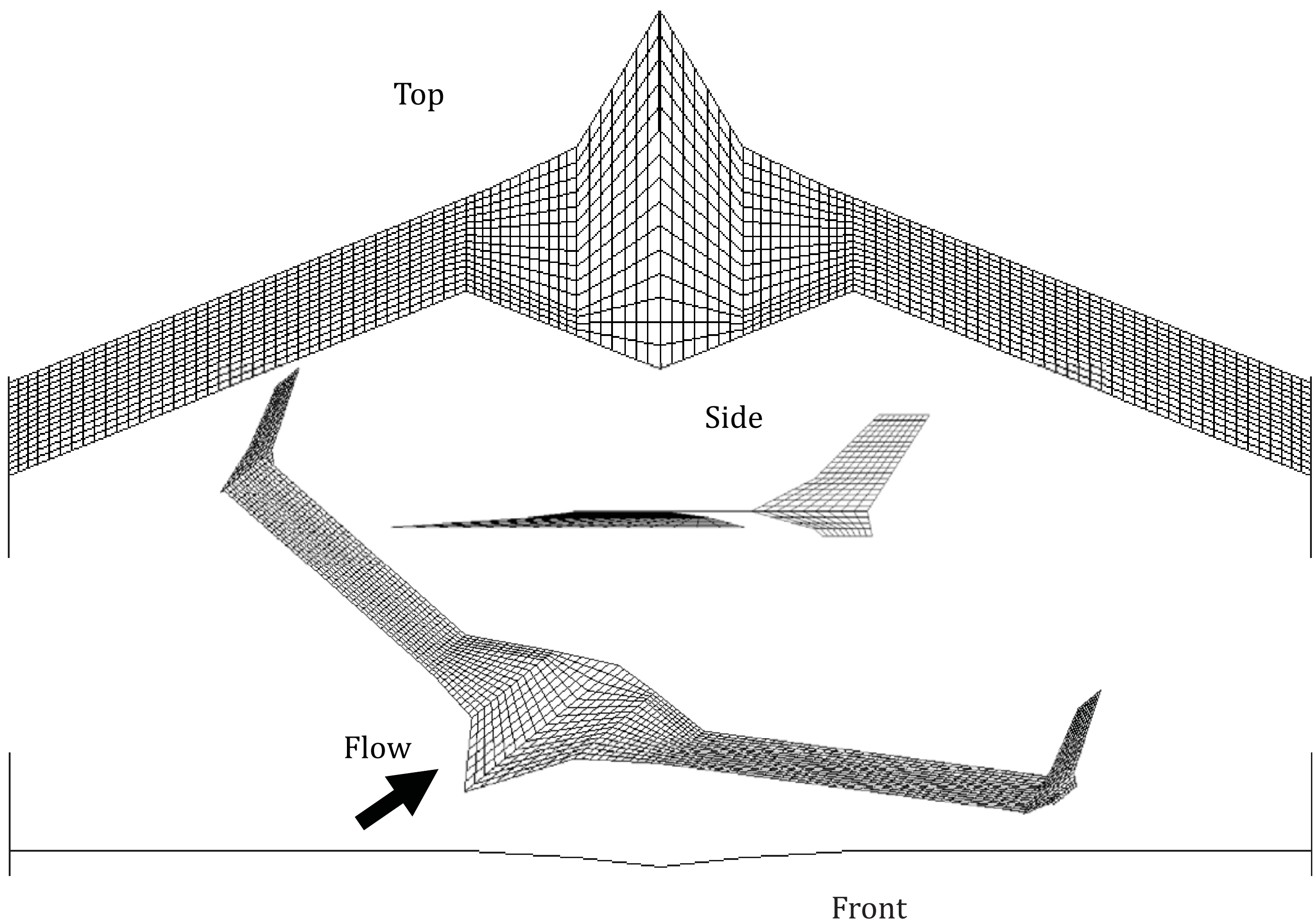
Frequencies of MUTT Aircraft: FFFW Case

Table 2. The first 24 flexible modes of the MUTT aircraft with full fuel full water before model tuning

GVT data			NASTRAN Results					Target error (%)
			Final Design		Baseline			
Mode Number	Mode Shape	Frequency	Frequency	Error (%)	Mode Number	Frequency	Error (%)	
7	SW1B	1.000	0.937	-6.3	7	1.001	0.1	3
8	AW1B	1.411	1.392	-1.3	8	1.398	-0.9	3
9	SW1T	2.938	2.608	-11.2	9	2.912	-0.9	3
10	SWFA	3.569	3.374	-5.5	10	3.445	-3.5	10
11	AW1T	3.651	2.932	-19.7	11	3.454	**-5.4**	3
12	SW2B	4.346	3.898	-10.3	12	4.285	-1.4	3
13	AMLGL	4.408	5.393	22.4	13	4.446	0.9	3
14	SMLGL	4.601	4.159	-9.6	14	4.944	**7.4**	3
15	AWL	5.065	4.339	-14.3	15	5.067	0.0	10
16	BoomH	5.276	4.476	-15.2	16	5.217	-1.1	5~10
17	BoomV	5.390	4.555	-15.5	17	5.336	-1.0	10
18	AW2B	5.795	5.015	-13.5	18	5.694	-1.7	10
19	SWL	6.144	5.251	-14.5	19	6.018	-2.0	5~10
20	SEngL	7.085	N/A	N/A	20	7.220	1.9	10
21	AEngL	7.270	N/A	N/A	21	7.283	0.2	10
22	AWFA	8.240	7.350	-10.8	22	7.848	-4.8	10
23	NLGL	8.490	9.788	15.3	23	8.071	-4.9	10
24	SW3B	8.657	8.161	-5.7	24	8.673	0.2	5~10
25	NLGFA	9.129	9.816	7.5	25	9.186	0.6	5~10
26	AW3B	9.965	9.112	-8.6	26	9.766	-2.0	10
27	SW2T	11.053	9.714	-12.1	28	11.148	0.9	10
28	AW2T	11.540	10.076	-12.7	30	11.704	1.4	5~10
29	AMLGFA	11.862	11.562	-2.5	27	10.576	**-10.84**	10
30	SMLGFA	11.977	11.130	-7.1	29	11.566	-3.4	10

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



Modal Participation Factor for EFEW Case

Table 9. Modal participation factors (%) of the MUTT aircraft with empty fuel empty water (EFEW)

	GVT Mode Number	Mode Shape	Final Design									Baseline Model								
			M=0.130			M=0.195			M=0.284			M=0.130			M=0.195			M=0.284		
			1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
Primary Modes	1-6	Rigid	31.6	30.7	40.3	27.5	32.6	33.0	25.0	34.3	25.2	33.7	33.3	42.8	27.9	35.7	40.5	24.6	39.0	40.2
	7	SW1B	15.0	9.5	0.0	12.1	8.8	0.0	9.7	8.1	0.0	17.0	10.0	0.0	14.9	9.2	0.0	13.0	8.6	0.0
	8	AW1B	0.0	0.0	27.3	0.0	0.0	31.1	0.0	0.0	35.1	0.0	0.0	8.3	0.0	0.0	12.5	0.0	0.0	28.1
	9	SW1T	44.3	54.6	0.0	51.1	54.4	0.0	56.1	54.1	0.0	38.6	43.0	0.0	47.8	41.5	0.0	53.7	39.7	0.0
	11	AW1T	0.0	0.0	27.3	0.0	0.0	31.1	0.0	0.0	35.1	1.9	2.8	0.0	1.8	2.5	0.0	1.7	2.2	0.0
	Sum of first five		**90.9**	**94.8**	**94.9**	**90.7**	**95.8**	**95.2**	**90.8**	**96.5**	**95.4**	**87.4**	**77.5**	**36.9**	**85.7**	**76.3**	**35.7**	**84.7**	**76.4**	**33.6**
	12	AMLGL	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	42.1	0.0	0.0	40.9	0.0	0.0	28.1
	13	SW2B	1.5	1.3	0.0	1.3	0.9	0.0	1.2	0.7	0.0	0.0	0.0	4.5	0.0	0.0	4.2	0.0	0.0	2.5
	14	SMLGL	1.3	0.7	0.0	1.2	0.6	0.0	1.2	0.6	0.0	2.6	7.1	0.0	1.7	7.6	0.0	1.2	7.5	0.0
	Total		**93.7**	**96.8**	**95.0**	**93.2**	**97.3**	**95.2**	**93.2**	**97.8**	**95.4**	**93.8**	**96.2**	**97.7**	**94.1**	**96.5**	**98.1**	**94.2**	**97.0**	**98.9**
Secondary Modes	10	SWFA	1.2	1.5	0.0	1.2	1.2	0.0	1.2	1.0	0.0	0.0	0.1	0.0	0.0	0.1	0.0	0.0	0.1	0.0
	15	BoomH	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.7	1.6	0.0	0.7	1.7	0.0	0.6	1.7	0.0
	18	AW2B	0.0	0.0	1.0	0.0	0.0	0.7	0.0	0.0	0.5	0.0	0.0	0.5	0.0	0.0	0.4	0.0	0.0	0.5
	19	SWL	1.0	0.3	0.0	1.0	0.2	0.0	1.1	0.1	0.0	0.0	0.0	1.0	0.0	0.0	0.7	0.0	0.0	0.1
	25	SW3B	1.1	0.5	0.0	1.2	0.4	0.0	1.3	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	26	AMLGFA	0.0	0.0	1.6	0.0	0.0	1.6	0.0	0.0	1.7	0.0	0.0	0.4	0.0	0.0	0.4	0.0	0.0	0.4
	28	SW2T	2.9	1.1	0.0	3.1	0.9	0.0	3.2	0.8	0.0	2.6	1.0	0.0	2.5	0.8	0.0	2.5	0.6	0.0
	30	AW2T	0.0	0.0	1.6	0.0	0.0	1.9	0.0	0.0	1.9	1.8	0.5	0.0	1.7	0.4	0.0	1.7	0.3	0.0
	Total		**6.2**	**3.4**	**4.3**	**6.5**	**2.7**	**4.2**	**6.8**	**2.2**	**4.1**	**5.1**	**3.2**	**1.9**	**4.9**	**3.0**	**1.5**	**4.8**	**2.7**	**1.0**

1st: First Flutter Mode
2nd: Second Flutter Mode
3rd: Third Flutter Mode

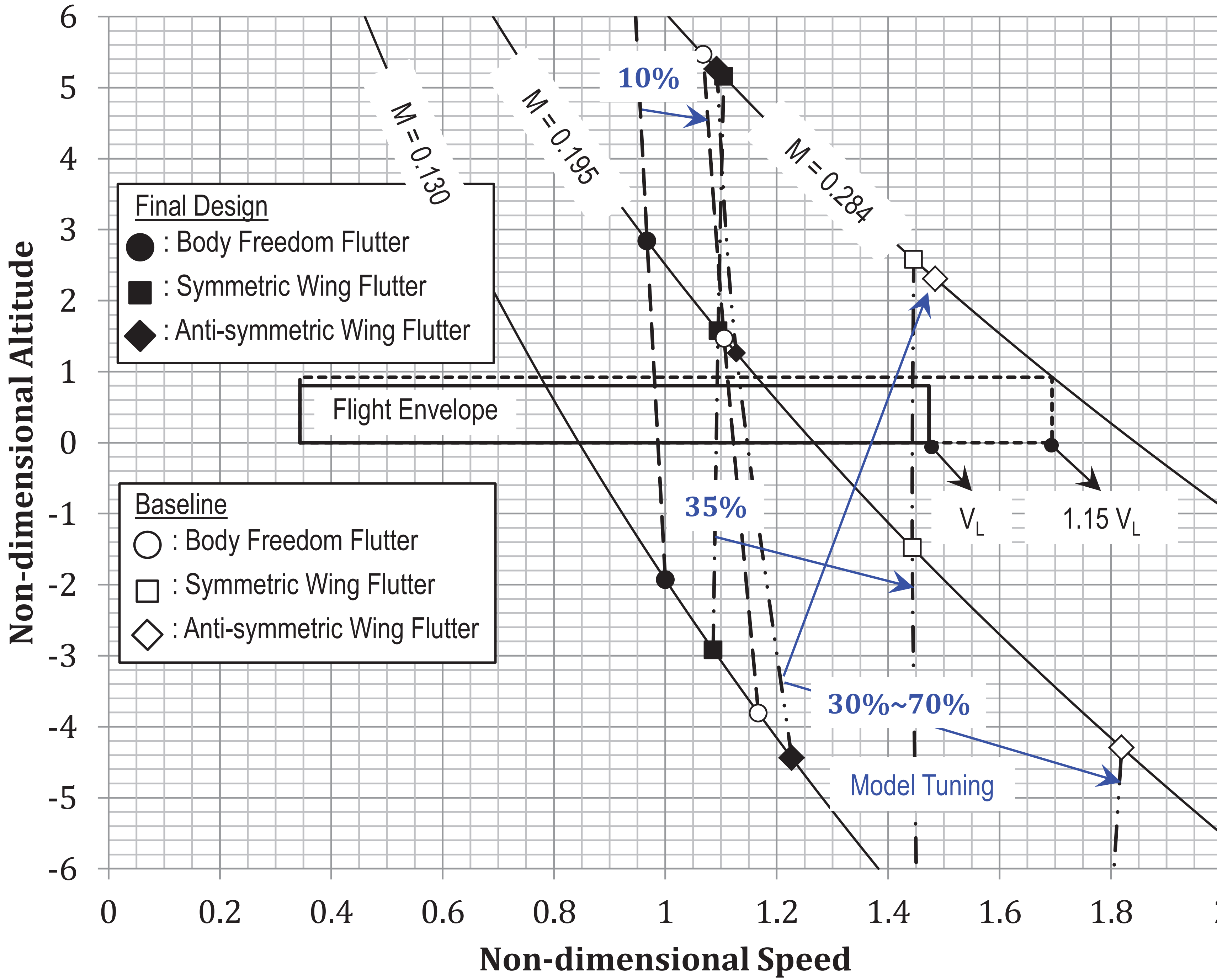
Modal Participation Factor for FFFW Case

Table 10. Modal participation factors (%) of the MUTT aircraft with full fuel full water (FFFW)

	GVT Mode Number	Mode Shape	Final Design									Baseline Model								
			M=0.130			M=0.195			M=0.284			M=0.130			M=0.195			M=0.284		
			1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
Primary Modes	1-6	Rigid	42.4	32.3	44.7	38.5	36.2	38.4	34.8	40.5	39.0	42.1	29.2	35.3	36.8	32.0	34.4	32.6	36.0	32.4
	7	SW1B	12.9	11.5	0.0	11.8	10.9	0.0	11.1	10.3	0.0	14.9	10.4	0.0	12.8	9.5	0.0	10.7	8.9	0.0
	8	AW1B	0.0	0.0	5.2	0.0	0.0	27.2	0.0	0.0	25.0	0.0	0.0	1.6	0.0	0.0	1.3	0.0	0.0	1.2
	9	SW1T	38.0	46.3	0.0	42.0	42.9	0.0	45.9	39.5	0.0	29.7	37.1	0.0	35.4	34.1	0.0	40.6	30.8	0.0
	11	AW1T	0.0	0.0	44.0	0.0	0.0	27.2	0.0	0.0	25.0	0.7	0.8	0.0	0.7	0.7	0.0	0.8	0.7	0.0
	Sum of first five		**93.3**	**90.1**	**93.9**	**92.3**	**90.0**	**92.8**	**91.8**	**90.3**	**89.0**	**91.2**	**89.1**	**51.1**	**92.4**	**88.9**	**53.0**	**93.0**	**89.5**	**68.3**
	12	SW2B	0.1	0.1	0.0	0.1	0.1	0.0	0.1	0.1	0.0	0.0	0.0	50.2	0.0	0.0	50.1	0.0	0.0	50.7
	13	AMLGL	0.0	0.0	2.5	0.0	0.0	1.3	0.0	0.0	1.4	7.6	20.3	0.0	8.2	21.9	0.0	8.6	22.2	0.0
	14	SMLGL	1.9	6.8	0.0	1.6	7.4	0.0	1.3	7.5	0.0	0.0	0.0	7.3	0.0	0.0	8.4	0.0	0.0	9.5
	Total		**95.3**	**97.0**	**96.4**	**94.0**	**97.5**	**94.1**	**93.2**	**97.9**	**90.4**	**95.0**	**97.8**	**94.4**	**93.9**	**98.2**	**94.2**	**93.3**	**98.6**	**93.8**
Secondary Modes	16	BoomH	0.0	0.0	1.1	0.0	0.0	1.2	0.0	0.0	1.4	0.0	0.0	1.8	0.0	0.0	1.9	0.0	0.0	2.1
	19	SWL	0.5	0.7	0.0	0.7	0.6	0.0	0.8	0.5	0.0	0.0	0.0	2.3	0.0	0.0	2.3	0.0	0.0	2.4
	24	SW3B	1.3	0.5	0.0	1.6	0.5	0.0	1.9	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	25	NLGFA	2.0	0.9	0.0	2.5	0.7	0.0	2.9	0.6	0.0	3.1	1.2	0.0	3.8	0.9	0.0	4.3	0.8	0.0
	30	AW2T	0.0	0.0	1.1	0.0	0.0	3.0	0.0	0.0	5.6	0.9	0.2	0.0	1.1	0.2	0.0	1.2	0.2	0.0
	Total		**3.8**	**2.1**	**2.2**	**4.8**	**1.8**	**4.2**	**5.6**	**1.6**	**7.0**	**4.0**	**1.4**	**4.1**	**4.9**	**1.1**	**4.2**	**5.5**	**1.0**	**4.5**

1st: First Flutter Mode
2nd: Second Flutter Mode
3rd: Third Flutter Mode

Flutter Boundaries



Optimization Run #1, #2, #3, & #4

- Optimizer: DOT
- Run #1, #2, & #3: Improve Frequency Correlations
  - Design Variables
    - Sectional properties of the main Landing Gear Beams
    - Young's Modulus E
    - Shear Modulus G
    - Design Variable Linking: Right = Left
- Run #4: Improve Orthonomalized Mass Matrix
  - Design Variables
    - Lumped mass properties of accelerometer cables

