Updating Finite Element Models to Match Ground Vibration Test Data

Chan-gi Pak, Ph.D.

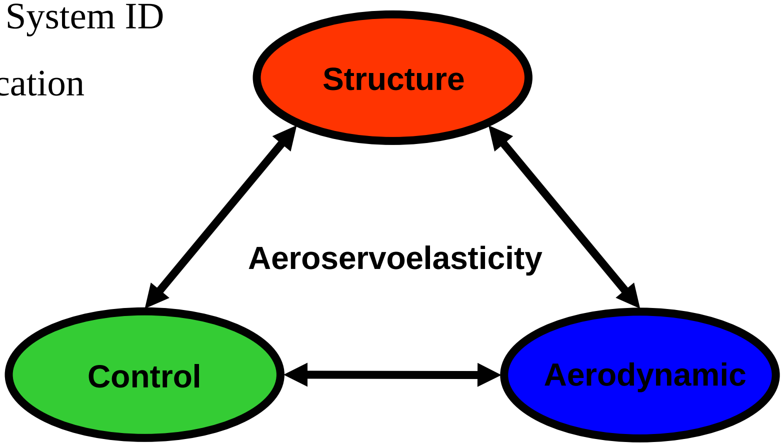
Leader, Structural Dynamics Group
Aerostructures Branch (Code RS)
NASA Dryden Flight Research Center

Structural Dynamics Group

- Functionality
  - Aeroelastic & Aeroservoelastic System Analysis, Clearance, Monitoring, & Research
- Skills
  - Structural Dynamic Finite Element Modeling, Analyses, & Tool Development
    - Use ProE, MSC/PATRAN, & MSC/NASTRAN codes for Structural Modeling & Analyses
    - In-house Tool Development for Structural Dynamic, Aeroelastic, & Aeroservoelastic Analyses
  - Ground Vibration Test and Finite Element Model Update
    - Improve Structural Dynamic FEM if needed
  - Aeroelastic and Aeroservoelastic Analyses
    - Flutter, Buzz, Divergence, and Closed-Loop Flutter Analyses
    - Subsonic and Supersonic Flight Regimes: Use Linear Lifting Surface Codes (ZAERO or MSC/NASTRAN)
    - Transonic Flight Regime: Use 3D CFD Codes (CFL3D version 4 or CAPTSDv etc.)
  - Structural Optimization with Stress/Strain and Flutter Constraints
    - Based on MSC/NASTRAN code

Structural Dynamics Group (continued)

- Skills (continued)
  - Structural Mode Interaction Test and Flight Control Model Update
    - Improve Flight Control Model if needed
  - Maneuver Load Alleviation and Control
    - Based on Minimization of the Maximum Bending Moment and/or Shear Force
  - Active Aeroelastic Control and Vibration Suppression
    - Based on Modern and Adaptive Control Techniques
  - Flight Flutter Testing & On-Line System Identification (Flutterometer)
    - Flutter Boundary Identification based on Flight Test Data
    - Linear and Nonlinear Robust Aeroservoelastic System ID
    - Time-frequency-scale (wavelet, HHT) Identification
  - Structural Health Monitoring
    - Use GVT & Mode Matching Technique
    - Linear/Nonlinear ID Methods



Introduction

- 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.

- MIL-STD-1540C Section 6.2.10
  - Test Requirements for Launch, Upper-Stage, & Space Vehicles
  - Less than 3% and 10% frequency errors for the primary and secondary modes, respectively
  - Less than 10% off-diagonal terms in mass matrix

- 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] and the analytical mass matrix [M] , the following operation is performed.

$$\Phi^T M \Phi$$

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.

Orthogonality Requirements for Structural Dynamics

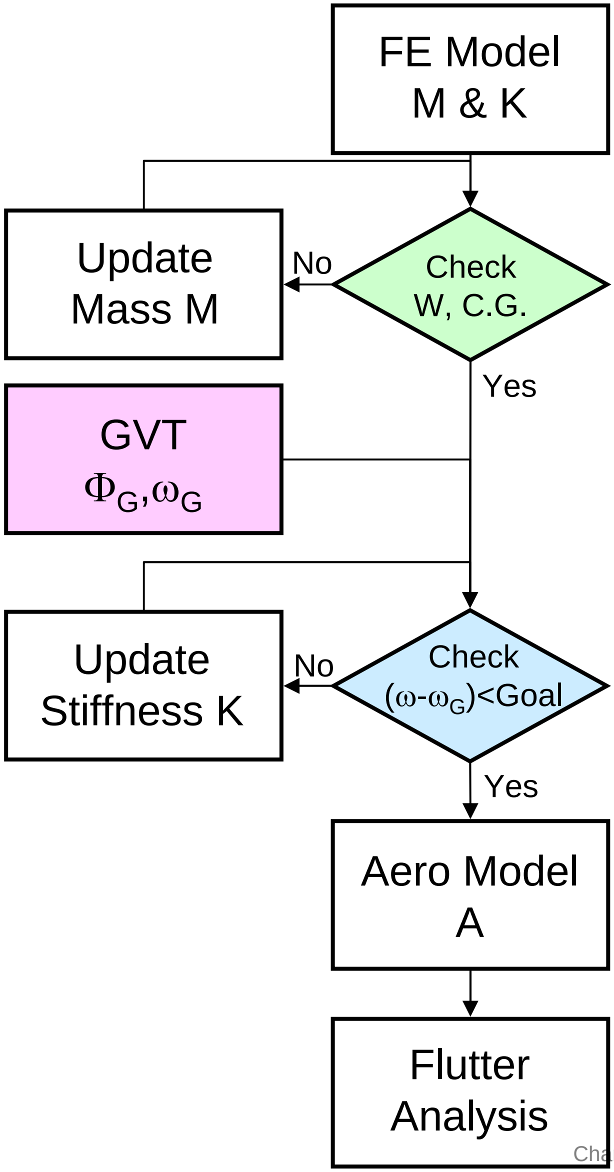
$$\Phi^{T} M \Phi = [I] \qquad \Phi^{T} K \Phi = [\omega^{2}]$$

M: Mass matrix
K: Stiffness matrix
Φ: Mode shaped (Eigen matrix)
ω: Frequencies (Eigen Values)

- ☐ Guarantee linear independency between mode shapes
- ☐ Superposition principle can be used for the aeroelastic and aeroservoelastic analyses