Optimization Run #1: EFEW Case

Objective Function | Constraints

GVT data			Nastran Results								Target Error (%)
			Final Design		Baseline			DOT1			
Mode #	Mode Shape	Freq	Freq	Error	Mode #	Freq	Error	Mode #	Freq	Error	
7	SW1B	1.067	1.035	-3.0	7	1.090	2.1	7	1.098	2.9	**3**
8	AW1B	1.543	1.534	-0.5	8	1.540	-0.2	8	1.555	0.8	**3**
9	SW1T	3.223	2.781	-13.7	9	3.159	-2.0	9	3.233	0.3	**3**
10	SWFA	3.607	3.068	-14.9	10	3.607	0.0	10	3.637	0.8	5~10
11	AW1T	3.839	3.522	-8.3	11	3.636	**-5.3**	11	3.747	**-2.4**	**3**
12	SW2B	4.440	4.127	-7.1	12	4.514	1.7	12	4.451	0.2	**3**
13	AMLGL	4.466	4.262	-4.6	13	4.567	2.3	13	4.600	3.0	**3**
14	SMLGL	4.666	4.467	-4.3	14	4.961	**6.3**	14	4.703	**0.8**	**3**
15	BoomH	5.273	4.530	-14.1	15	5.223	-0.9	15	5.215	-1.1	5~10
16	AWL	5.305	4.569	-13.9	16	5.294	-0.2	16	5.236	-1.3	10
17	BoomV	5.399	5.159	-4.4	17	5.349	-0.9	17	5.350	-0.9	10
18	AW2B	6.026	5.404	-10.3	18	6.061	0.6	18	6.105	1.3	5~10
19	SWL	6.264	5.815	-7.2	19	6.189	-1.2	19	6.218	-0.7	5~10
20	SEngL	7.067	N/A	N/A	20	7.283	3.0	20	7.283	3.0	10
21	AEngL	7.238	N/A	N/A	21	7.381	2.0	21	7.392	2.1	10
22	AWFA	8.484	8.133	-4.1	22	8.574	1.1	22	8.625	1.7	10
23	NLGL	8.490	8.812	3.8	23	8.085	-4.8	23	8.068	-5.0	10
24	NLGFA	9.217	9.433	2.3	24	9.205	-0.1	24	9.206	-0.1	10
25	SW3B	9.346	9.798	4.8	25	9.416	0.8	25	9.487	1.5	5~10
26	AW3B	10.598	9.889	-6.7	27	11.048	4.2	27	11.086	4.6	10
27	SW2T	11.370	10.186	-10.4	28	11.462	0.8	28	11.537	1.5	5~10
28	AMLGFA	11.930	10.969	-8.1	26	10.035	**-15.9**	26	10.034	**-15.9**	**15.9**
29	SMLGFA	12.235	11.355	-7.2	29	11.835	-3.3	29	11.897	-2.8	10
30	AW2T	12.405	11.986	-3.4	30	12.811	3.3	30	13.008	4.9	5~10

Optimization Run #1: FFFW Case

Objective Function

Constraints

GVT data			Nastran Results								Target Error (%)
			Final Design		Baseline			DOT1			
Mode #	Mode Shape	Freq	Freq	Error	Mode #	Freq	Error	Mode #	Freq	Error	
7	SW1B	1.000	0.937	-6.3	7	1.001	0.1	7	1.008	0.8	3
8	AW1B	1.411	1.392	-1.3	8	1.398	-0.9	8	1.412	0.1	3
9	SW1T	2.938	2.608	-11.2	9	2.912	-0.9	9	2.972	1.1	3
10	SWFA	3.569	3.374	-5.5	10	3.445	-3.5	10	3.474	-2.7	10
11	AW1T	3.651	2.932	-19.7	11	3.454	**-5.4**	11	3.553	**-2.7**	3
12	SW2B	4.346	3.898	-10.3	12	4.285	-1.4	12	4.387	0.9	3
13	AMLGL	4.408	5.393	22.4	13	4.446	0.9	13	4.390	-0.4	3
14	SMLGL	4.601	4.159	-9.6	14	4.944	**7.4**	14	4.679	**1.7**	3
15	AWL	5.065	4.339	-14.3	15	5.067	0.0	15	4.952	-2.2	10
16	BoomH	5.276	4.476	-15.2	16	5.217	-1.1	16	5.219	-1.1	5~10
17	BoomV	5.390	4.555	-15.5	17	5.336	-1.0	17	5.336	-1.0	10
18	AW2B	5.795	5.015	-13.5	18	5.694	-1.7	18	5.738	-1.0	10
19	SWL	6.144	5.251	-14.5	19	6.018	-2.0	19	6.042	-1.6	5~10
20	SEngL	7.085	N/A	N/A	20	7.220	1.9	20	7.238	2.2	10
21	AEngL	7.270	N/A	N/A	21	7.283	0.2	21	7.283	0.2	10
22	AWFA	8.240	7.350	-10.8	22	7.848	-4.8	22	7.875	-4.4	10
23	NLGL	8.490	9.788	15.3	23	8.071	-4.9	23	8.081	-4.8	10
24	SW3B	8.657	8.161	-5.7	24	8.673	0.2	24	8.750	1.1	5~10
25	NLGFA	9.129	9.816	7.5	25	9.186	0.6	25	9.187	0.6	5~10
26	AW3B	9.965	9.112	-8.6	26	9.766	-2.0	26	9.791	-1.7	10
27	SW2T	11.053	9.714	-12.1	28	11.148	0.9	28	11.215	1.5	10
28	AW2T	11.540	10.076	-12.7	30	11.704	1.4	30	11.854	2.7	5~10
29	AMLGFA	11.862	11.562	-2.5	27	10.576	**-10.84**	27	10.610	**-10.6**	10
30	SMLGFA	11.977	11.130	-7.1	29	11.566	-3.4	29	11.618	-3.0	10

Optimization Run #2: EFEW Case

GVT data			Nastran Results						Target Error (%)
			DOT1			DOT2			
Mode #	Mode Shape	Freq	Mode #	Freq	Error	Mode #	Freq	Error	
7	SW1B	1.067	7	1.098	2.9	7	1.099	3.0	**3**
8	AW1B	1.543	8	1.555	0.8	8	1.554	0.8	**3**
9	SW1T	3.223	9	3.233	0.3	9	3.229	0.2	**3**
10	SWFA	3.607	10	3.637	0.8	10	3.634	0.8	5~10
11	AW1T	3.839	11	3.747	**-2.4**	11	3.747	-2.4	**3**
12	SW2B	4.440	12	4.451	0.2	**13**	4.600	**3.6**	**3**
13	AMLGL	4.466	13	4.600	3.0	**12**	4.498	0.7	**3**
14	SMLGL	4.666	14	4.703	**0.8**	14	4.758	2.0	**3**
15	BoomH	5.273	15	5.215	-1.1	15	5.219	-1.0	5~10
16	AWL	5.305	16	5.236	-1.3	16	5.240	-1.2	10
17	BoomV	5.399	17	5.350	-0.9	17	5.351	-0.9	10
18	AW2B	6.026	18	6.105	1.3	18	6.104	1.3	5~10
19	SWL	6.264	19	6.218	-0.7	19	6.216	-0.8	5~10
20	SEngL	7.067	20	7.283	3.0	20	7.283	3.0	10
21	AEngL	7.238	21	7.392	2.1	21	7.391	2.1	10
22	AWFA	8.484	22	8.625	1.7	22	8.627	1.7	10
23	NLGL	8.490	23	8.068	-5.0	23	8.068	-5.0	10
24	NLGFA	9.217	24	9.206	-0.1	24	9.214	0.0	10
25	SW3B	9.346	25	9.487	1.5	25	9.483	1.5	5~10
26	AW3B	10.598	27	11.086	4.6	27	11.195	5.6	10
27	SW2T	11.370	28	11.537	1.5	28	11.532	1.4	5~10
28	AMLGFA	11.930	26	10.034	**-15.9**	26	10.345	**-13.3**	**5~10**
29	SMLGFA	12.235	29	11.897	-2.8	29	12.395	1.3	10
30	AW2T	12.405	30	13.008	4.9	30	13.014	4.9	5~10

Objective Function

Constraints

Optimization Run #2: FFFW Case

Objective Function

Constraints

GVT data			Nastran Results						Target Error (%)
			DOT1			DOT2			
Mode #	Mode Shape	Freq	Mode #	Freq	Error	Mode #	Freq	Error	
7	SW1B	1.000	7	1.008	0.8	7	1.009	0.9	**3**
8	AW1B	1.411	8	1.412	0.1	8	1.411	0.0	**3**
9	SW1T	2.938	9	2.972	1.1	9	2.968	1.0	**3**
10	SWFA	3.569	10	3.474	-2.7	10	3.471	-2.7	10
11	AW1T	3.651	11	3.553	**-2.7**	11	3.552	**-2.7**	**3**
12	SW2B	4.346	12	4.387	0.9	12	4.385	0.9	**3**
13	AMLGL	4.408	13	4.390	-0.4	13	4.425	0.4	**3**
14	SMLGL	4.601	14	4.679	**1.7**	14	4.739	**3.0**	**3**
15	AWL	5.065	15	4.952	-2.2	15	4.972	-1.8	10
16	BoomH	5.276	16	5.219	-1.1	16	5.218	-1.1	5~10
17	BoomV	5.390	17	5.336	-1.0	17	5.336	-1.0	10
18	AW2B	5.795	18	5.738	-1.0	18	5.736	-1.0	10
19	SWL	6.144	19	6.042	-1.6	19	6.040	-1.7	5~10
20	SEngL	7.085	20	7.238	2.2	20	7.236	2.1	10
21	AEngL	7.270	21	7.283	0.2	21	7.283	0.2	10
22	AWFA	8.240	22	7.875	-4.4	22	7.874	-4.5	10
23	NLGL	8.490	23	8.081	-4.8	23	8.081	-4.8	10
24	SW3B	8.657	24	8.750	1.1	24	8.743	1.0	5~10
25	NLGFA	9.129	25	9.187	0.6	25	9.192	0.7	5~10
26	AW3B	9.965	26	9.791	-1.7	26	9.943	-0.2	10
27	SW2T	11.053	28	11.215	1.5	28	11.213	1.5	10
28	AW2T	11.540	30	11.854	2.7	**29**	11.860	2.8	5~10
29	AMLGFA	11.862	27	10.610	**-10.6**	27	10.885	**-8.2**	**10**
30	SMLGFA	11.977	29	11.618	-3.0	**30**	12.117	1.2	10

Optimization Run #3: EFEW Case

Objective Function

Constraints

GVT data			Nastran Results						Target Error (%)
			DOT2			DOT3			
Mode #	Mode Shape	Freq	Mode #	Freq	Error	Mode #	Freq	Error	
7	SW1B	1.067	7	1.099	3.0	7	1.097	2.7	3
8	AW1B	1.543	8	1.554	0.8	8	1.550	0.5	3
9	SW1T	3.223	9	3.229	0.2	9	3.220	-0.1	3
10	SWFA	3.607	10	3.634	0.8	10	3.627	0.6	5~10
11	AW1T	3.839	11	3.747	-2.4	11	3.735	-2.7	3
12	SW2B	4.440	13	4.600	3.6	13	4.590	3.4	3~5
13	AMLGL	4.466	12	4.498	0.7	12	4.495	0.6	3
14	SMLGL	4.666	14	4.758	2.0	14	4.758	2.0	3
15	BoomH	5.273	15	5.219	-1.0	15	5.217	-1.1	5~10
16	AWL	5.305	16	5.240	-1.2	16	5.237	-1.3	10
17	BoomV	5.399	17	5.351	-0.9	17	5.351	-0.9	10
18	AW2B	6.026	18	6.104	1.3	18	6.093	1.1	5~10
19	SWL	6.264	19	6.216	-0.8	19	6.211	-0.8	5~10
20	SEngL	7.067	20	7.283	3.0	20	7.283	3.0	10
21	AEngL	7.238	21	7.391	2.1	21	7.388	2.1	10
22	AWFA	8.484	22	8.627	1.7	22	8.614	1.5	10
23	NLGL	8.490	23	8.068	-5.0	23	8.067	-5.0	10
24	NLGFA	9.217	24	9.214	0.0	24	9.214	0.0	10
25	SW3B	9.346	25	9.483	1.5	25	9.466	1.3	5~10
26	AW3B	10.598	27	11.195	5.6	27	11.192	5.6	10
27	SW2T	11.370	28	11.532	1.4	28	11.522	1.3	5~10
28	AMLGFA	11.930	26	10.345	-13.3	26	10.344	-13.3	13.3
29	SMLGFA	12.235	29	12.395	1.3	29	12.407	1.4	10
30	AW2T	12.405	30	13.014	4.9	30	12.989	4.7	5~10

Optimization Run #3: FFFW Case

Constraints

GVT data			Nastran Results						Target Error (%)
			DOT2			DOT3			
Mode #	Mode Shape	Freq	Mode #	Freq	Error	Mode #	Freq	Error	
7	SW1B	1.000	7	1.009	0.9	7	1.006	0.6	**3**
8	AW1B	1.411	8	1.411	0.0	8	1.407	-0.3	**3**
9	SW1T	2.938	9	2.968	1.0	9	2.960	0.7	**3**
10	SWFA	3.569	10	3.471	-2.7	10	3.464	-2.9	10
11	AW1T	3.651	11	3.552	-2.7	11	3.541	-3.0	**3**
12	SW2B	4.346	12	4.385	0.9	12	4.372	0.6	**3**
13	AMLGL	4.408	13	4.425	0.4	13	4.420	0.3	**3**
14	SMLGL	4.601	14	4.739	3.0	14	4.739	3.0	**3**
15	AWL	5.065	15	4.972	-1.8	15	4.967	-1.9	10
16	BoomH	5.276	16	5.218	-1.1	16	5.218	-1.1	5~10
17	BoomV	5.390	17	5.336	-1.0	17	5.336	-1.0	10
18	AW2B	5.795	18	5.736	-1.0	18	5.727	-1.2	10
19	SWL	6.144	19	6.040	-1.7	19	6.036	-1.8	5~10
20	SEngL	7.085	20	7.236	2.1	20	7.232	2.1	10
21	AEngL	7.270	21	7.283	0.2	21	7.283	0.2	10
22	AWFA	8.240	22	7.874	-4.5	22	7.867	-4.5	10
23	NLGL	8.490	23	8.081	-4.8	23	8.078	-4.8	10
24	SW3B	8.657	24	8.743	1.0	24	8.725	0.8	5~10
25	NLGFA	9.129	25	9.192	0.7	25	9.192	0.7	5~10
26	AW3B	9.965	26	9.943	-0.2	26	9.932	-0.3	10
27	SW2T	11.053	28	11.213	1.5	28	11.205	1.4	10
28	AW2T	11.540	**29**	11.860	2.8	29	11.843	2.6	5~10
29	AMLGFA	11.862	27	10.885	-8.2	27	10.888	-8.2	10
30	SMLGFA	11.977	**30**	12.117	1.2	30	12.128	1.3	10

Orthonormalized Mass Matrices After #3

Constraints

Table 15. Orthonormalized mass matrix of the MUTT aircraft after the third model tuning procedure (with empty o Correlation)

Mode Shape	GVT Mode Number	**7**	**8**	**9**	10	**11**	**12**	**13**	**14**	15	18	19	25	27	28	30
SW1B	**7**	1.00	-0.02	-0.05	-0.04	-0.01	0.03	0.02	-0.03	-0.02	-0.02	-0.01	0.03	-0.02	0.01	0.02
AW1B	**8**	-0.02	1.00	0.01	0.03	0.00	0.00	0.05	0.00	0.01	-0.03	0.00	0.00	0.02	-0.03	0.01
SW1T	**9**	-0.05	0.01	1.00	-0.07	0.00	0.03	-0.01	-0.02	0.01	0.02	0.05	-0.02	0.02	0.01	-0.02
SWFA	10	-0.04	0.03	-0.07	1.00	0.05	-0.06	-0.08	-0.08	0.00	0.04	0.07	0.07	-0.10	-0.02	-0.02
AW1T	**11**	-0.01	0.00	0.00	0.05	1.00	0.02	-0.10	0.00	-0.01	0.05	-0.01	-0.02	0.02	0.02	-0.09
SW2B	**12**	0.03	0.00	0.03	-0.06	0.02	1.00	**-0.14**	**0.18**	0.01	0.03	-0.03	-0.05	-0.07	-0.01	-0.09
AMLGL	**13**	0.02	0.05	-0.01	-0.08	-0.10	**-0.14**	1.00	0.01	-0.04	**-0.11**	0.04	0.01	-0.03	-0.08	**0.16**
SMLGL	**14**	-0.03	0.00	-0.02	-0.08	0.00	**0.18**	0.01	1.00	0.01	0.01	-0.04	0.00	-0.01	0.02	0.04
BoomH	15	-0.02	0.01	0.01	0.00	-0.01	0.01	-0.04	0.01	1.00	0.08	-0.03	0.00	-0.01	-0.02	0.04
AW2B	18	-0.02	-0.03	0.02	0.04	0.05	0.03	**-0.11**	0.01	0.08	1.00	-0.05	-0.01	0.00	0.04	0.02
SWL	19	-0.01	0.00	0.05	0.07	-0.01	-0.03	0.04	-0.04	-0.03	-0.05	1.00	-0.05	0.03	0.00	0.00
SW3B	25	0.03	0.00	-0.02	0.07	-0.02	-0.05	0.01	0.00	0.00	-0.01	-0.05	1.00	0.06	0.06	-0.01
SW2T	27	-0.02	0.02	0.02	-0.10	0.02	-0.07	-0.03	-0.01	-0.01	0.00	0.03	0.06	1.00	-0.01	0.00
AMLGFA	28	0.01	-0.03	0.01	-0.02	0.02	-0.01	-0.08	0.02	-0.02	0.04	0.00	0.06	-0.01	1.00	**0.17**
AW2T	30	0.02	0.01	0.02	0.02	0.09	-0.09	**0.16**	0.04	0.04	0.02	0.00	-0.01	0.00	**0.17**	1.00

Objective Function

Table 16. Orthonormalized mass matrix of the MUTT after the third model tuning procedure (with full fuel full water; Auto Correlation)

Mode Shape	GVT Mode Number	**7**	**8**	**9**	**11**	**12**	**13**	**14**	16	19	24	25	28
SW1B	**7**	1.00	0.01	-0.05	0.01	0.02	0.01	-0.07	-0.01	-0.02	0.03	0.00	0.00
AW1B	**8**	0.01	1.00	-0.01	0.01	0.00	-0.06	-0.01	0.00	0.00	0.01	0.02	-0.04
SW1T	**9**	-0.05	-0.01	1.00	-0.02	0.01	-0.01	-0.03	0.00	0.05	0.00	-0.01	-0.01
AW1T	**11**	0.01	0.01	-0.02	1.00	-0.03	0.10	0.02	-0.01	0.01	0.02	0.01	0.07
SW2B	**12**	0.02	0.00	0.01	-0.03	1.00	0.01	**0.18**	0.00	-0.01	-0.05	0.01	-0.01
AMLGL	**13**	0.01	-0.06	-0.01	0.10	0.01	1.00	-0.08	-0.01	0.02	0.00	-0.05	0.10
SMLGL	**14**	-0.07	-0.01	-0.03	0.02	**0.18**	-0.08	1.00	0.01	-0.02	0.02	0.01	-0.03
BoomH	16	-0.01	0.00	0.00	-0.01	0.00	-0.01	0.01	1.00	-0.02	0.00	0.00	0.02
SWL	19	-0.02	0.00	0.05	0.01	-0.01	0.02	-0.02	-0.02	1.00	-0.04	-0.01	0.00
SW3B	24	0.03	0.01	0.00	0.02	-0.05	0.00	0.02	0.00	-0.04	1.00	0.01	0.00
NLGFA	25	0.00	0.02	-0.01	0.01	0.01	-0.05	0.01	0.00	-0.01	0.01	1.00	-0.05
AW2T	28	0.00	-0.04	-0.01	0.07	-0.01	0.10	-0.03	0.02	0.00	0.00	-0.05	1.00

Optimization Run #4: EFEW Case

Constraints

GVT data			Nastran Results						Target Error (%)
			DOT3			DOT4			
Mode #	Mode Shape	Freq	Mode #	Freq	Error	Mode #	Freq	Error	
7	SW1B	1.067	7	1.097	2.7	7	1.091	2.2	**3**
8	AW1B	1.543	8	1.550	0.5	8	1.553	0.7	**3**
9	SW1T	3.223	9	3.220	-0.1	9	3.220	-0.1	**3**
10	SWFA	3.607	10	3.627	0.6	10	3.628	0.6	5~10
11	AW1T	3.839	11	3.735	-2.7	11	3.742	-2.5	**3**
12	SW2B	4.440	13	4.590	**3.4**	13	4.591	**3.4**	**3.4**
13	AMLGL	4.466	12	4.495	0.6	12	4.492	0.6	**3**
14	SMLGL	4.666	14	4.758	2.0	14	4.757	2.0	**3**
15	BoomH	5.273	15	5.217	-1.1	15	5.218	-1.0	5~10
16	AWL	5.305	16	5.237	-1.3	16	5.240	-1.2	10
17	BoomV	5.399	17	5.351	-0.9	17	5.350	-0.9	10
18	AW2B	6.026	18	6.093	1.1	18	6.089	1.0	5~10
19	SWL	6.264	19	6.211	-0.8	19	6.222	-0.7	5~10
20	SEngL	7.067	20	7.283	3.0	20	7.283	3.0	10
21	AEngL	7.238	21	7.388	2.1	21	7.392	2.1	10
22	AWFA	8.484	22	8.614	1.5	22	8.615	1.5	10
23	NLGL	8.490	23	8.067	-5.0	23	8.068	-5.0	10
24	NLGFA	9.217	24	9.214	0.0	24	9.214	0.0	10
25	SW3B	9.346	25	9.466	1.3	25	9.477	1.4	5~10
26	AW3B	10.598	27	11.192	5.6	27	11.198	5.7	10
27	SW2T	11.370	28	11.522	1.3	28	11.533	1.4	5~10
28	AMLGFA	11.930	26	10.344	**-13.3**	26	10.344	**-13.3**	**13.3**
29	SMLGFA	12.235	29	12.407	1.4	29	12.393	1.3	10
30	AW2T	12.405	30	12.989	4.7	30	12.993	4.7	5~10

Optimization Run #4: FFFW Case

Constraints

GVT data			Nastran Results						Target Error (%)
			DOT3			DOT4			
Mode #	Mode Shape	Freq	Mode #	Freq	Error	Mode #	Freq	Error	
7	SW1B	1.000	7	1.006	0.6	7	1.003	0.3	3
8	AW1B	1.411	8	1.407	-0.3	8	1.409	-0.1	3
9	SW1T	2.938	9	2.960	0.7	9	2.961	0.8	3
10	SWFA	3.569	10	3.464	-2.9	10	3.465	-2.9	10
11	AW1T	3.651	11	3.541	-3.0	11	3.547	-2.9	3
12	SW2B	4.346	12	4.372	0.6	12	4.365	0.4	3
13	AMLGL	4.408	13	4.420	0.3	13	4.429	0.5	3
14	SMLGL	4.601	14	4.739	3.0	14	4.739	3.0	3
15	AWL	5.065	15	4.967	-1.9	15	4.970	-1.9	10
16	BoomH	5.276	16	5.218	-1.1	16	5.218	-1.1	5~10
17	BoomV	5.390	17	5.336	-1.0	17	5.336	-1.0	10
18	AW2B	5.795	18	5.727	-1.2	18	5.723	-1.2	10
19	SWL	6.144	19	6.036	-1.8	19	6.045	-1.6	5~10
20	SEngL	7.085	20	7.232	2.1	20	7.237	2.1	10
21	AEngL	7.270	21	7.283	0.2	21	7.283	0.2	10
22	AWFA	8.240	22	7.867	-4.5	22	7.867	-4.5	10
23	NLGL	8.490	23	8.078	-4.8	23	8.080	-4.8	10
24	SW3B	8.657	24	8.725	0.8	24	8.736	0.9	5~10
25	NLGFA	9.129	25	9.192	0.7	25	9.191	0.7	5~10
26	AW3B	9.965	26	9.932	-0.3	26	9.933	-0.3	10
27	SW2T	11.053	28	11.205	1.4	28	11.212	1.4	10
28	AW2T	11.540	29	11.843	2.6	29	11.847	2.7	5~10
29	AMLGFA	11.862	27	10.888	-8.2	27	10.892	-8.2	10
30	SMLGFA	11.977	30	12.128	1.3	30	12.122	1.2	10

Orthonormalized Mass Matrices After #4

Table 17. Orthonormalized mass matrix of the MUTT aircraft after the fourth model tuning procedure (with empty fuel empty water; Auto Correlation)

Mode Shape	GVT Mode Number	**7**	**8**	**9**	10	**11**	**12**	**13**	**14**	15	18	19	25	27	28	30
SW1B	**7**	1.00	-0.01	-0.05	-0.03	0.00	0.03	0.02	-0.04	-0.02	-0.02	-0.01	0.03	-0.01	0.00	0.02
AW1B	**8**	-0.01	1.00	0.00	0.03	0.00	0.00	0.04	0.00	0.01	-0.03	-0.01	0.00	0.02	-0.03	0.01
SW1T	**9**	-0.05	0.00	1.00	-0.08	-0.01	0.03	0.00	-0.03	0.01	0.02	0.05	-0.02	0.02	0.01	-0.02
SWFA	10	-0.03	0.03	-0.08	1.00	0.06	-0.06	-0.09	-0.08	0.00	0.05	0.07	0.07	-0.10	-0.02	-0.02
AW1T	**11**	0.00	0.00	-0.01	0.06	1.00	0.01	-0.10	0.00	-0.01	0.05	-0.01	-0.01	0.02	0.03	-0.09
SW2B	**12**	0.03	0.00	0.03	-0.06	0.01	1.00	**-0.13**	**0.17**	0.01	0.02	-0.03	-0.05	-0.07	-0.01	-0.08
AMLGL	**13**	0.02	0.04	0.00	-0.09	-0.10	**-0.13**	1.00	0.02	-0.04	**-0.11**	0.03	0.01	-0.04	-0.08	**0.16**
SMLGL	**14**	-0.04	0.00	-0.03	-0.08	0.00	**0.17**	0.02	1.00	0.00	0.00	-0.04	0.00	-0.01	0.02	0.04
BoomH	15	-0.02	0.01	0.01	0.00	-0.01	0.01	-0.04	0.00	1.00	0.08	-0.02	0.00	-0.01	-0.02	0.05
AW2B	18	-0.02	-0.03	0.02	0.05	0.05	0.02	**-0.11**	0.00	0.08	1.00	-0.04	-0.01	0.00	0.04	0.02
SWL	19	-0.01	-0.01	0.05	0.07	-0.01	-0.03	0.03	-0.04	-0.02	-0.04	1.00	-0.04	0.03	0.01	-0.01
SW3B	25	0.03	0.00	-0.02	0.07	-0.01	-0.05	0.01	0.00	0.00	-0.01	-0.04	1.00	0.06	0.06	-0.02
SW2T	27	-0.01	0.02	0.02	-0.10	0.02	-0.07	-0.04	-0.01	-0.01	0.00	0.03	0.06	1.00	-0.01	-0.01
AMLGFA	28	0.00	-0.03	0.01	-0.02	0.03	-0.01	-0.08	0.02	-0.02	0.04	0.01	0.06	-0.01	1.00	**0.16**
AW2T	30	0.02	0.01	-0.02	-0.02	-0.09	-0.08	**0.16**	0.04	0.05	0.02	-0.01	-0.02	-0.01	**0.16**	1.00

Table 18. Orthonormalized mass matrix of the MUTT after the fourth model tuning procedure (with full fuel full water; Auto Correlation)

Mode Shape	GVT Mode Number	**7**	**8**	**9**	**11**	**12**	**13**	**14**	16	19	24	25	28
SW1B	**7**	1.00	0.01	-0.05	0.01	0.02	0.01	-0.07	-0.01	-0.02	0.03	0.00	-0.01
AW1B	**8**	0.01	1.00	0.00	0.01	0.00	-0.06	-0.01	0.00	0.01	0.00	0.02	-0.04
SW1T	**9**	-0.05	0.00	1.00	-0.01	0.01	-0.01	-0.03	0.00	0.05	0.00	-0.01	0.00
AW1T	**11**	0.01	0.01	-0.01	1.00	-0.02	0.10	0.02	-0.01	0.01	0.01	0.01	0.07
SW2B	**12**	0.02	0.00	0.01	-0.02	1.00	0.02	**0.18**	0.00	-0.01	-0.04	0.01	-0.01
AMLGL	**13**	0.01	-0.06	-0.01	0.10	0.02	1.00	-0.07	-0.01	0.01	0.00	-0.05	0.10
SMLGL	**14**	-0.07	-0.01	-0.03	0.02	**0.18**	-0.07	1.00	0.01	-0.02	0.02	0.01	-0.03
BoomH	16	-0.01	0.00	0.00	-0.01	0.00	-0.01	0.01	1.00	-0.02	0.00	0.00	0.02
SWL	19	-0.02	0.01	0.05	0.01	-0.01	0.01	-0.02	-0.02	1.00	-0.04	-0.01	-0.01
SW3B	24	0.03	0.00	0.00	0.01	-0.04	0.00	0.02	0.00	-0.04	1.00	0.01	0.00
NLGFA	25	0.00	0.02	-0.01	0.01	0.01	-0.05	0.01	0.00	-0.01	0.01	1.00	-0.05
AW2T	28	-0.01	-0.04	0.00	0.07	-0.01	0.10	-0.03	0.02	-0.01	0.00	-0.05	1.00

Summary: EFEW Case

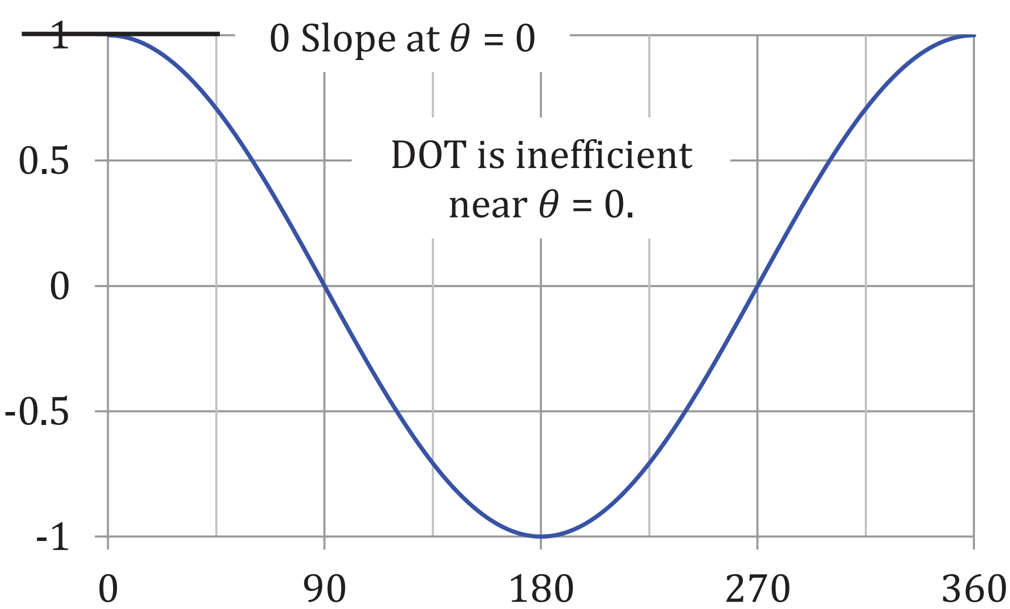
GVT data			Nastran Results								Target Error (%)
			Final Design		Baseline			DOT4			
Mode #	Mode Shape	Freq	Freq	Error	Mode #	Freq	Error	Mode #	Freq	Error	
7	SW1B	1.067	1.035	-3.0	7	1.090	2.1	7	1.091	2.2	**3**
8	AW1B	1.543	1.534	-0.5	8	1.540	-0.2	8	1.553	0.7	**3**
9	SW1T	3.223	2.781	**-13.7**	9	3.159	-2.0	9	3.220	-0.1	**3**
10	SWFA	3.607	3.068	-14.9	10	3.607	0.0	10	3.628	0.6	5~10
11	AW1T	3.839	3.522	**-8.3**	11	3.636	**-5.3**	11	3.742	-2.5	**3**
12	SW2B	4.440	4.127	**-7.1**	12	4.514	1.7	13	4.591	**3.4**	**3.4**
13	AMLGL	4.466	4.262	**-4.6**	13	4.567	2.3	12	4.492	0.6	**3**
14	SMLGL	4.666	4.467	**-4.3**	14	4.961	**6.3**	14	4.757	2.0	**3**
15	BoomH	5.273	4.530	-14.1	15	5.223	-0.9	15	5.218	-1.0	5~10
16	AWL	5.305	4.569	-13.9	16	5.294	-0.2	16	5.240	-1.2	10
17	BoomV	5.399	5.159	-4.4	17	5.349	-0.9	17	5.350	-0.9	10
18	AW2B	6.026	5.404	-10.3	18	6.061	0.6	18	6.089	1.0	5~10
19	SWL	6.264	5.815	-7.2	19	6.189	-1.2	19	6.222	-0.7	5~10
20	SEngL	7.067	N/A	N/A	20	7.283	3.0	20	7.283	3.0	10
21	AEngL	7.238	N/A	N/A	21	7.381	2.0	21	7.392	2.1	10
22	AWFA	8.484	8.133	-4.1	22	8.574	1.1	22	8.615	1.5	10
23	NLGL	8.490	8.812	3.8	23	8.085	-4.8	23	8.068	-5.0	10
24	NLGFA	9.217	9.433	2.3	24	9.205	-0.1	24	9.214	0.0	10
25	SW3B	9.346	9.798	4.8	25	9.416	0.8	25	9.477	1.4	5~10
26	AW3B	10.598	9.889	-6.7	27	11.048	4.2	27	11.198	5.7	10
27	SW2T	11.370	10.186	-10.4	28	11.462	0.8	28	11.533	1.4	5~10
28	AMLGFA	11.930	10.969	-8.1	26	10.035	**-15.9**	26	10.344	**-13.3**	**13.3**
29	SMLGFA	12.235	11.355	-7.2	29	11.835	-3.3	29	12.393	1.3	10
30	AW2T	12.405	11.986	-3.4	30	12.811	3.3	30	12.993	4.7	5~10