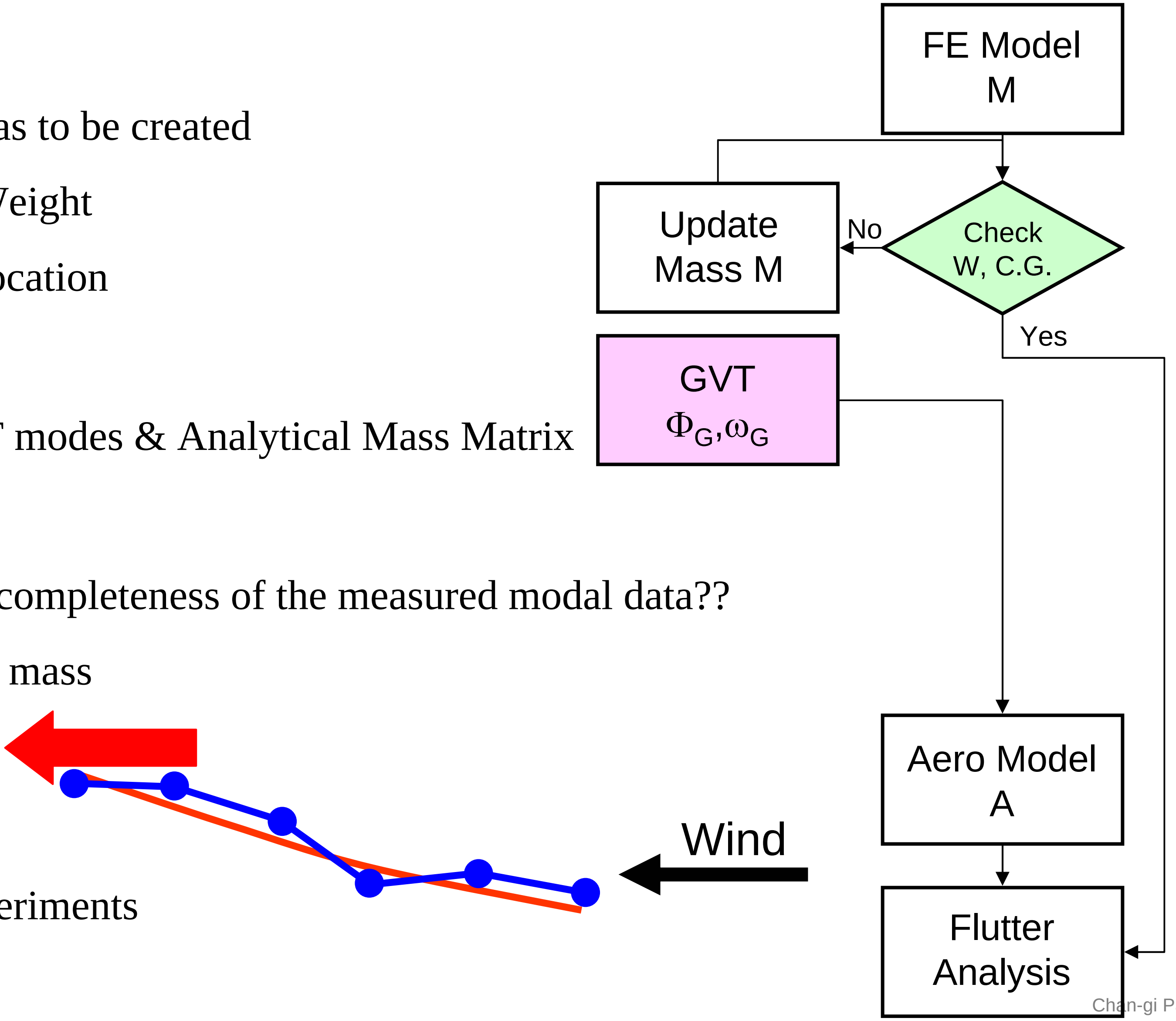
FEM Based Flutter Analysis: Approach #1

- Update Mass
  - Match Total Weight
  - Match C.G. Location
- Update Stiffness
  - Frequency difference
  - Goal=5% (Primary modes) ~ 10% (Secondary modes)
- Flutter Analysis
  - Based on analytical mass & modes
  - NOT based on GVT Mode Shapes
- Summarize
  - FEM updated manually
  - Best estimated mass
  - $\Phi_G^T M \Phi_G \neq [I]$
- Applications
  - F-18 SRA, AAW, ATW, & B-52B



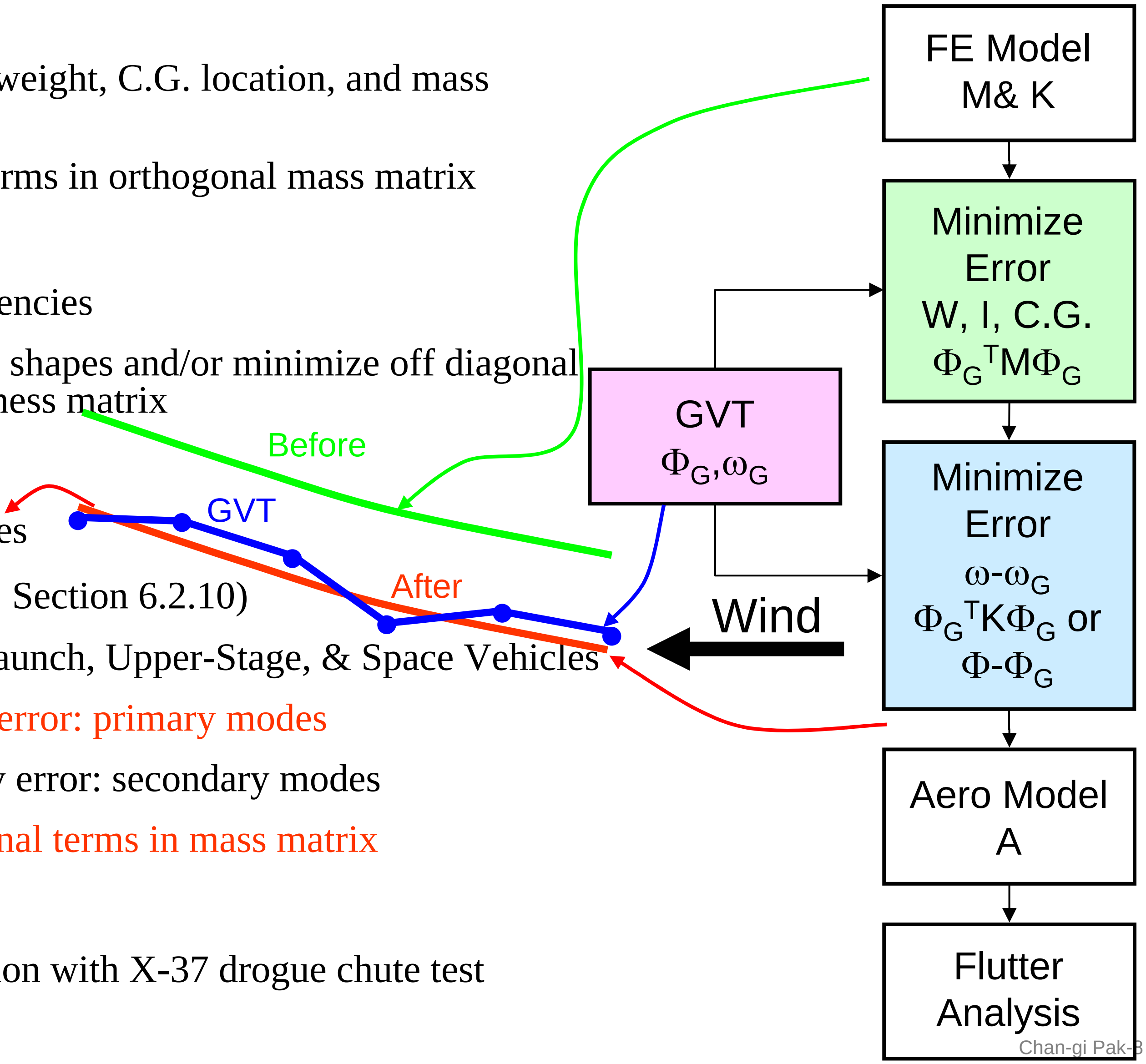
GVT Based Flutter Analysis: Approach #2

- ☐ Update Mass
  - ❖ Mass Model has to be created
  - ❖ Match Total Weight
  - ❖ Match C.G. Location
- ☐ Flutter Analysis
  - ❖ Based on GVT modes & Analytical Mass Matrix
- ☐ Summarize
  - ❖ Accuracy and completeness of the measured modal data??
  - ❖ Best estimated mass
  - ❖ $\Phi_G^T M \Phi_G \neq [I]$
- ☐ Applications
  - ❖ All F-15B experiments