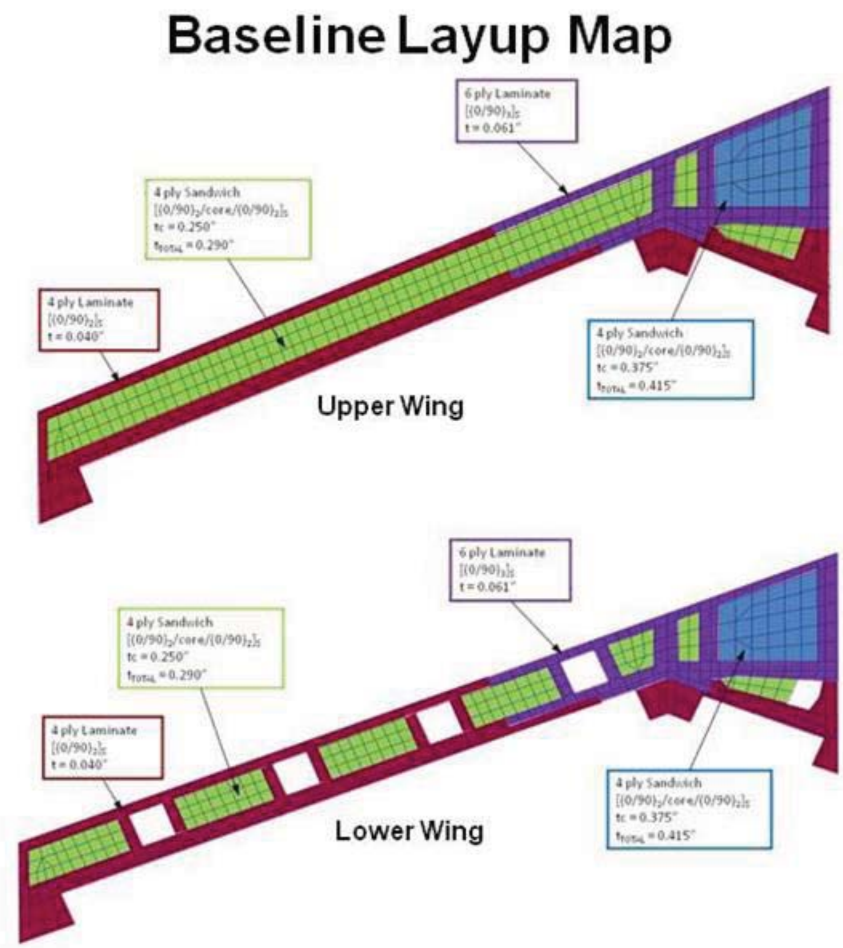
Summary: FFFW Case

GVT data			Nastran Results									Target Error (%)
			Final Design		Baseline			DOT4				
Mode #	Mode Shape	Freq	Freq	Error	Mode #	Freq	Error	Mode #	Freq	Error		
7	SW1B	1.000	0.937	-6.3	7	1.001	0.1	7	1.003	0.3		3
8	AW1B	1.411	1.392	-1.3	8	1.398	-0.9	8	1.409	-0.1		3
9	SW1T	2.938	2.608	-11.2	9	2.912	-0.9	9	2.961	0.8		3
10	SWFA	3.569	3.374	-5.5	10	3.445	-3.5	10	3.465	-2.9		10
11	AW1T	3.651	2.932	-19.7	11	3.454	-5.4	11	3.547	-2.9		3
12	SW2B	4.346	3.898	-10.3	12	4.285	-1.4	12	4.365	0.4		3
13	AMLGL	4.408	5.393	22.4	13	4.446	0.9	13	4.429	0.5		3
14	SMLGL	4.601	4.159	-9.6	14	4.944	7.4	14	4.739	3.0		3
15	AWL	5.065	4.339	-14.3	15	5.067	0.0	15	4.970	-1.9		10
16	BoomH	5.276	4.476	-15.2	16	5.217	-1.1	16	5.218	-1.1		5~10
17	BoomV	5.390	4.555	-15.5	17	5.336	-1.0	17	5.336	-1.0		10
18	AW2B	5.795	5.015	-13.5	18	5.694	-1.7	18	5.723	-1.2		10
19	SWL	6.144	5.251	-14.5	19	6.018	-2.0	19	6.045	-1.6		5~10
20	SEngL	7.085	N/A	N/A	20	7.220	1.9	20	7.237	2.1		10
21	AEngL	7.270	N/A	N/A	21	7.283	0.2	21	7.283	0.2		10
22	AWFA	8.240	7.350	-10.8	22	7.848	-4.8	22	7.867	-4.5		10
23	NLGL	8.490	9.788	15.3	23	8.071	-4.9	23	8.080	-4.8		10
24	SW3B	8.657	8.161	-5.7	24	8.673	0.2	24	8.736	0.9		5~10
25	NLGFA	9.129	9.816	7.5	25	9.186	0.6	25	9.191	0.7		5~10
26	AW3B	9.965	9.112	-8.6	26	9.766	-2.0	26	9.933	-0.3		10
27	SW2T	11.053	9.714	-12.1	28	11.148	0.9	28	11.212	1.4		10
28	AW2T	11.540	10.076	-12.7	30	11.704	1.4	29	11.847	2.7		5~10
29	AMLGFA	11.862	11.562	-2.5	27	10.576	-10.84	27	10.892	-8.2		10
30	SMLGFA	11.977	11.130	-7.1	29	11.566	-3.4	30	12.122	1.2		10

Optimization Run #5 ~

- Design Variables
  - PCOMP elements for Wings
    - Ply Angles and Thicknesses





- Optimizer: Big-Bang Big-Crunch + DOT
- Objective Functions
  - Off-diagonal Terms of Orthonormalized Mass Matrices, Mode Shape Matrices (cross-correlation Matrices), and MAC Matrices
- Constraints
  - Frequency errors
  - Off-diagonal Terms of Orthonormalized Mass Matrices, Mode Shape Matrices (cross-correlation Matrices), and MAC Matrices not selected as objective functions

Development of unsteady aerodynamic model tuning tool

Unsteady aerodynamic model tuning tool using MDAO and test data

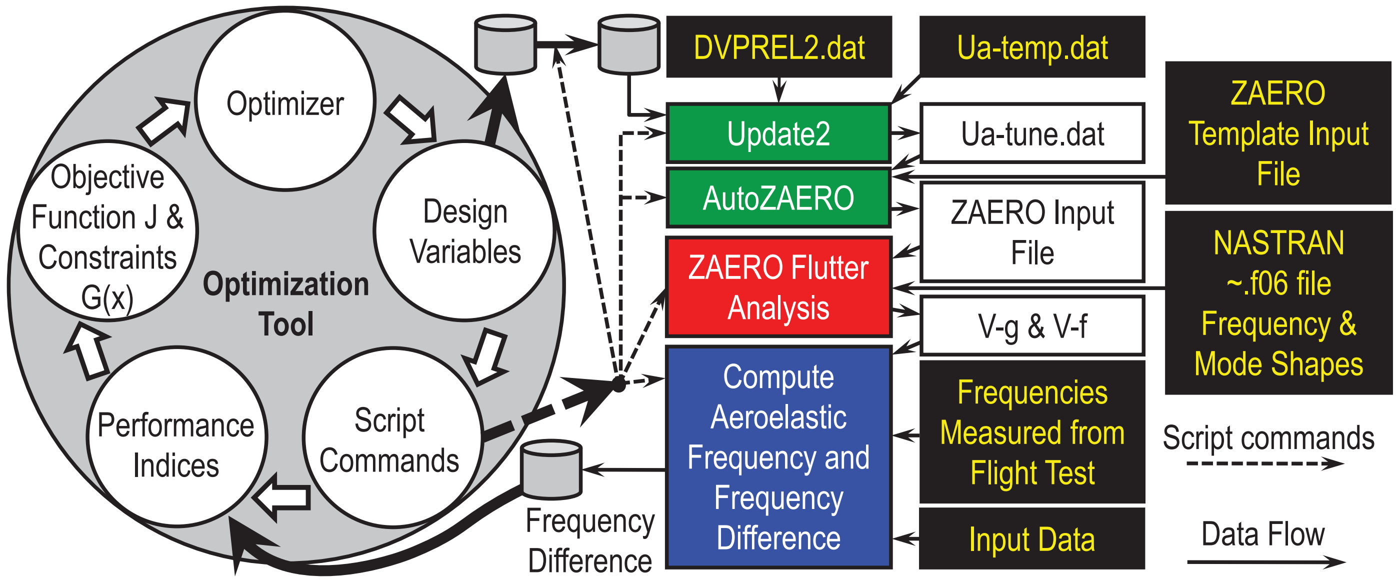
Problem

- ❑ To use the 15% flutter margin requirement in Mil Spec, unsteady aerodynamic model might be validated with respect to flight test data.
- ❑ If needed, then model should be tuned.

Objective

Minimize uncertainty in an aerodynamic model.

In-direct Method



Approach

- ❑ Direct Method (already developed)
  - ❖ Faster than in-direct method
  - ❖ Update AIC matrices
  - ❖ Design Variables
    - ➢ Scaling factor for each element of AIC matrices
- ❑ In-direct Method (current development)
  - ❖ Physics based approach
  - ❖ Update AIC matrices through the change of aerodynamic panel geometry
  - ❖ Design Variables
    - ➢ Aerodynamic mesh geometries

Computation of wing deflection and slope from measured strain

What the technology does

Problem Statement

- Wing deflection and slope (complete degrees of freedom) are essential quantities for load computations during flight.
  - Loads can be computed from the following governing equations of motion.

$$\mathbf{M}\ddot{\boldsymbol{q}}(\boldsymbol{t}) + \mathbf{G}\dot{\boldsymbol{q}}(\boldsymbol{t}) + \mathbf{K}\boldsymbol{q}(\boldsymbol{t}) = \boldsymbol{F_a}(\boldsymbol{Mach}, \boldsymbol{q}(\boldsymbol{t}))$$

- Internal Loads: using finite element structure model
  - ✓ $\mathbf{M}\ddot{\boldsymbol{q}}(\boldsymbol{t})$: Inertia Force
  - ✓ $\mathbf{G}\dot{\boldsymbol{q}}(\boldsymbol{t})$: Damping Force
  - ✓ $\mathbf{K}\boldsymbol{q}(\boldsymbol{t})$: Elastic Force
- External Load: using unsteady aerodynamic model
  - ✓ $\boldsymbol{F_a}$: Aerodynamic Force

$$\boldsymbol{q}(\boldsymbol{t}) = \begin{Bmatrix} \delta_x \\ \delta_y \\ \delta_z \\ \theta_x \\ \theta_y \\ \theta_z \end{Bmatrix}$$

$\delta_x, \delta_y, \delta_z$ → Deflection

$\theta_x, \theta_y, \theta_z$ → Slope (angle)

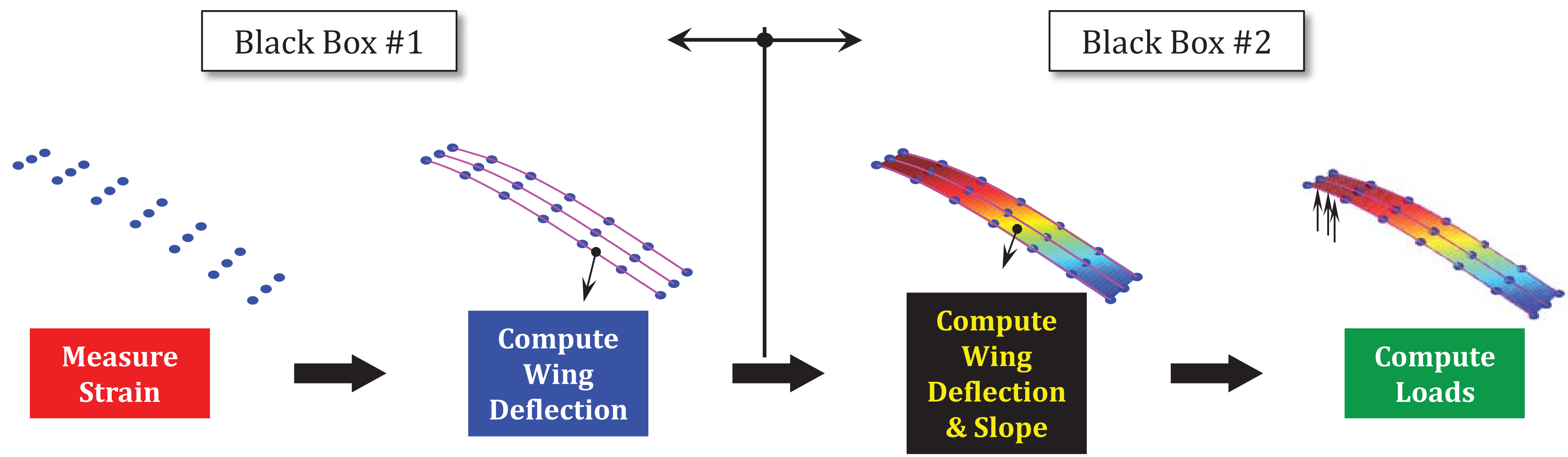
Complete degrees of freedom

- Real-time measurement of deflection and slope in flight is a valuable tool.
- Several methods predict deflection and slope at discrete locations, but few predict deflection or slope of “entire structures”.
- Wing slope is not easy to measure during flight.

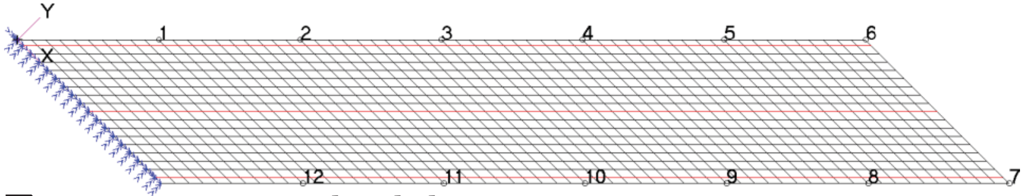
Technical features of new technology

Proposed solutions:

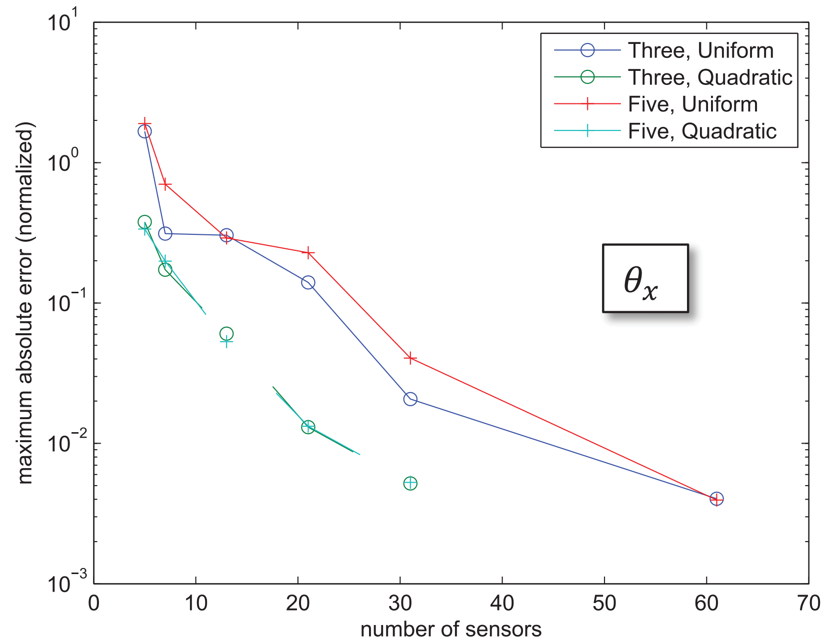
- The new method for obtaining the deflection over a flexible full 3D aircraft structure is based on the following two steps.
  - First Step: Compute wing deflection along fibers using measure strain data (Black Box #1)
    - Wing deflection will be computed along the fiber optic sensor line.
    - This is a finite element model independent method.
  - Second Step: Compute wing slope and deflection of entire structures (Black Box #2)
    - Slope computation will be based on a model dependent technique.
    - Wing deflection and slope will be computed at all the finite element grid points.

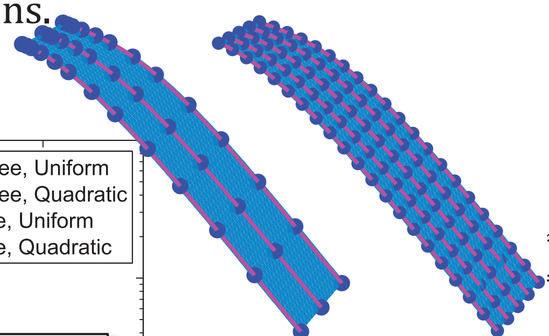


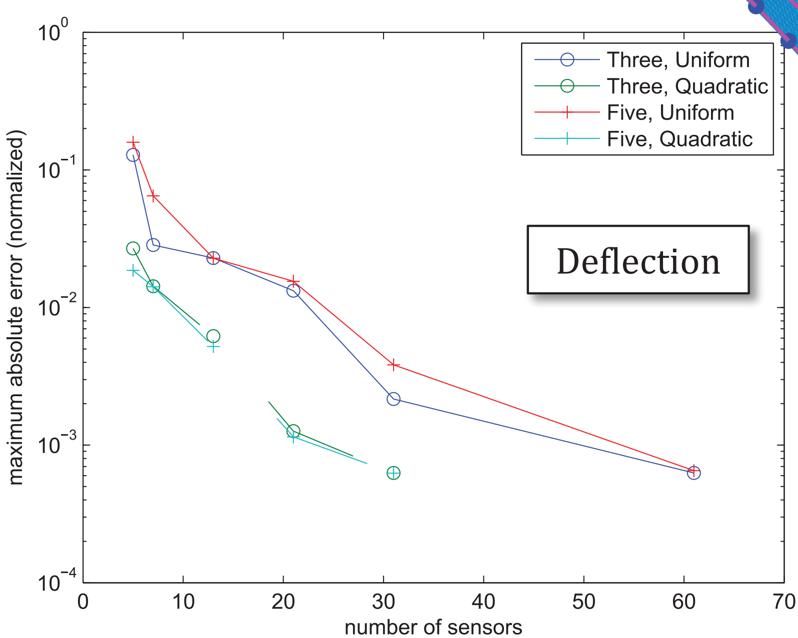
Sample Results: Cantilevered Swept Back Wing

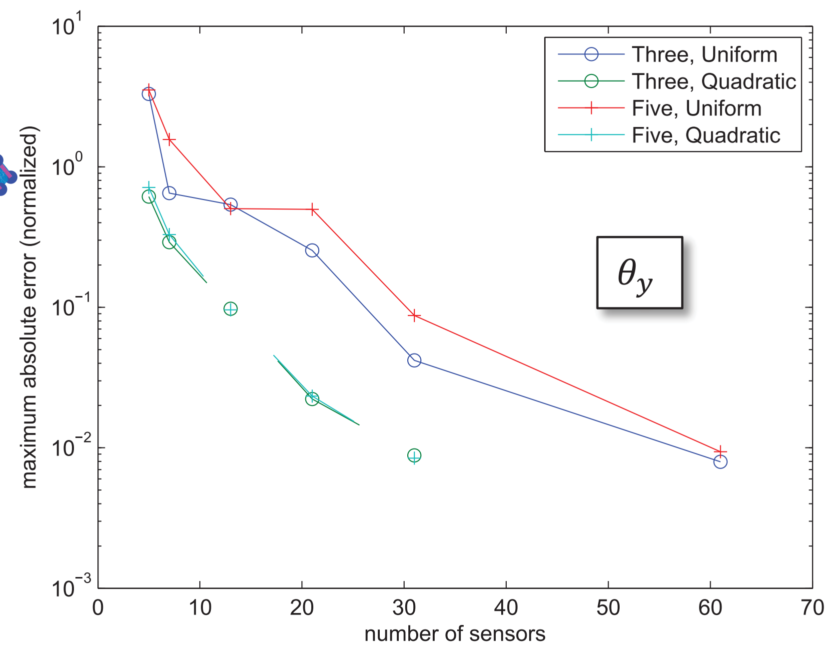


- Computational Validation
  - Strain and deflection at sensor point are computed using MSC/NASTRAN code.
    - Strain: use as if measured values
    - Deflection: use as an exact solutions (target deflections)
  - A total of 22 sensor configurations were tested
  - Deflections are computed from the strain values and compared with target deflections.