Updated FEM Based Flutter Analysis: New Approach

- ❑ Update Mass
  - ❖ Minimize errors in total weight, C.G. location, and mass moment of inertia
  - ❖ Minimize off diagonal terms in orthogonal mass matrix
- ❑ Update Stiffness
  - ❖ Minimize errors in frequencies
  - ❖ Minimize errors in mode shapes and/or minimize off diagonal terms in orthogonal stiffness matrix
- ❑ Flutter Analysis
  - ❖ Based on analytical modes
- ❑ Discussion (MIL-STD-1540C Section 6.2.10)
  - ❖ Test Requirements for Launch, Upper-Stage, & Space Vehicles
  - ❖ Less than 3% frequency error: primary modes
  - ❖ Less than 10% frequency error: secondary modes
  - ❖ Less than 10% off-diagonal terms in mass matrix
- ❑ Applications
  - ❖ X-43A Stack, B-52H Pylon with X-37 drogue chute test fixture, & X-37 ALTV



FE Model
M& K

Minimize
Error
W, I, C.G.
$\Phi_G^T M \Phi_G$

GVT
Φ_G, ω_G

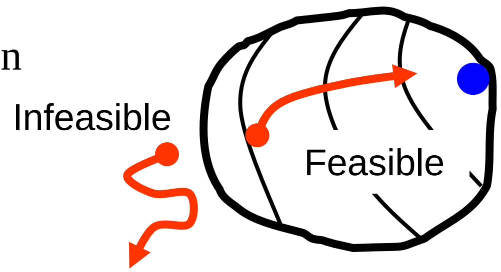
Minimize
Error
$\omega - \omega_G$
$\Phi_G^T K \Phi_G$ or
$\Phi - \Phi_G$

Aero Model
A

Flutter
Analysis

Model Update Technique

- ☐ Step 1: Mass Properties
  - To start optimization procedure inside the feasible domain
  - Match Total Mass
  - Match CG Locations
  - Match Mass Moment of Inertias



Statement Number	Objective Function	Constraints
1	$J_1 = W - W_G$	Unconstraint
2	$J_2 = X - X_G$	$\lvert J_1 \rvert < \varepsilon$
3	$J_3 = Y - Y_G$	$\lvert J_i \rvert < \varepsilon \quad i=1,2$
4	$J_4 = Z - Z_G$	$\lvert J_i \rvert < \varepsilon \quad i=1, \ldots 3$
5	$J_5 = I_{XX} - (I_{XX})_G$	$\lvert J_i \rvert < \varepsilon \quad i=1, \ldots 4$
6	$J_6 = I_{YY} - (I_{YY})_G$	$\lvert J_i \rvert < \varepsilon \quad i=1, \ldots 5$
7	$J_7 = I_{ZZ} - (I_{ZZ})_G$	$\lvert J_i \rvert < \varepsilon \quad i=1, \ldots 6$
8	$J_8 = I_{XY} - (I_{XY})_G$	$\lvert J_i \rvert < \varepsilon \quad i=1, \ldots 7$
9	$J_9 = I_{YZ} - (I_{YZ})_G$	$\lvert J_i \rvert < \varepsilon \quad i=1, \ldots 8$
10	$J_{10} = I_{ZX} - (I_{ZX})_G$	$\lvert J_i \rvert < \varepsilon \quad i=1, \ldots 9$

Model Update Technique (Continued)

- Step 2: Improve Mass Matrix
  - Orthonormalized Mass Matrix: $\underline{\mathbf{M}} = \mathbf{\Phi}^T \mathbf{M}\, \mathbf{\Phi}$
  - Minimize J

$$J \equiv \sum_{i=1,\, j=1,\, i \neq j}^{n} \underline{M}_{ij}$$

Such that,

- $|W-W_G| < \varepsilon$: Total Mass
- $|X-X_G| < \varepsilon$, $|Y-Y_G| < \varepsilon$, & $|Z-Z_G| < \varepsilon$: CG Locations
- $|I_{XX}-(I_{XX})_G| < \varepsilon$, $|I_{YY}-(I_{YY})_G| < \varepsilon$, $|I_{ZZ}-(I_{ZZ})_G| < \varepsilon$, $|I_{XY}-(I_{XY})_G| < \varepsilon$, $|I_{YZ}-(I_{YZ})_G| < \varepsilon$, $|I_{ZX}-(I_{ZX})_G| < \varepsilon$: Mass Moment of Inertia at CG
- Positive Definiteness of Lumped Masses

Model Update Technique (continued)

- Step 3: Frequencies and Mode Shapes
  - Option 1: Minimize Errors in Frequencies and off-diagonal terms in $\underline{\mathbf{K}}$
    - Orthonormalized Stiffness Matrix: $\underline{\mathbf{K}} = \mathbf{\Phi}^T \mathbf{K} \mathbf{\Phi}$
    - Minimize J

$$J \equiv \sum_{i=1}^{n} \left| \frac{\Omega_i^2 - \underline{K}_{ii} \big/ \underline{M}_{ii}}{\Omega_i^2} \right| + \beta \sum_{i=1,\, j=1,\, i \neq j}^{n} \underline{K}_{ij}$$

  - Option 2: Minimize Errors in Frequencies and Mode Shapes
    - Eigen-Solver is based on
      - Subspace Iteration Method
      - Simplified Approach
    - Minimize J

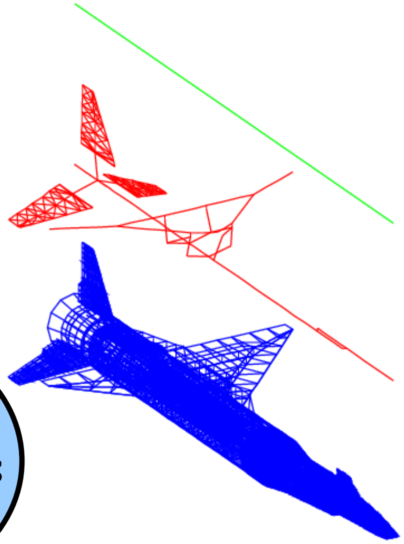
$$J \equiv \sum_{i=1}^{n} \left| \frac{\Omega_i^2 - \underline{K}_{ii} \big/ \underline{M}_{ii}}{\Omega_i^2} \right| + \beta \sum_{j=1}^{m} \left(\Phi_j - \Phi_{jG} \right)$$

where, i=1,..,n j=1,…,m n: number of modes m: number of sensors

Application of Mode Matching Technique: Type 1

☐ Generation of a Reduced Order Finite Element Model

- ❖ More Accurate than a Simple Beam Model
- ❖ More Efficient than Detailed FEM
- ❖ Maintain Accuracy of Detailed FEM
- ❖ Match Analytical Modes Obtained from Detailed and Reduced Order FEMs