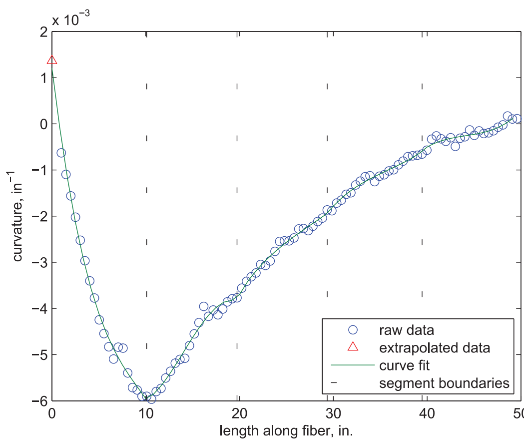


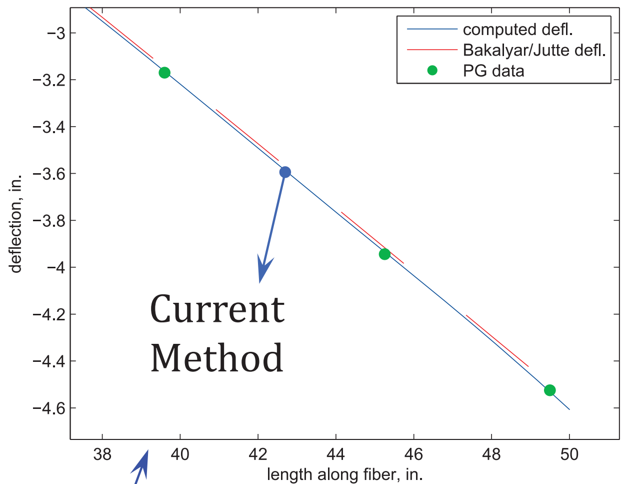




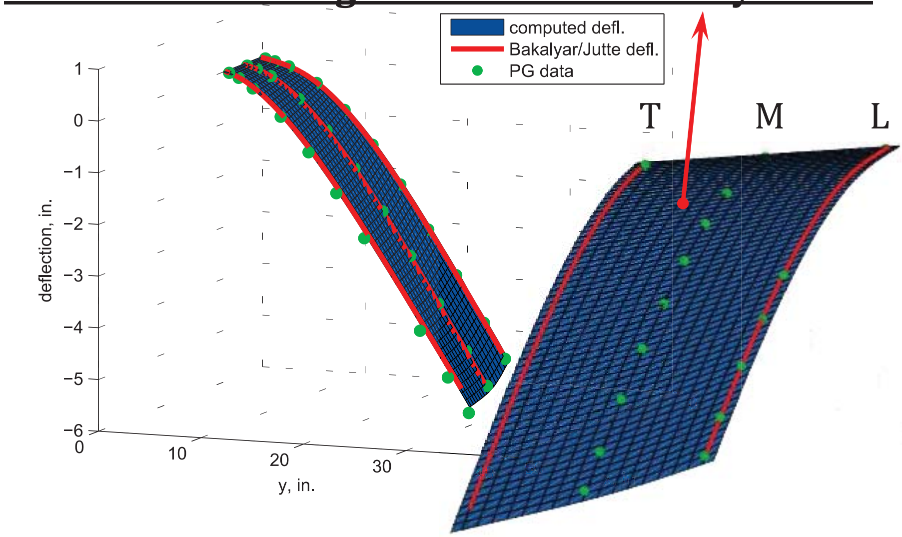
Sample Results: Cantilevered Swept Back Wing (continued)

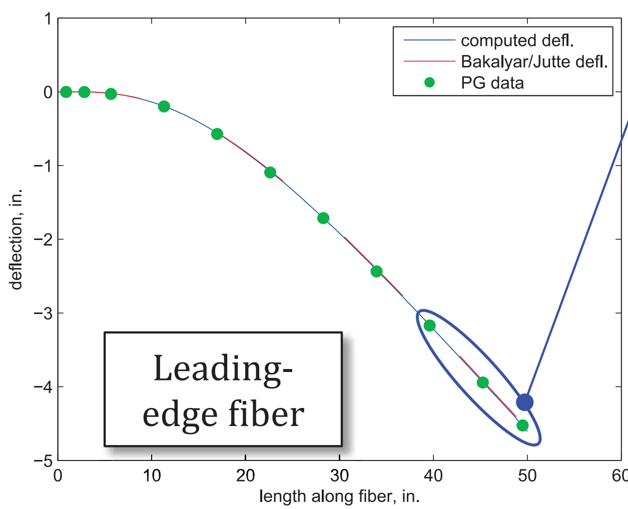
- Experimental Testing
  - Experimental results were compared to photogrammetry data and to deflection results computed by Bakalyar and Jutte for the same test data
  - Strain at the root of each fiber was extrapolated using a fifth-order polynomial
  - Curvature measurements from each pair of upper and lower fibers were averaged to eliminate the effect of any axial load

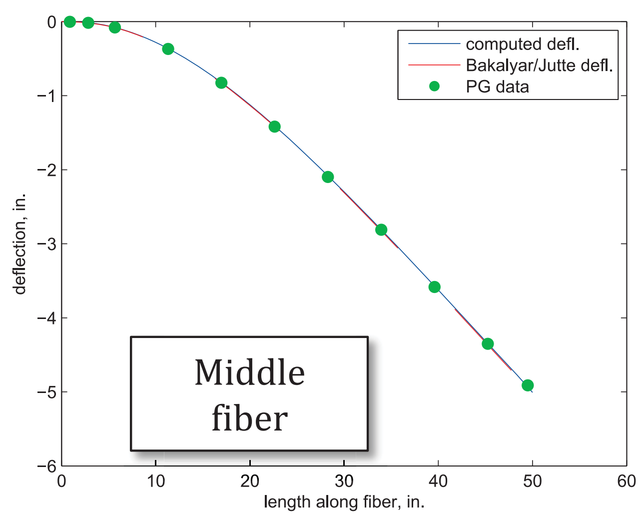


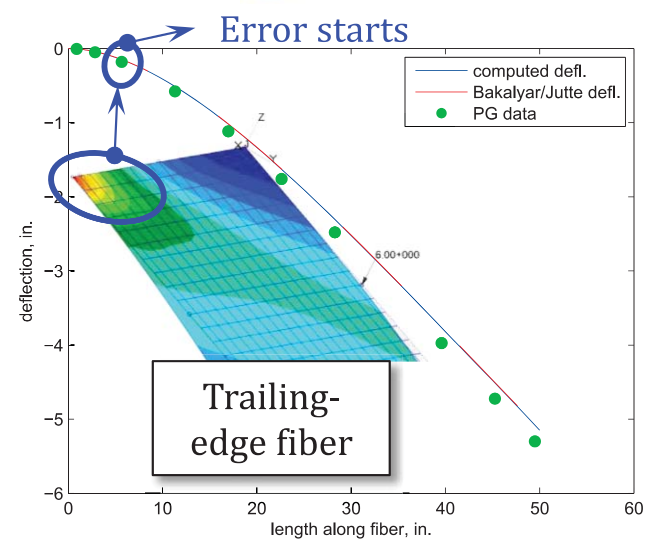


Deflection and angle are available everywhere





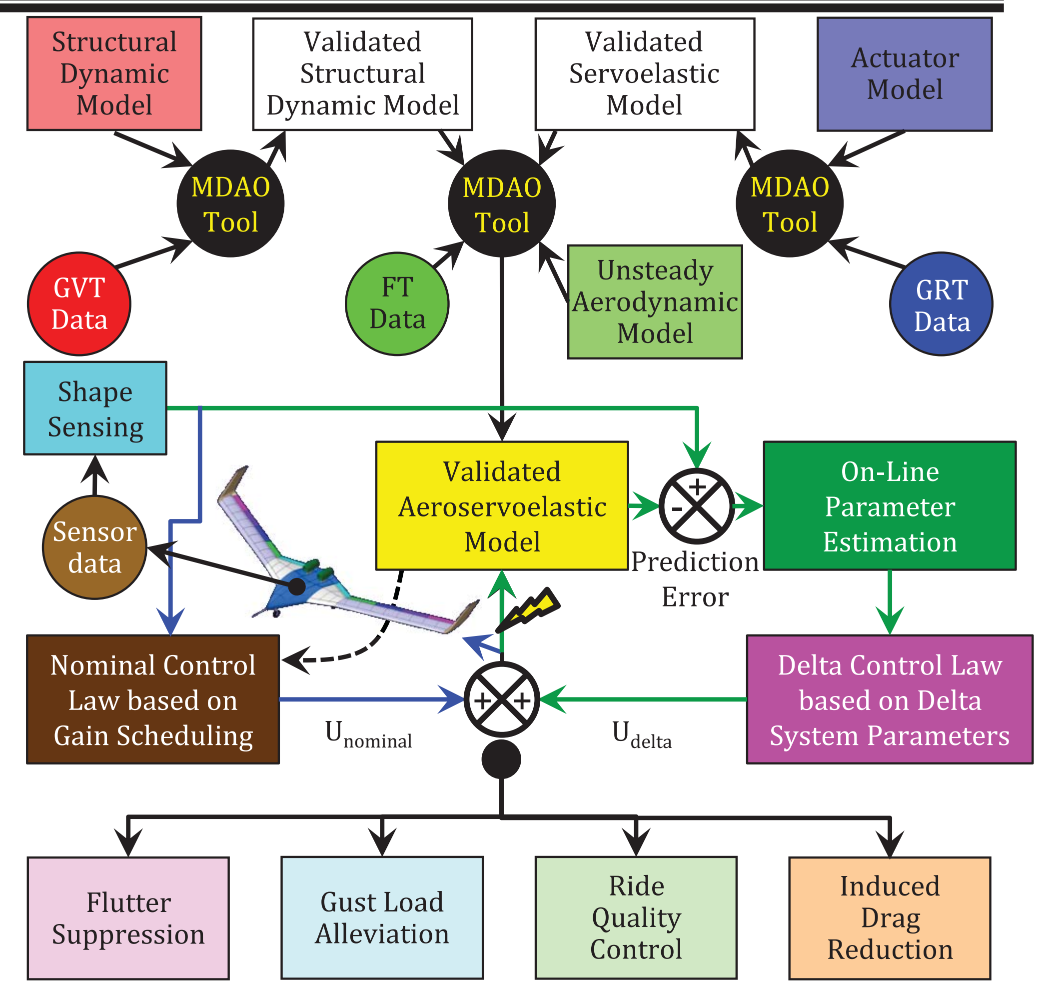




Future Work

- ❑ Nominal Control Law Design using Validated Aeroservoelastic Model
- ❑ On-line Parameter Estimator for a MIMO System
- ❑ Delta Control Law Design
- ❑ Flexible Motion Control in Subsonic, Transonic, and Supersonic Flight Regimes
  - ❖ Subsonic Regime: use MUTT
  - ❖ Subsonic, Transonic, and Supersonic Regimes: use N+2 Low Boom Supersonic Aircraft
    - ➢ Use CFD code (CFL3D and/or CAPTSDv)

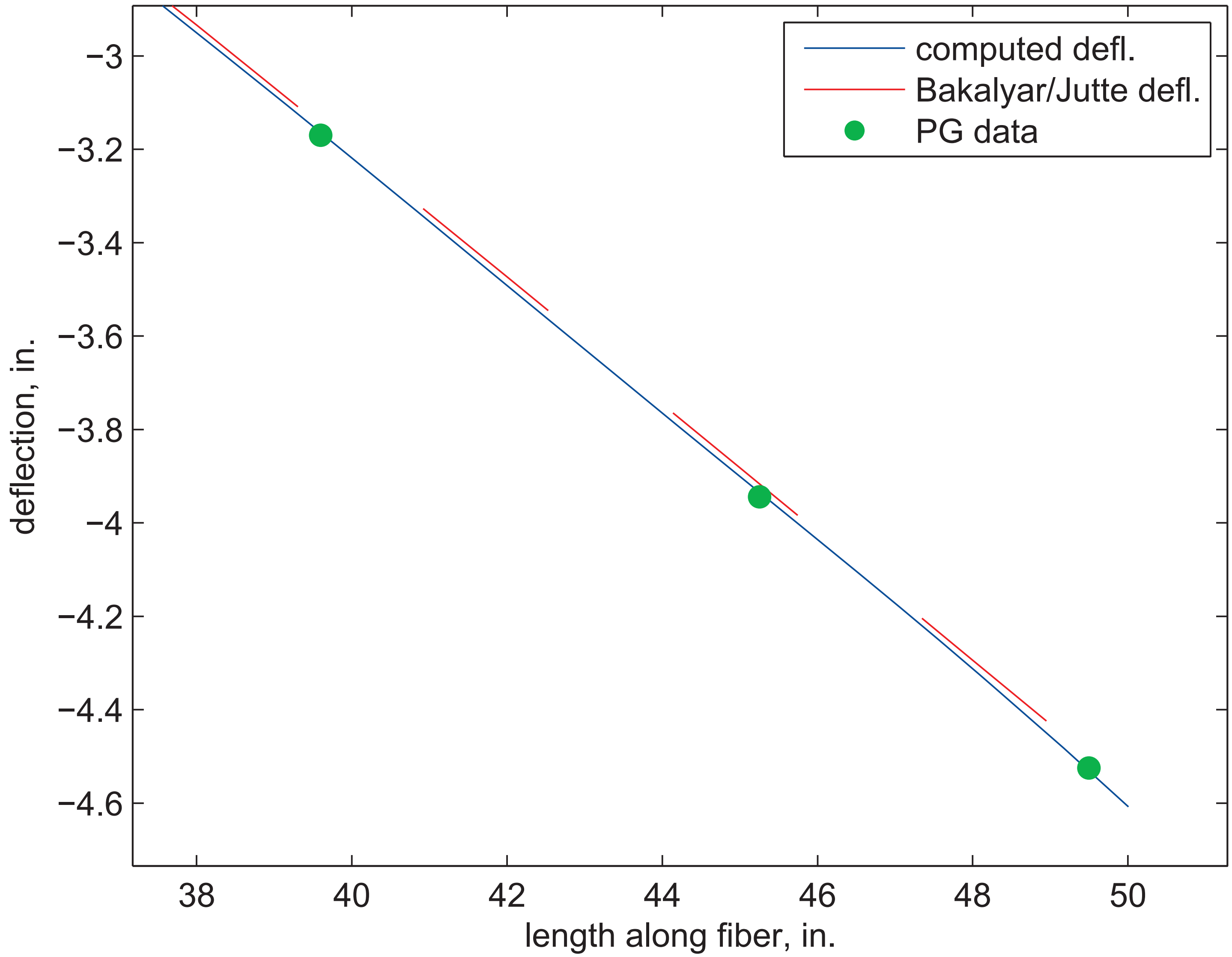
- ❑ Team Members
  - ❖ Chan-gi Pak: PI
  - ❖ Samson Truong
    - ➢ Create Validated Aeroservoelastic model
  - ❖ Ashante Jordan
    - ➢ Testing Shape Sensing codes
    - ➢ Work with Internship Students
  - ❖ Alex Chin & Marty Brenner: Supported by Fixed Wing Project
    - ➢ Nominal Control Law Design
    - ➢ On-line Parameter Estimator for a MIMO System
    - ➢ Delta Control Law Design



On-line Adaptive Active Flexible Motion Control System

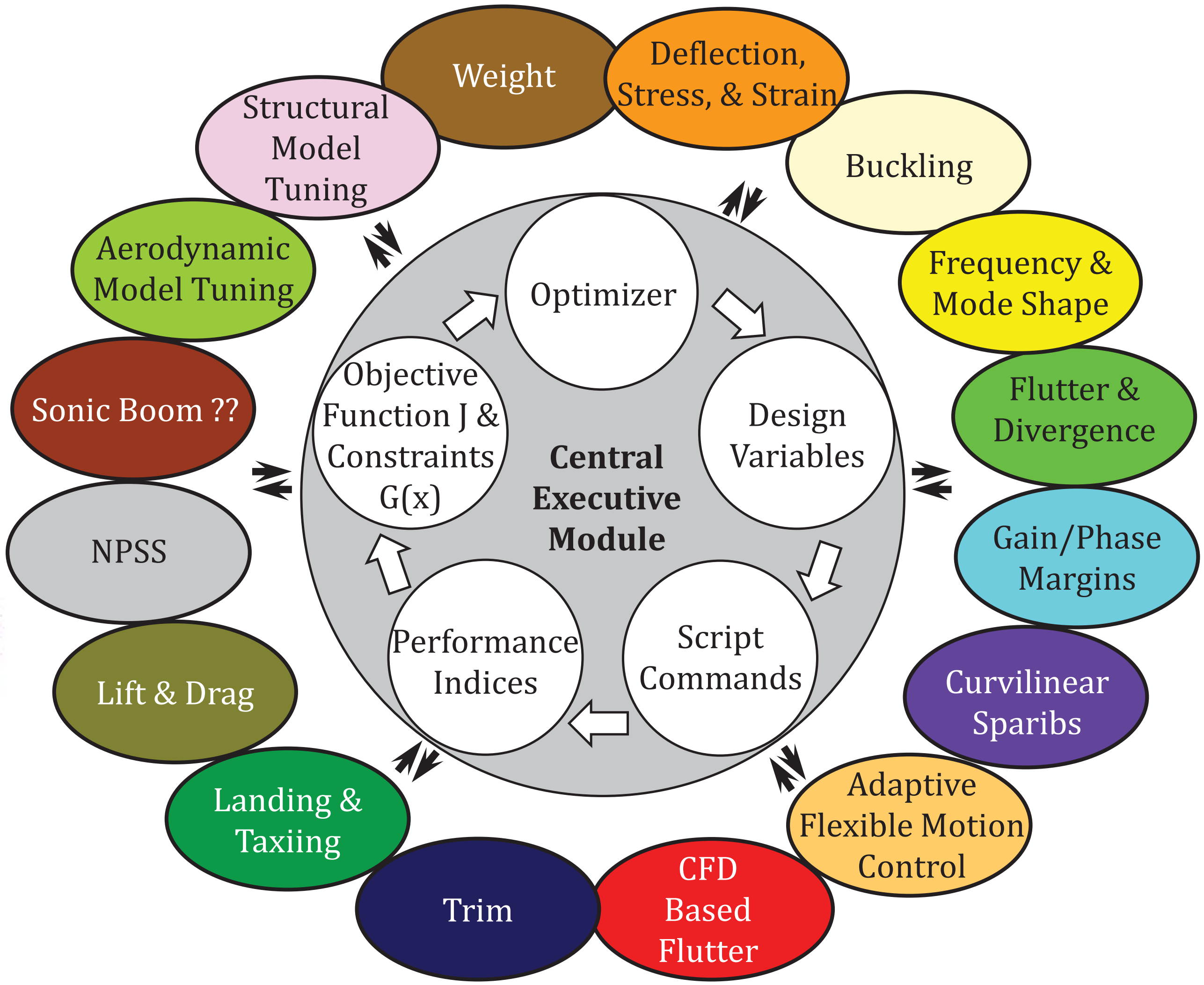
- ❖ Kelley Hutchins (Fellowship Student)
  - ➢ Ph.D. Candidate at University of Texas, Austin
    - ✓ Dissertation Topic
    - ✓ Advisor: Prof. Maruthi R. Akella

Questions ?



computed defl.
Bakalyar/Jutte defl.
PG data
deflection, in.
−3
−3.2
−3.4
−3.6
−3.8
−4
−4.2
−4.4
−4.6
38
40
42
44
46
48
50
length along fiber, in.