FE Model

Target Modes

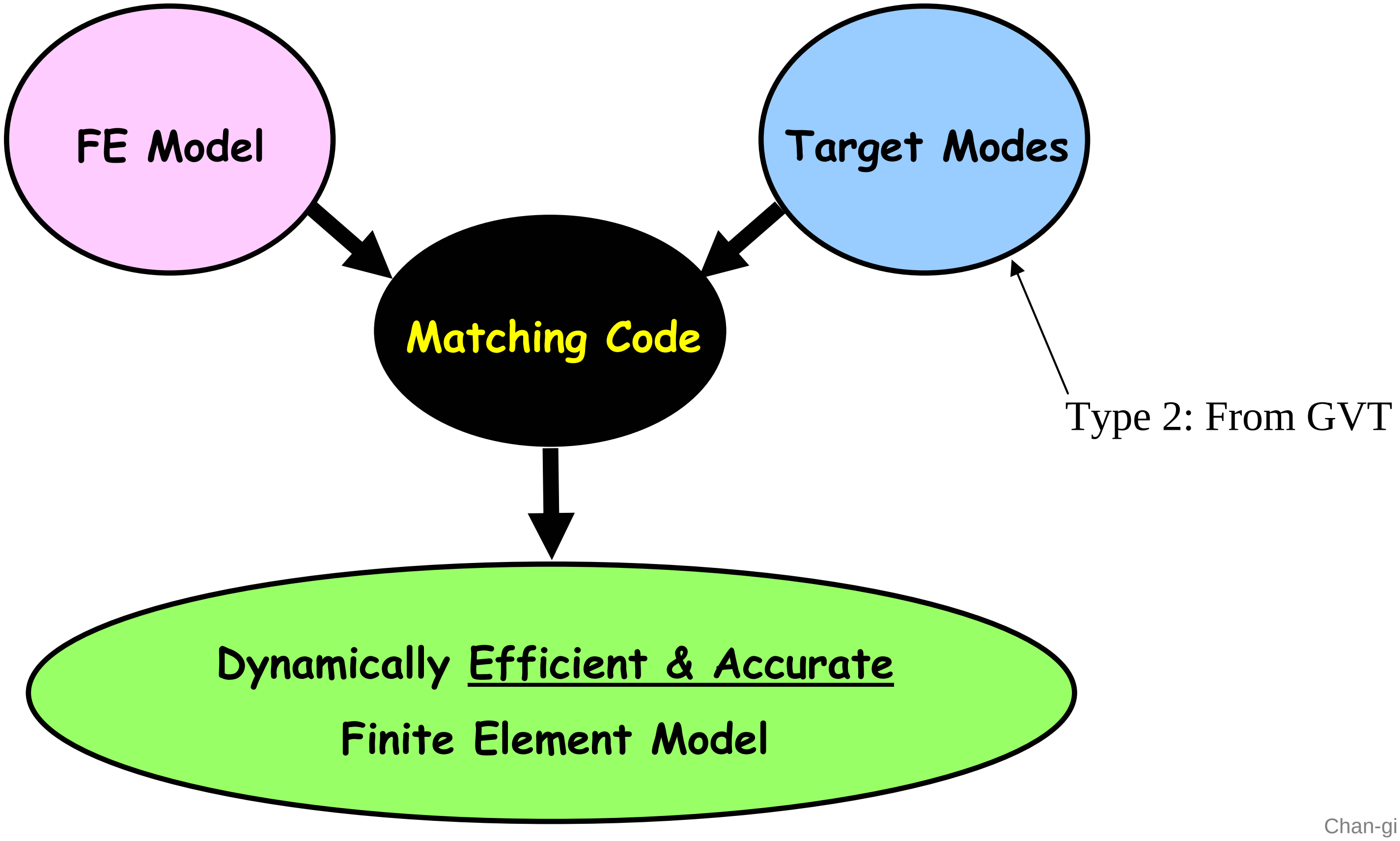
Type 1: From Detailed FEM

Matching Code

Dynamically <u>Efficient & Accurate</u>
Finite Element Model

Application of Mode Matching Technique: Type 2

- Finite Element Model Update using GVT Data
  - Minimize the structural modeling error in aeroelastic and/or aeroservoelastic stability analyses.



FE Model

Target Modes

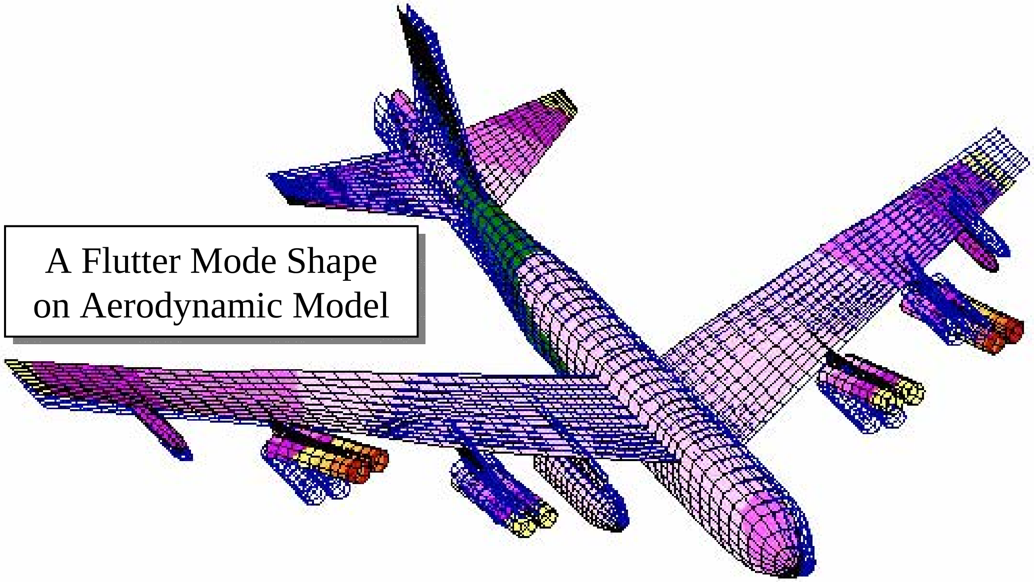
Matching Code

Type 2: From GVT

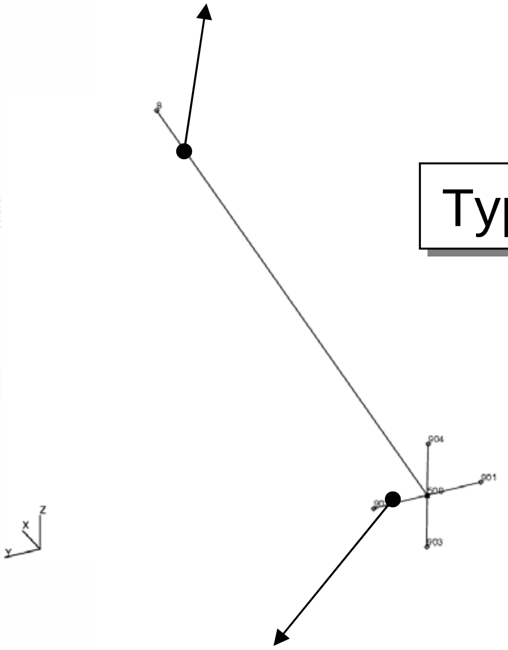
Dynamically <u>Efficient & Accurate</u>
Finite Element Model

Case 1: B-52H Engine Modeling using GVT Data

- ☐ Half aircraft model from Boeing Wichita
- ☐ Make tip-to-tip model
- ☐ Use B-52B Engine Properties as an initial B-52H Engine Properties
  - ❖ GVT data for B-52H engines
- ☐ I_1, I_2, and J: Design Variables



A Flutter Mode Shape on Aerodynamic Model



Single Beam Engine Model

Type 2

Rigid Bars For Mode Visualization

Case 1: Results

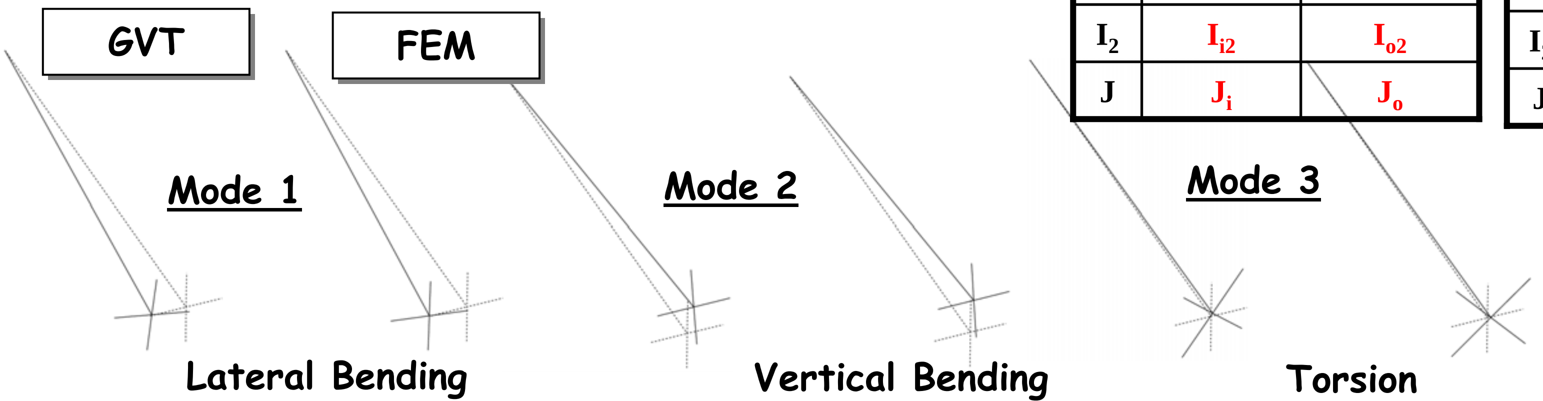
Mode	Inboard Engine (Hz)		Outboard Engine (Hz)	
	Initial FEM	Final FEM	Initial FEM	Final FEM
1	-8.3%	0%	-7.6%	0%
2	-14%	-.02%	-6.2%	-.03%
3	-3.7%	0%	-4.7%	-.02%

Initial Beam Properties

	Inboard Engine	Outboard Engine
E	E_i	E_o
ν	ν_i	ν_o
A	A_i	A_o
I_1	I_{i1}	I_{o1}
I_2	I_{i2}	I_{o2}
J	J_i	J_o

Updated Beam Properties

	Inboard Engine	Outboard Engine
E	E_i	E_o
ν	ν_i	ν_o
A	A_i	A_o
I_1	1.34 I_{i1}	1.14 I_{o1}
I_2	1.19 I_{i2}	1.17 I_{o2}
J	1.16 J_i	1.18 J_o



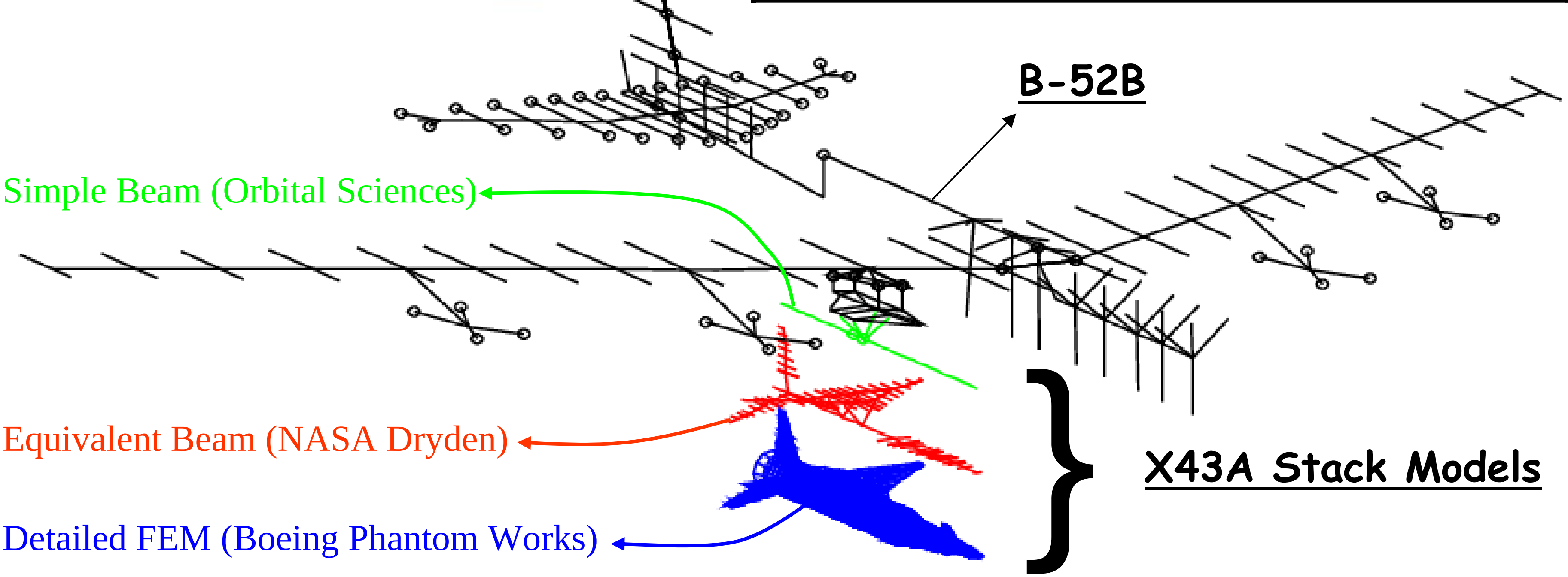
Mode	Inboard Engine (MAC*)			Outboard Engine (MAC*)		
	Initial FEM	Final FEM	GVT	Initial FEM	Final FEM	GVT
1	98.95	98.98	100	97.79	97.92	100
2	96.37	98.30	100	97.99	99.33	100
3	92.22	89.16	100	88.77	82.71	100

✶ **MAC: Modal Assurance Criteria**

Case 2: X-43A Stack Equivalent Beam Model

Type 1

		Number of Nodes
B-52B		375
X-43A Stack	Simple Beam	69
	Equivalent Beam	107
	Detailed FEM	31338



B-52B

Simple Beam (Orbital Sciences)

Equivalent Beam (NASA Dryden)

Detailed FEM (Boeing Phantom Works)