Design of an Aeroservoelastically Tailored Wings and Aircraft for AeroScience, Fixed Wing, and High Speed Projects



Chan-gi Pak, Ph.D. & Wesley Li

Structural Dynamics Group, Aerostructures Branch (RS)
NASA Dryden Flight Research Center

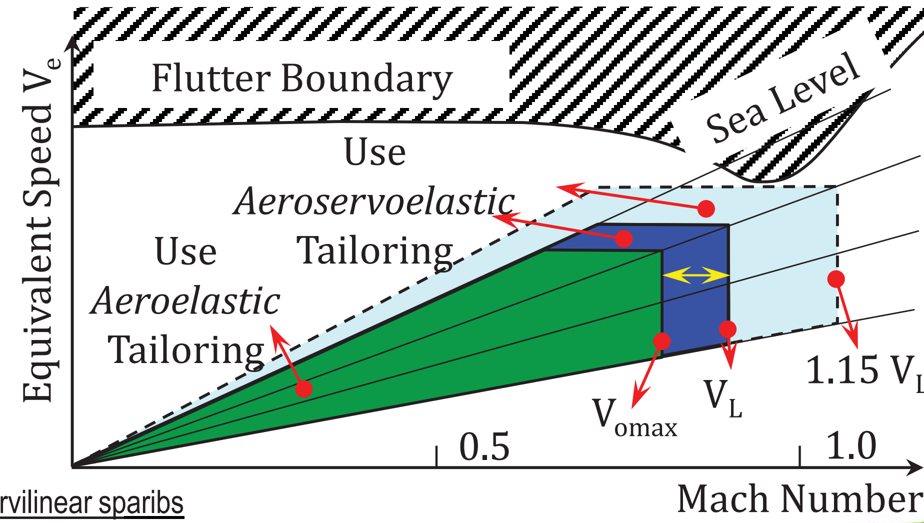
Design of an Aeroservoelastically Tailored Wings and Aircraft for AeroScience, Fixed Wing, and High Speed Projects

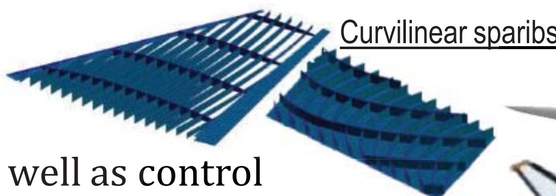
Problem

Design innovations are needed to further down the weight of an aircraft which current design technologies can take care of.

Objective

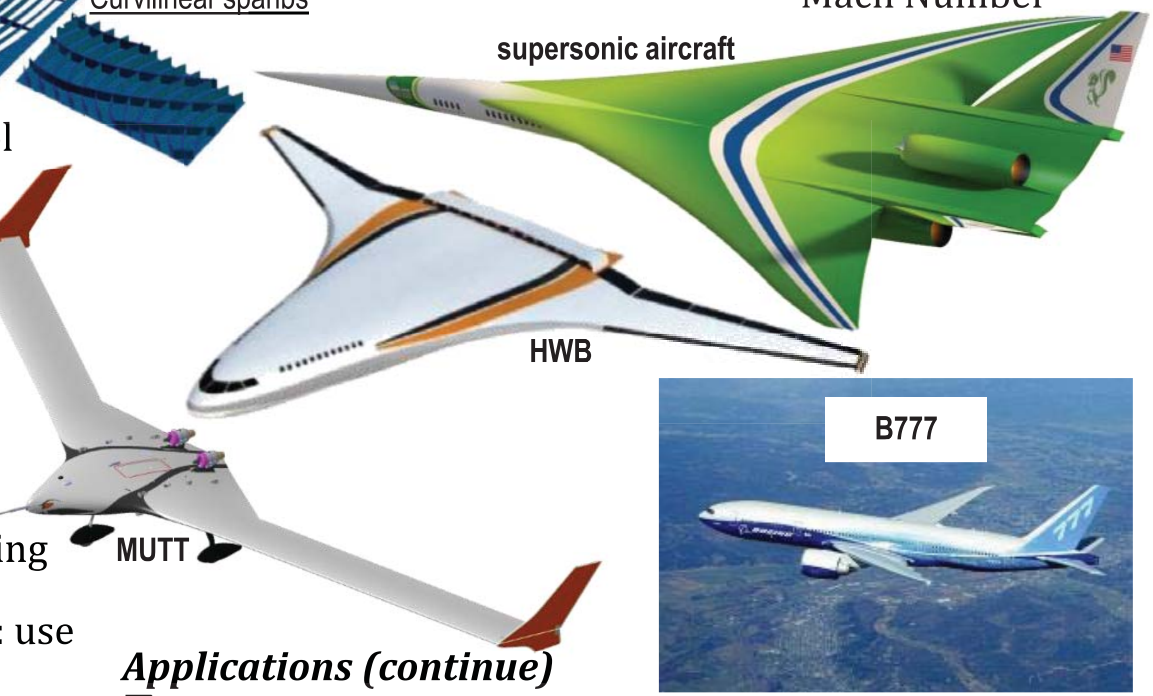
- ❑ Use aeroelastic tailoring theory and active flexible motion control technique to satisfy the overall strain, aeroelastic, and aeroservoelastic instability requirements within given flight envelopes
- ❑ Use curvilinear sparib concept as well as composite ply angles for aeroelastic tailoring





Approach

- ❑ <u>Simultaneously update</u> structural as well as control design variables during early design phase
  - ❖ Perform topology optimization with curvilinear sparibs
  - ❖ Use aeroelastic tailoring up to V_{omax} line
  - ❖ Use aeroservoelastic tailoring between V_{omax} and $1.15\ V_L$



Applications

- ❑ **Support Fixed Wing Project**
  - ❖ Optimization of MUTT aircraft: Aeroelastic tailoring and mass balancing studies
  - ❖ Optimization of Common Research Model (CRM): use B-777 type of wing
- ❑ **Support High Speed Project**
  - ❖ Optimization of a low-boom supersonic aircraft: Use LM's concept aircraft

Applications (continue)

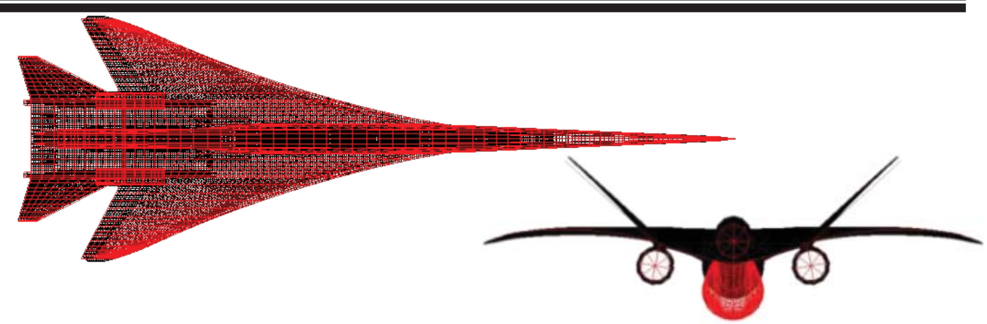
- ❑ **Support AeroScience Project**
  - ❖ Optimization of an unconventional aircraft: Use N3-X HWB aircraft with turbo-electric distributed propulsion system

Structure and control systems are simultaneously improved.

Design of an Aeroservoelastically Tailored Wings and Aircraft for AeroScience, Fixed Wing, and High Speed Projects (continued)

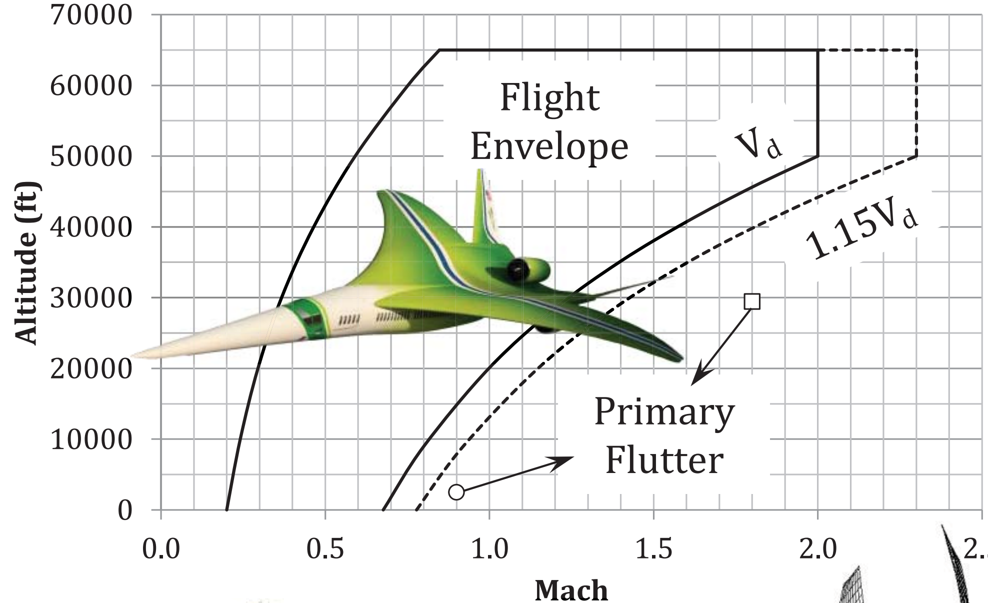
RESULTS

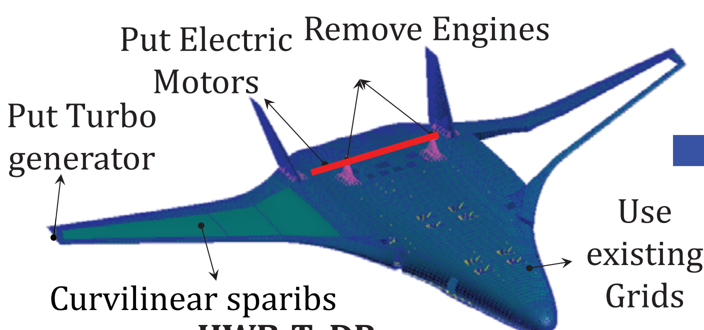
- ❑ Support Fixed Wing Project
  - ❖ Flutter speeds of the current MUTT aircraft is too high for the active flutter suppression study. (some flutter speeds are outside the flight envelope where aircraft can't reach with current propulsion systems.)
    - ➢ Keep working on a critical optimization study with MUTT aircraft. Through the use of lumped masses together with our MDAO tool, flutter speeds will be tuned within the flight envelope.
  - ❖ Generated a finite element model (FEM) of full-scale CRM for aeroelastic tailoring optimization.
    - ➢ Creating wing skins using laminated composites is underway.
- ❑ Support High Speed Project
  - ❖ Preparing for optimization using baseline configuration
  - ❖ Create unsteady aerodynamic model and perform modal & flutter analyses
- ❑ Support AeroScience Project
  - ❖ Keep working on for creating a finite element model



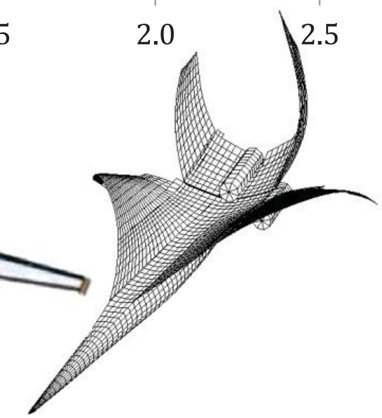
N+2 Low Boom Supersonic Aircraft

Flutter Boundaries at Mach 0.9 & 1.8





HWB-TeDP



Structure and control systems are simultaneously improved.

Flutter Optimization Study for MUTT Aircraft with Flexible Wing Configuration

Flutter Speed and Frequency Constraints

- Design requirement (**non-dimensional)**
  - 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

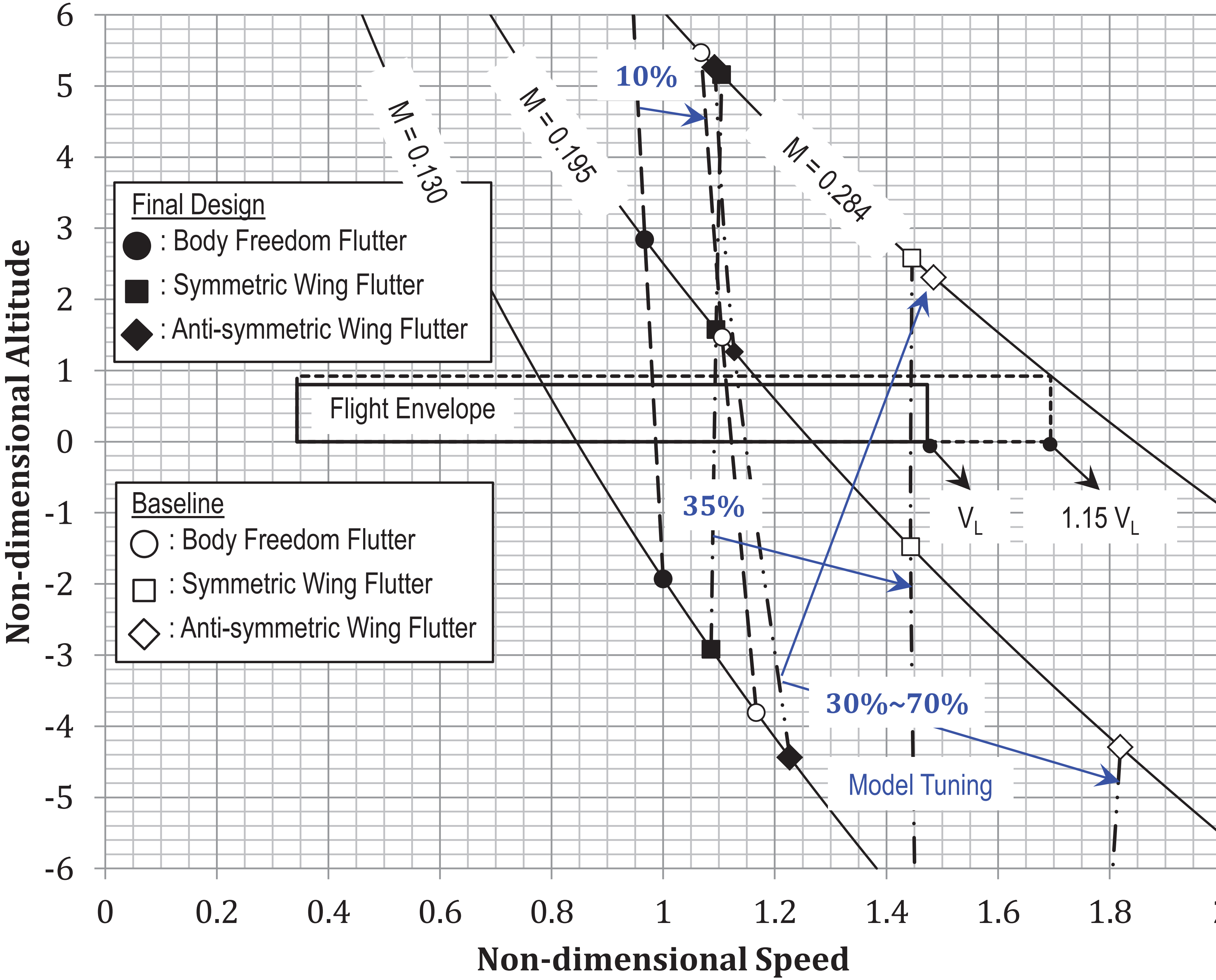
*Note: optimization constraints for Aft Wing Tip Boom Optimization

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

Flutter mode	Baseline flutter points at Mach = 0.16							
	Speed (Keas)				Frequency (Hz)			
	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

Flutter Boundaries



Optimization Problem Statement

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

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

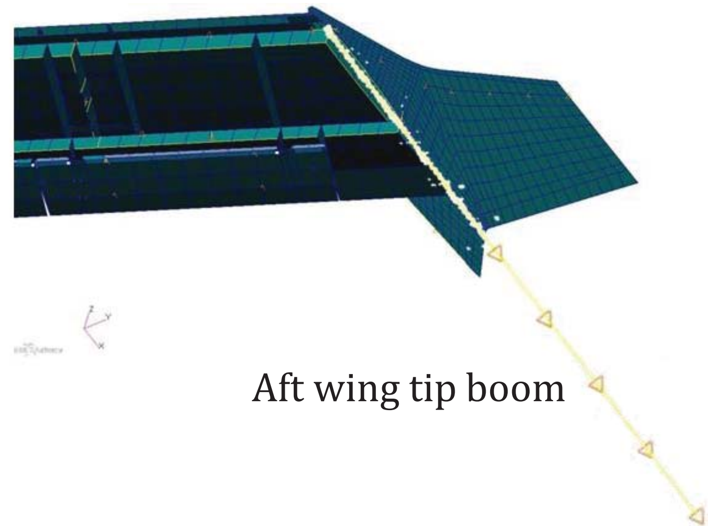
    - such that:
      - ✓ Flutter speed constraints
        $V_{Lj} \leq V_{EFEWj}(\mathbf{X}) \leq V_{Uj}\ \ \&\ \ V_{Lj} \leq V_{FFFWj}(\mathbf{X}) \leq V_{Uj} \quad j = 1, 2, \&\ 3$
      - ✓ Flutter frequency constraints
        $f_{Lj} \leq f_{EFEWj}(\mathbf{X}) \leq f_{Uj}\ \ \&\ \ f_{Lj} \leq f_{FFFWj}(\mathbf{X})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