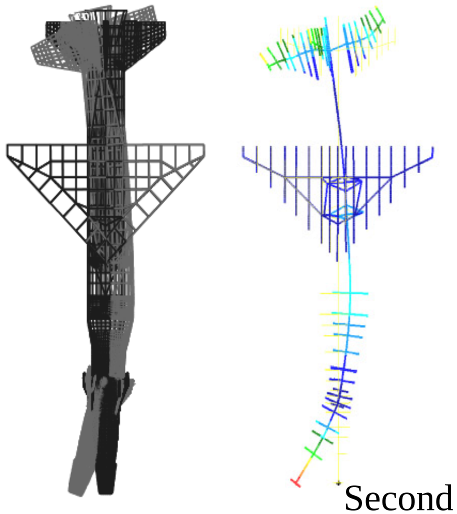
X43A Stack Models

Case 2: Results

Frequencies (Hz)

Mode	**Simple Beam**	**Equivalent Beam**	**Detailed FEM**
1	31%	-.09%(99.3)	f_1
2	83%	-.02%(89.6)	f_2
3	168%	2%(94.8)	f_3
4	200%	1%(91.1)	f_4
5	159%	-1.1%(82.1)	f_5

(*): MAC Value

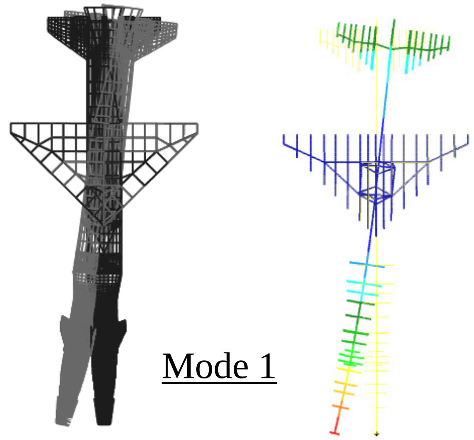


Mode 5

Second Lateral Bending

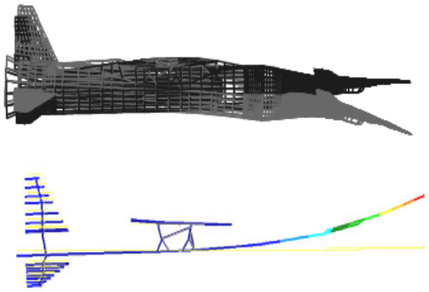
Detail

Equivalent



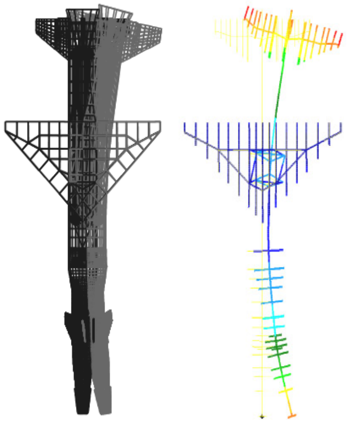
Mode 1

Yawing



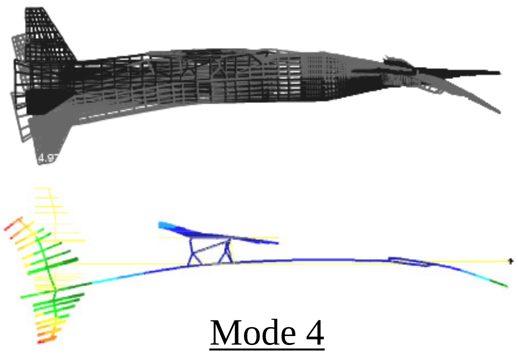
Mode 2

Pitching



Mode 3

Lateral Bending

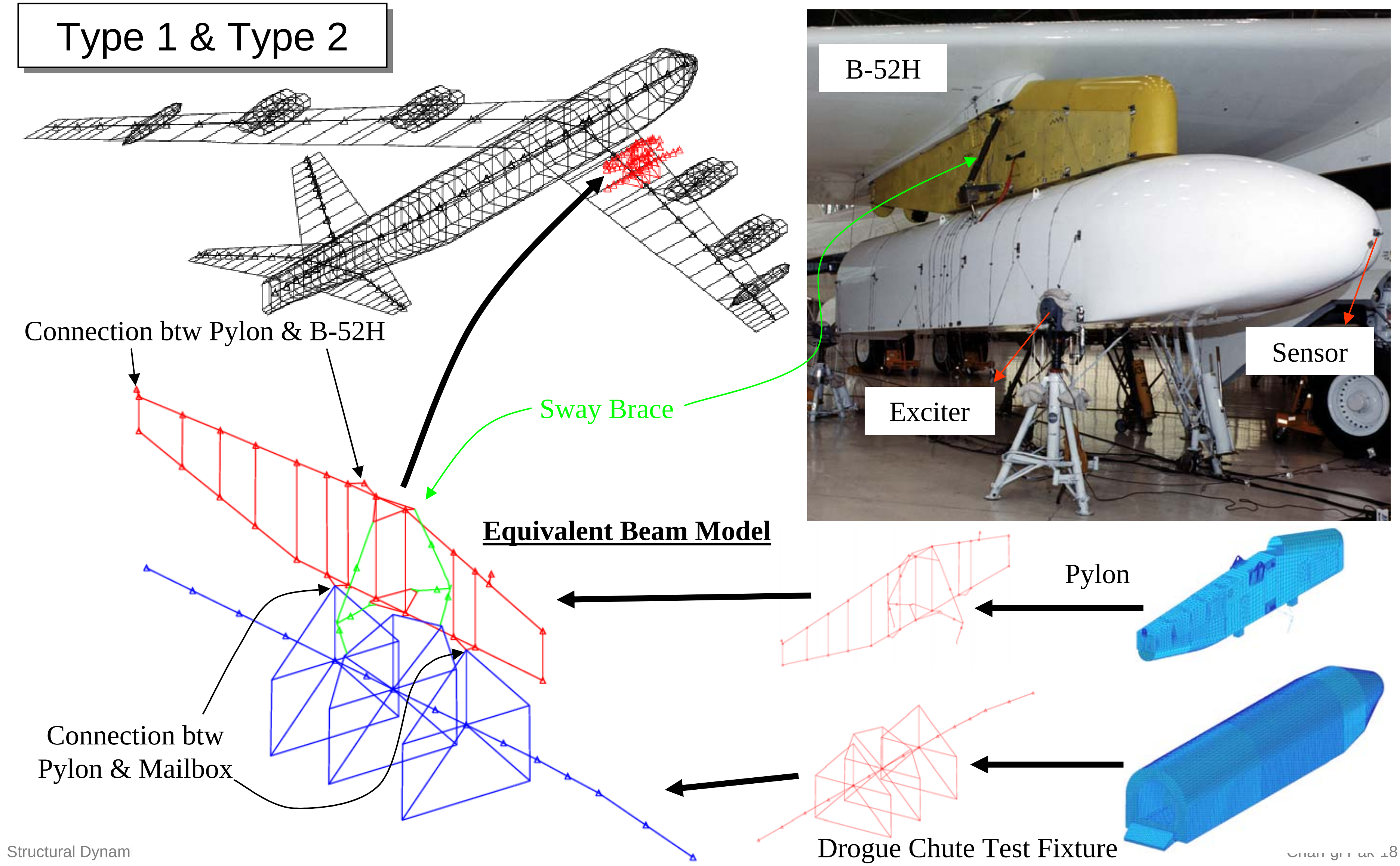


Mode 4

Vertical Bending

Case 3: B-52H Pylon + X-37 DCTF Model Update using GVT Data

Type 1 & Type 2



Case 3: Results

Mode	Equivalent Beam (% error)		MAC	GVT
	Guyan Reduction	Full Order		
1	-.04%	-.08%	94.4	f_1
2	-.01%	-.03%	84.7	f_2
3	-.01%	-.03%	50.6	f_3
4	-.05%	-4.1%	82.3	f_4

(*): MAC Value

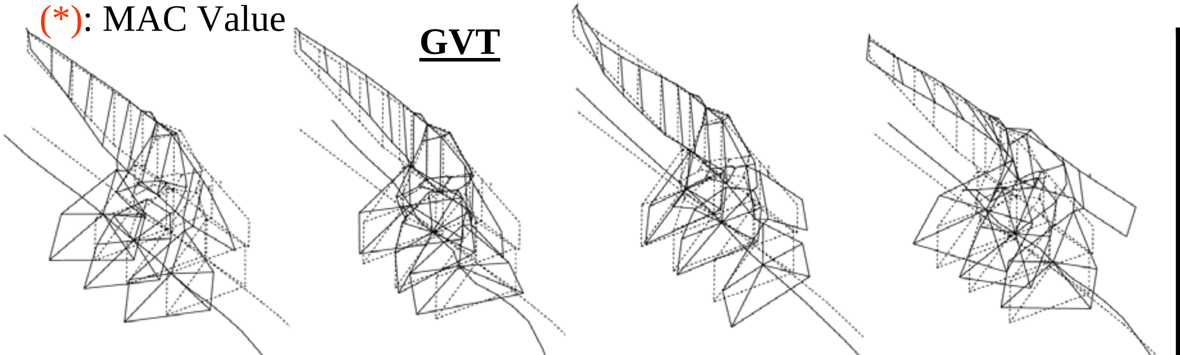
Generalized Mass

1	1%	-2%	-8%
.011	1	-6%	5%
-.016	-.063	1	2%
-.076	.046	.020	1

Generalized Stiffness

1	2%	-2%	1%
.022	1	-8%	-1%
-.017	-.075	1	0%
-.005	-.010	-.001	1

GVT

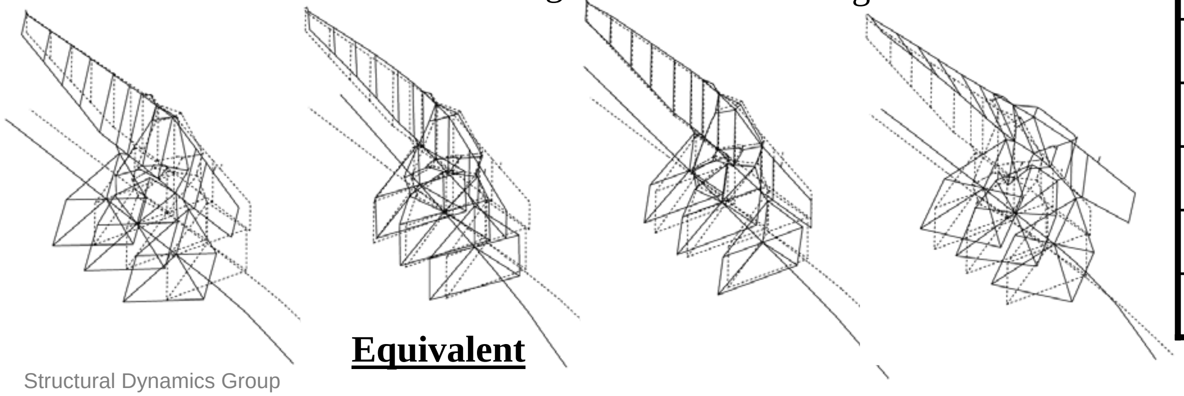


Mode 1 — 1st Pendulum

Mode 2 — Mailbox Yawing

Mode 3 — Mailbox Pitching

Mode 4 — 2nd Pendulum



Equivalent

	Detailed FEM	Equiv. Beam	Error
Weight	-	-	-.10%
X_{CG}	Measured	-	.07%
Y_{CG}		-	-.01%
Z_{CG}	-	-	.18%
I_{XX}	-	-	.21%
I_{YX}	-	-	-.20%
I_{YY}	Computed	-	-.19%
I_{ZX}		-	-.11%
I_{ZY}	-	-	.15%
I_{ZZ}	-	-	-.16%

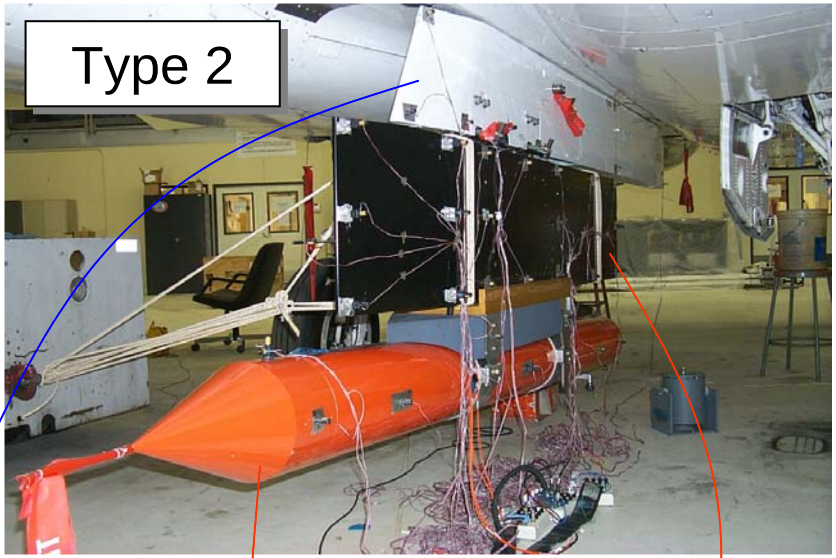
Case 4: F-15B Cone Drag Experiment

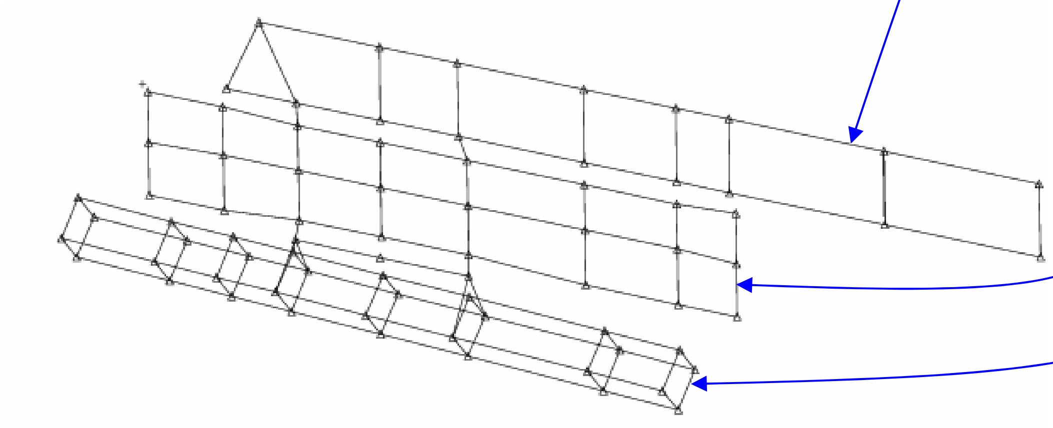
Task Statements

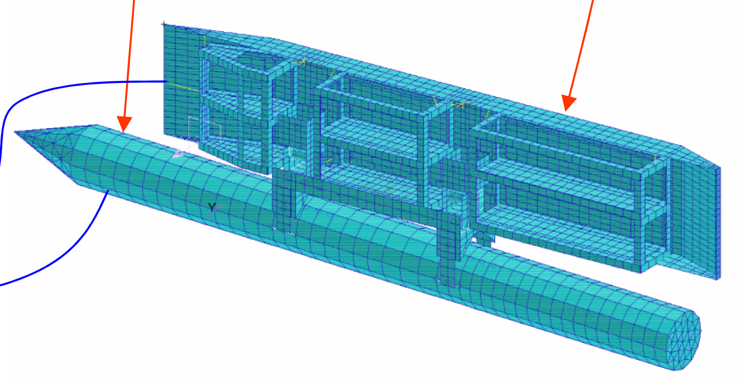
- Compare Flutter Boundaries from Previous and New Methodologies for the Flutter Analysis