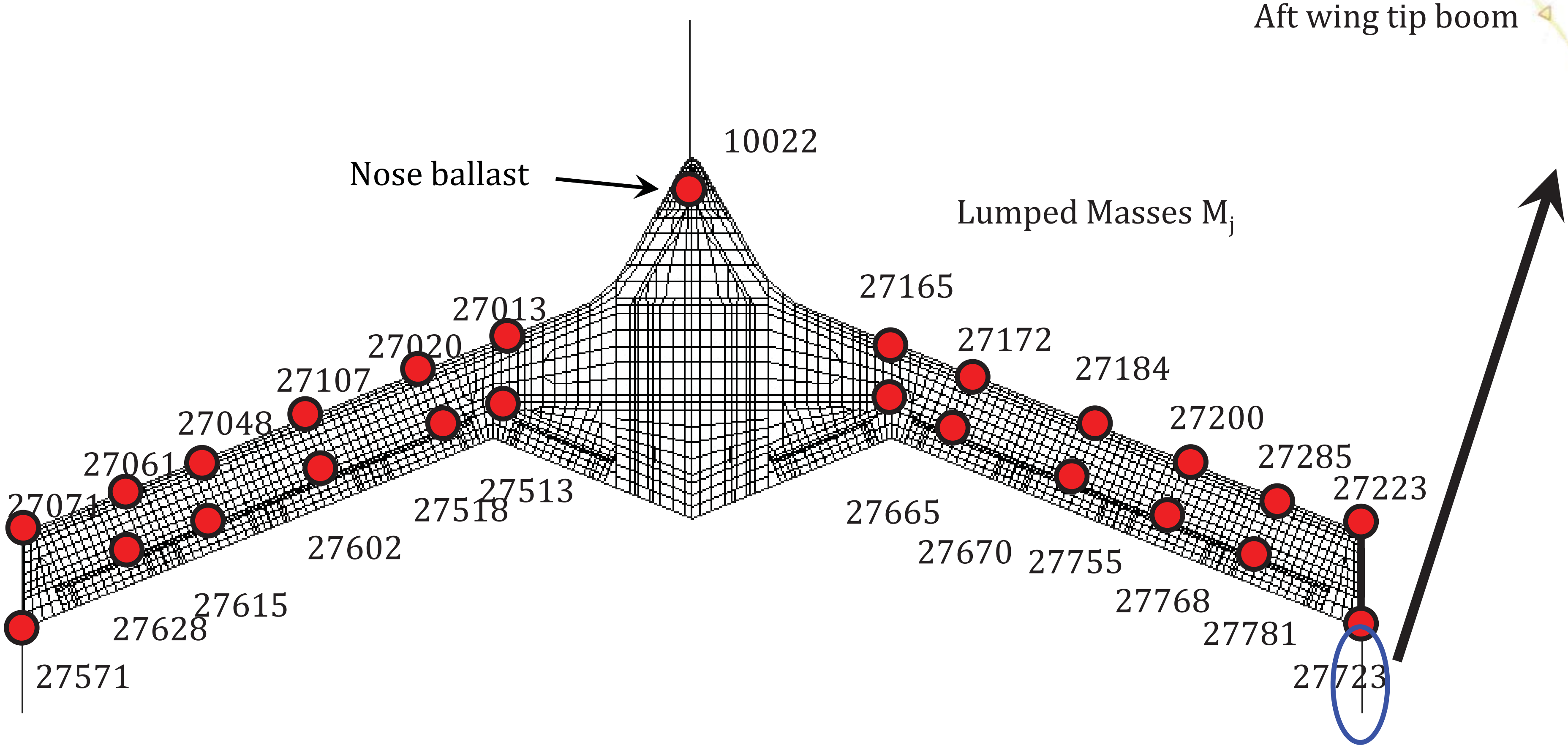
  - $0 \leq x_j \leq x_{Uj}$: Side constraints
  - When j-th flutter speed is selected for an objective function, then j-th flutter speed is not included as a constraint function.

- Flutter speed and frequency constraints will be computed using two different weight configurations, i.e. empty fuel empty water (EFEW) and full fuel full water (FFFW) configurations
  - Two different weight configurations will be taken into account in a **single** optimization run.

Summary of Optimization Approach

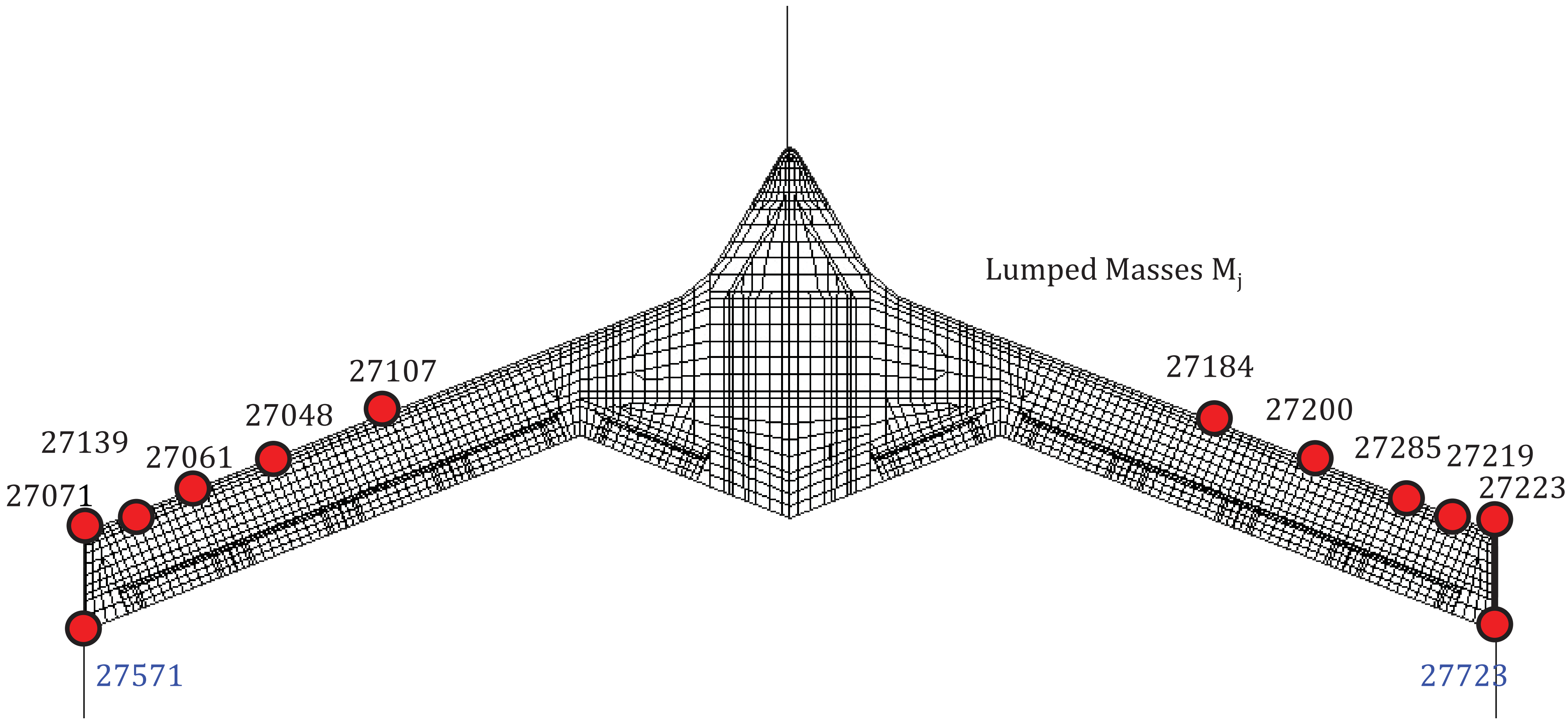
- Based on DOT, a gradient-based optimization
- Lumped mass design variables (0 to 5 lbs. each = side constraints)
  - Use design variable linking for wing symmetric masses
  - Wing leading and trailing edge (12 design variables)
  - 25” long aft wing tip boom (5 design variables)
- Nose ballast (up to 20.0 lbs.)
  - Primarily to reduce body freedom flutter speed





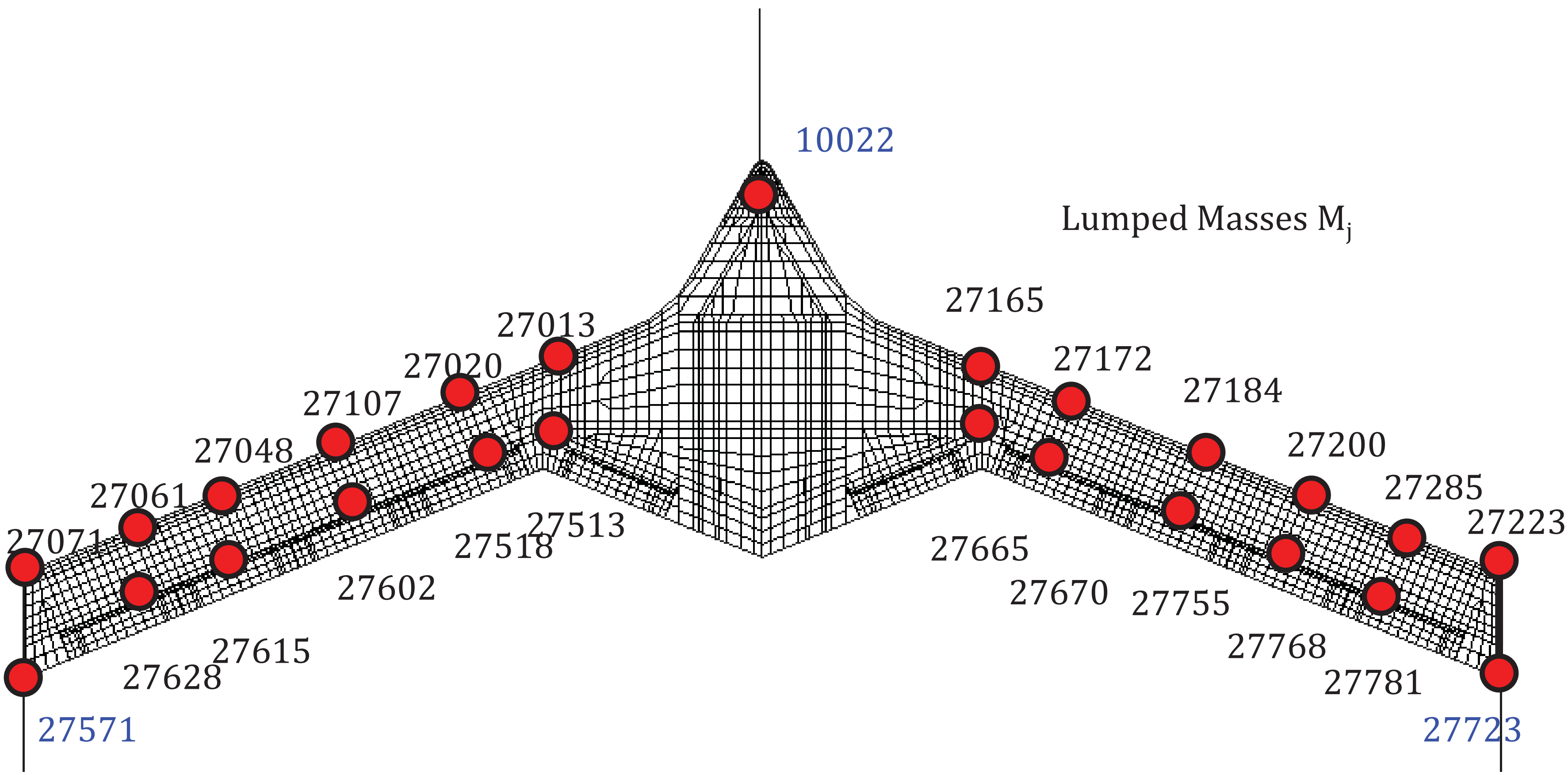
Optimization Run #1

- Make masses install symmetrically
  - 6 design variables
  - Wing lumped masses (0 to 5 lbs.)
  - Use design variable linking for these symmetric masses.
  - Optimization results: two 5 lbs. masses were added at aft wing tip location, node 27723 and 27571.



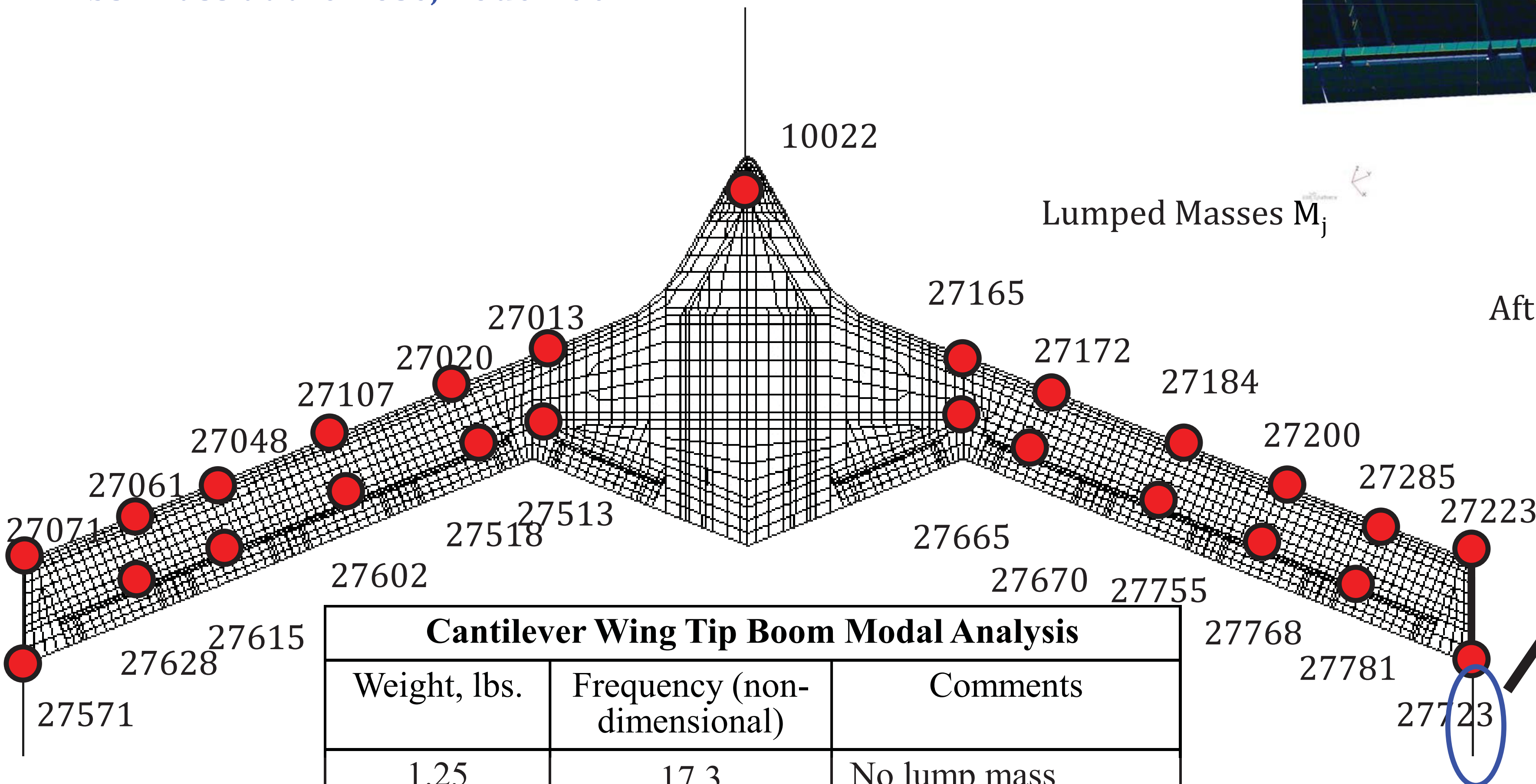
Optimization Run #2

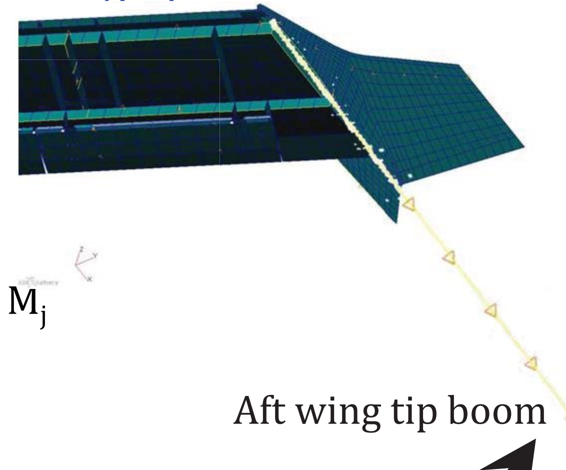
- Make masses install symmetrically
  - 12 wing and 1 nose design variables
  - Wing lumped mass (0 to 5 lbs.)
  - Nose ballast (0 to 20 lbs.)
  - Use design variable linking for wing symmetric masses.
  - Optimization results: two 5 lbs. masses were added at aft wing tip location, node 27723 and 27571. Also a 20 lbs. mass at the nose, node 10022.



Optimization Run #3

- Nose ballast (0 to 20 lbs.)
- Add a 25” long aft wing tip boom with lumped masses (0 to 5 lbs.)
- Optimization results: two 5 lbs. masses were added to the tip of the aft wing tip boom. Also a 20 lbs. mass at the nose, node 10022.





Cantilever Wing Tip Boom Modal Analysis		
Weight, lbs.	Frequency (non-dimensional)	Comments
1.25	17.3	No lump mass
3.75	7.3	0.5 lbs. at each nodes
6.25	5.4	1.0 lbs. at each nodes
6.25	17.3	5.0 lbs. at tip

Optimization Run #3 (continued)

- Objective: Min 1st flutter speed ($0.79<f_1<1.18$)
- Constraints: 2nd and 3rd flutter speed ($0.98<f_2<1.18$, $0.98<f_3<1.3$)
- Several optimization runs with different initial condition were performed
- Results: the 2nd and 3rd flutter speed are reduced mainly. Not the body freedom flutter. Nose ballasts change the Body freedom flutter speed.

		EFEW		FFFW	
Case	Flutter	Flutter Speed	Flutter Frequency	Flutter Speed	Flutter Frequency
Baseline					
	1st	1.13	0.68	1.16	0.53
	2nd	1.48	2.34	1.48	2.25
	3rd	1.68	1.52	1.68	2.43
With Wing Tip Boom Optimization					
201	**1st**	**1.13**	**0.72**	**1.14**	**0.58**
	2nd	1.11	1.07	1.18	1.03
	3rd	1.29	1.57	1.26	1.55
202	**1st**	**1.13**	**0.72**	**1.14**	**0.58**
	2nd	1.12	1.07	1.18	1.03
	3rd	1.29	1.57	1.26	1.55
203	2nd	1.06	0.99	1.10	0.95
	1st	**1.14**	**0.71**	**1.14**	**0.57**
	3rd	1.30	1.44	1.26	1.42

Final Design Variables			
DESVAR	**Case 201**	**Case 202**	**Case 203**
Nose Lumped Mass			
1	20.0	20.0	20.0
Wing Tip Boom Lumped Mass			
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 Mass Grid X Location			
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**

Case 201 is the best design

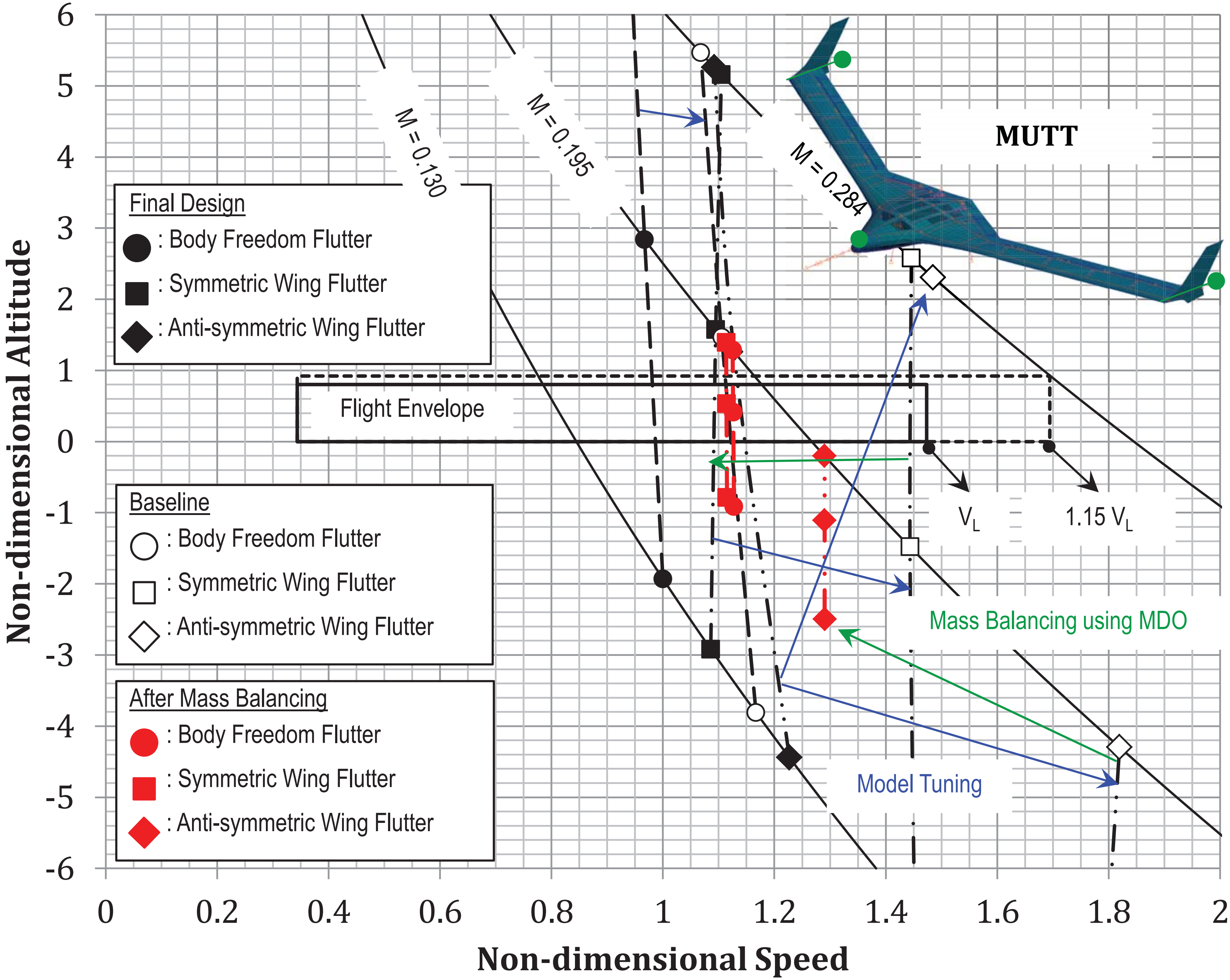
Too Low !!
Symmetric flutter first and then BBF

Optimization Results

- Several optimization runs with different initial condition were performed.
- Objective: Min flutter speeds (1st, 2nd, or 3rd)
  - With or without constraints: 2nd and 3rd flutter speed
- The 2nd and 3rd flutter speed can be reduced by adding aft wing tip boom mass.
- The Body freedom flutter speed can be reduced by Nose ballast.

Flutter mode	Flutter Speeds							
	Lower Bounds	Baseline		Run #1 & #2		Run #3		Upper Bounds
		EFEW	FFFW	EFEW	FFFW	EFEW	FFFW	
1st	0.79	1.13	1.16	1.12	1.12	1.13	1.14	0.98
2nd	0.98	1.48	1.48	1.55	1.49	1.11	1.18	1.18
3rd	0.98	1.68	1.68	1.67	1.56	1.29	1.26	1.30
Flutter mode	Flutter Frequency							
	Lower Bounds	Baseline		Run #1 & #2		Run #3		Upper Bounds
		EFEW	FFFW	EFEW	FFFW	EFEW	FFFW	
1st	0.53	0.68	0.53	0.58	0.71	0.72	0.58	1.76
2nd	1.17	2.34	2.25	2.01	1.28	1.07	1.03	2.35
3rd	1.50	1.52	2.43	1.25	2.07	1.57	1.55	3.52

Flutter Boundaries



Optimization Observation

- Body freedom flutter can be reduced by adding nose ballasts.
  - But not that much
- 2nd and 3rd flutter can be reduced by adding ballasts at aft wing tip.
  - Aft wing tip boom is added.
- Recommendation
  - 20 lb & 4 lb configuration looks the best choice
    - At least 0.04 (non-dimensional) speed separation for the first and second flutter modes

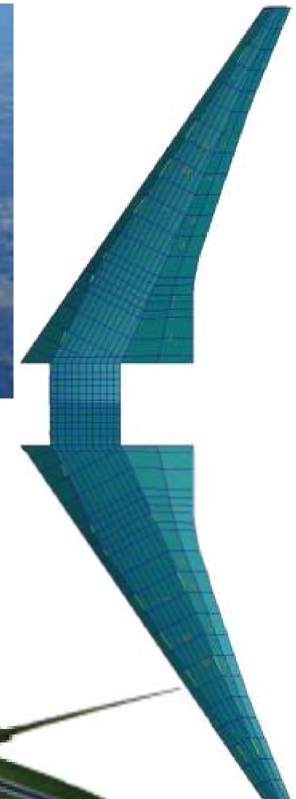
Configuration	1st EFEW		2nd EFEW		3rd EFEW		1st FFFW		2nd FFFW		3rd FFFW	
	Speed	Freq.	Speed	Freq.	Speed	Freq.	Speed	Freq.	Speed	Freq.	Speed	Freq.
Baseline	1.13	0.68	1.48	2.34	1.68	1.52	1.16	0.53	1.48	2.25	1.68	2.43
20* & 1**	1.11	0.73	1.39	1.30	1.38	2.02	1.12	0.59	1.60	1.29	1.37	1.96
20 & 2	1.12	0.73	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

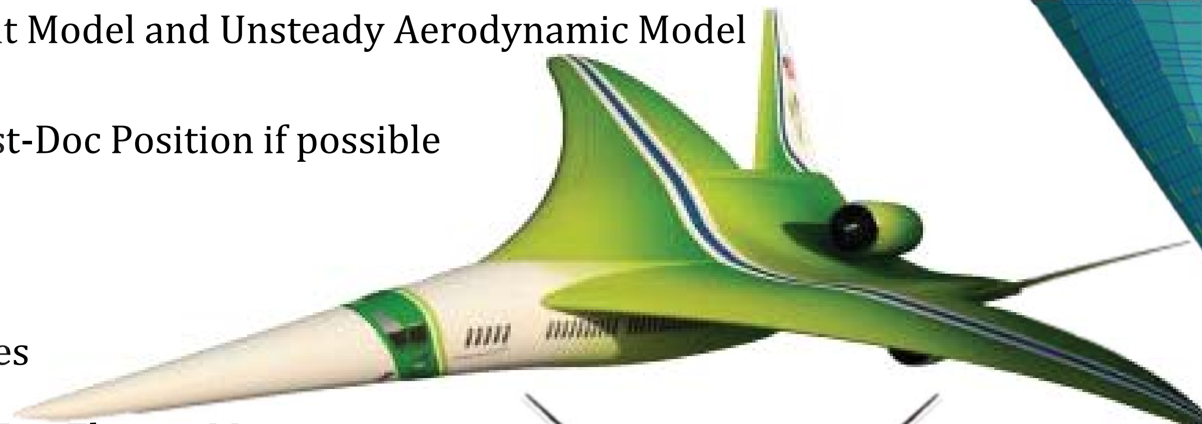
* : Nose Mass (lb)
** : Wing tip mass (lb)

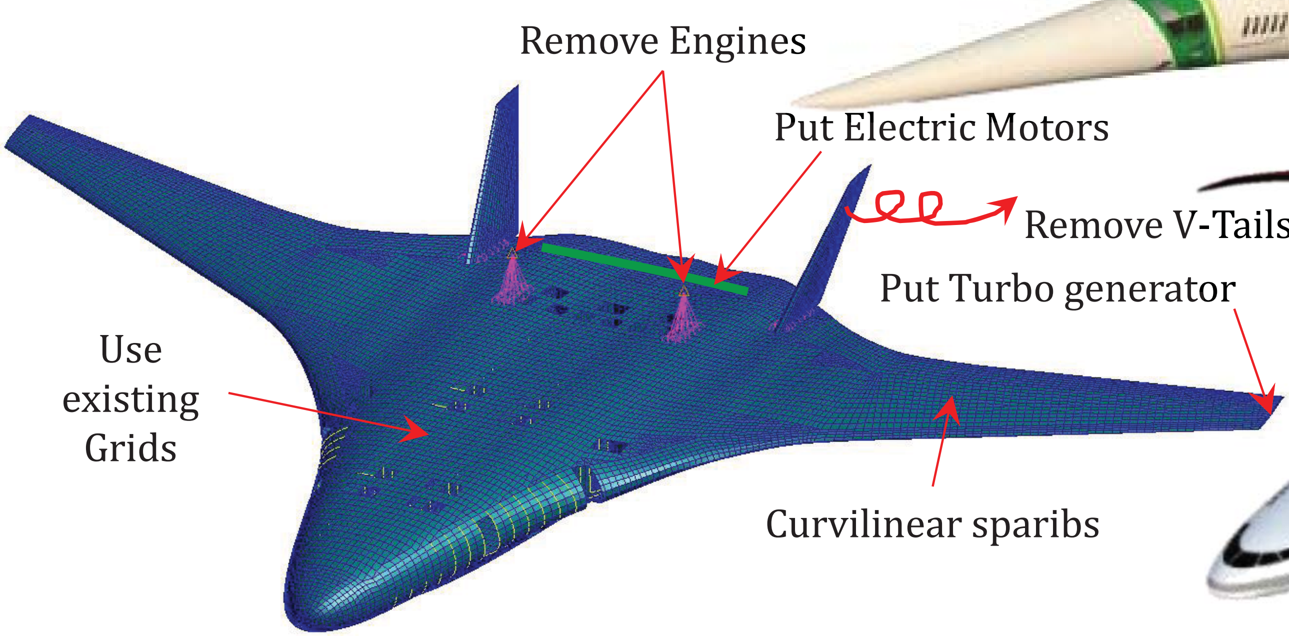
Too low

Future Work

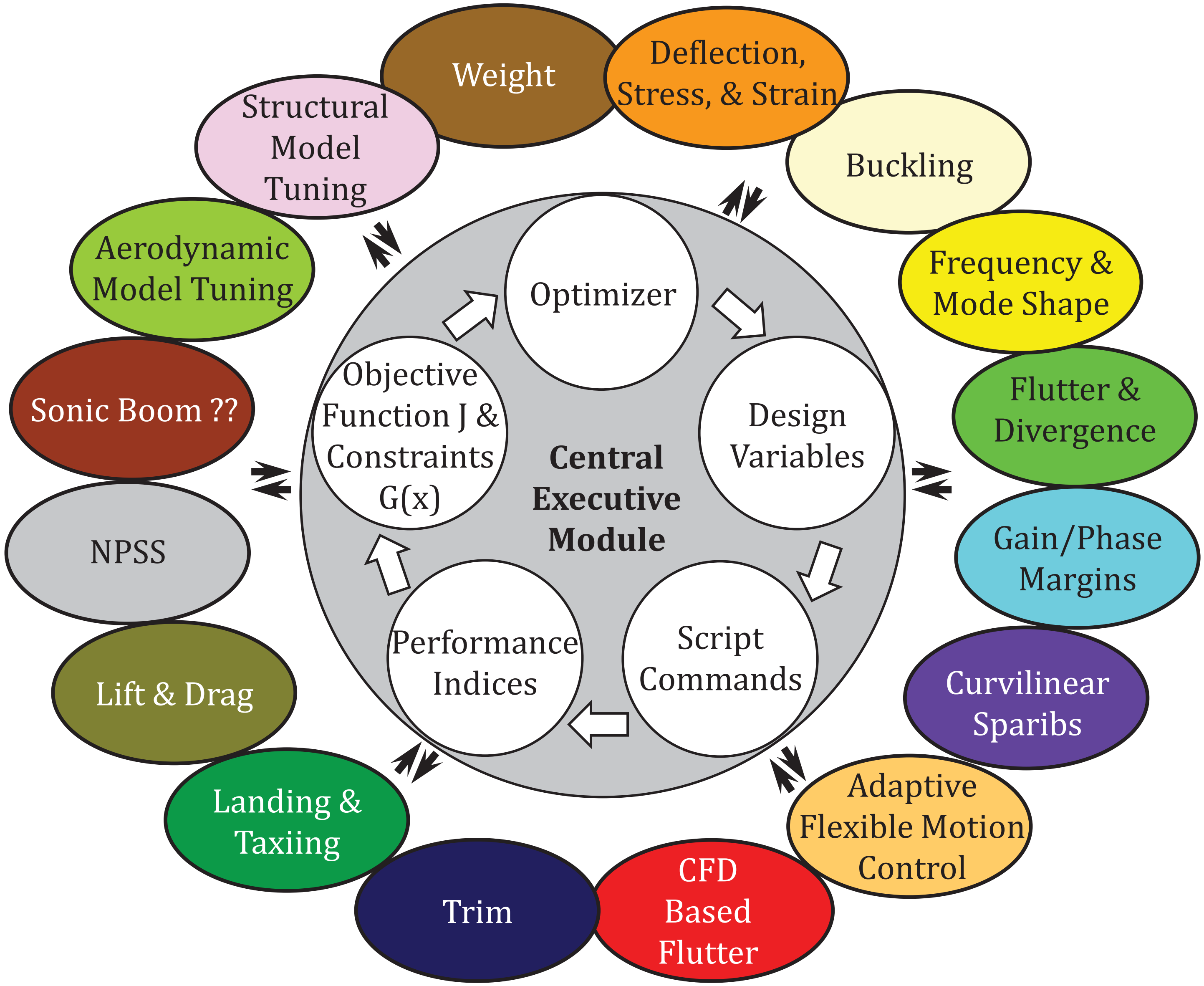
- Team Members
  - Chan-gi Pak: PI
    - Designing N+2 Low Boom Supersonic Aircraft
  - Wesley Li
    - Designing Common Research Model (B-777 Type of Wing)
    - Incorporating Curvilinear Mesh Generation code
  - Roger Truax
    - Designing Hybrid Wing Body Aircraft with Turboelectric Distributed Propulsion
      - ✓ Create Structural Finite Element Model and Unsteady Aerodynamic Model
      - ✓ Perform Optimization
  - Create One Fellowship Student or Post-Doc Position if possible







Questions ?



Weight
Deflection, Stress, & Strain
Buckling
Frequency & Mode Shape
Flutter & Divergence
Gain/Phase Margins
Curvilinear Sparibs
Adaptive Flexible Motion Control
CFD Based Flutter
Trim
Landing & Taxiing
Lift & Drag
NPSS
Sonic Boom ??
Aerodynamic Model Tuning
Structural Model Tuning
Optimizer
Design Variables
Script Commands
Performance Indices
Objective Function J & Constraints G(x)
Central Executive Module

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,…, N) using <u>uniform</u> random number generator such that
      - ✓ $\mathbf{XL}_i \leq \mathbf{X}_i \leq \mathbf{XU}_i$
    - Current design configuration is saved in the design variable vector $\mathbf{X}_1$.
  - 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 <u>standard normal</u> random number generator

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

      - ✓ 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 α=1 and β=0.2 for the truss design problems and α=1 and β=0.7 for the parameter estimation problems.
  - Go to the second step until converge