Approaches

- Previous Flutter Analysis: Approach #2
  - Frequencies & Mode Shapes: From GVT
  - Mass Matrix: Best Guess Mass Distribution
- New Flutter Analysis
  - Frequencies & Mode Shapes: From Equivalent Beam
    - Equivalent Beam is obtained from GVT Mode Matching Technique
  - Mass Matrix: Orthogonal to GVT mode shapes







Case 4: Results

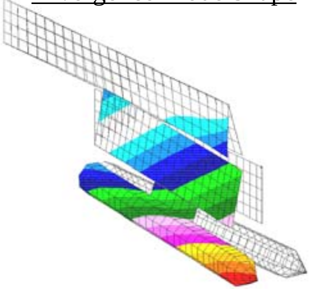
Mode	Equivalent Beam	GVT
1	-4.65%(98.7)	f_1
2	1.30%(93.5)	f_2
3	2.86%(85.9)	f_3
4	-1.00%(92.9)	f_4

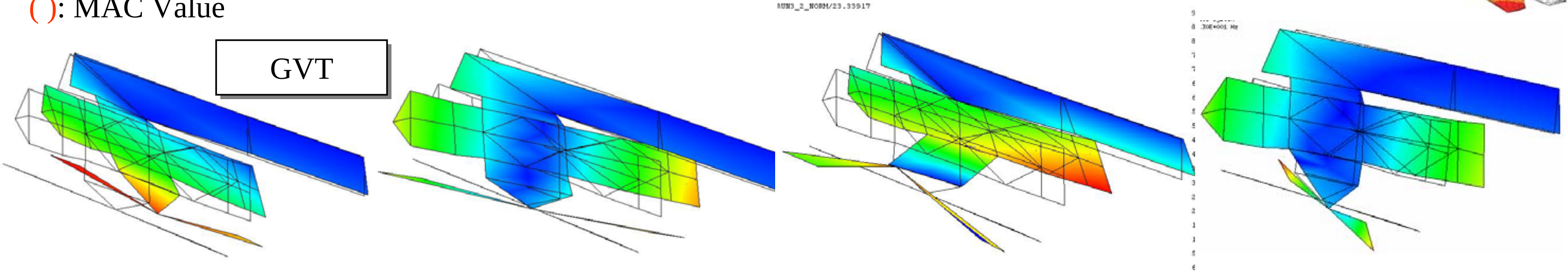
( ): MAC Value

Mach #	Approach #2	New Approach	% Diff.
0.9	-		-17.7
1.2	-	-	-18.0
1.6		-	-17.3
2.0		-	-16.0

Divergence Speed

Divergence Mode Shape



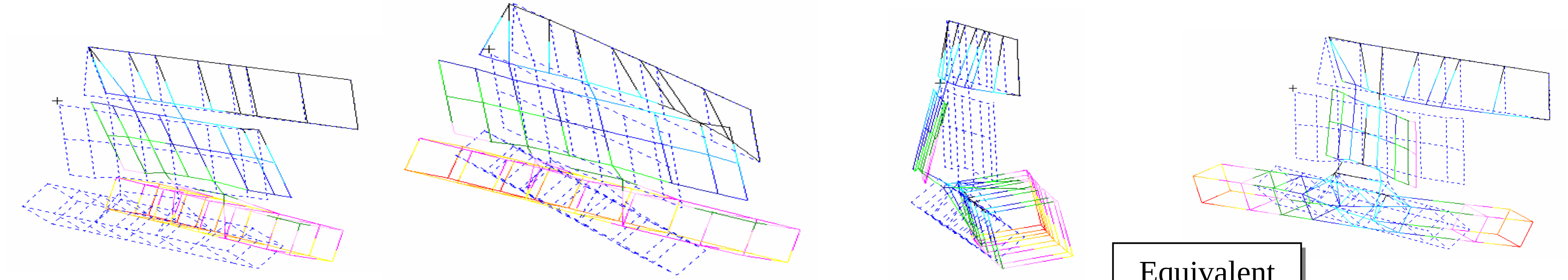


Mode 1
1st Bending

Mode 2
1st Torsion

Mode 3
2nd Bending

Mode 4
2nd Torsion

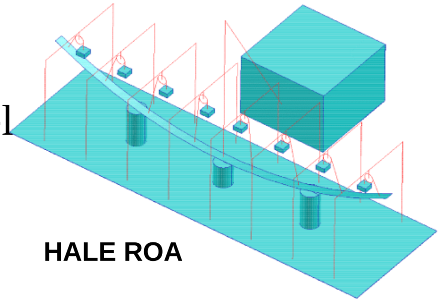


Equivalent

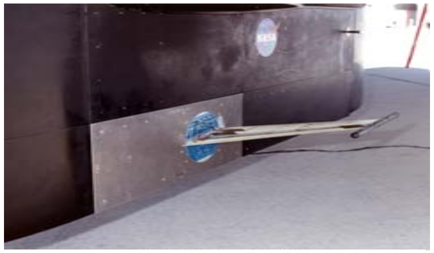
Structural Dynamic Research Activities at NASA Dryden Flight Research Center

Project Supports & Researches (FY05 - Present)

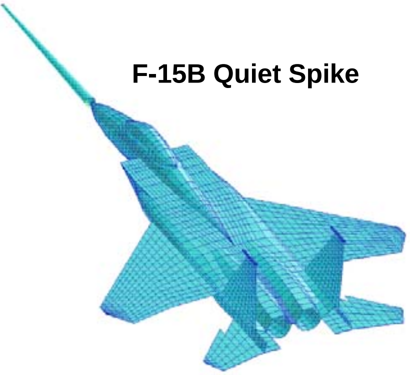
- ☐ High Altitude Long Endurance Remotely Operated Aircraft
  - ❖ Create and Update Beam Equivalent Model for a High Aspect Ratio Wing
  - ❖ Develop New GVT Methodology
  - ❖ Preparing Structural Dynamics R&D Proposals for Modeling/Simulation/Control
- ☐ F-15B Quiet Spike Boom
  - ❖ Update F-15B & Quite Spike Boom Models for the Open-Loop Flutter Clearance
- ☐ F-15B LIFT
  - ❖ For Space Shuttle Return to Flight
  - ❖ Flutter Clearance
- ☐ ATW2
  - ❖ Flutter Clearance and Sensor Research
- ☐ AAW
  - ❖ ASE Flight Research
- ☐ F-15 IFCS
  - ❖ ASE Clearance with Adaptive Controller



HALE ROA

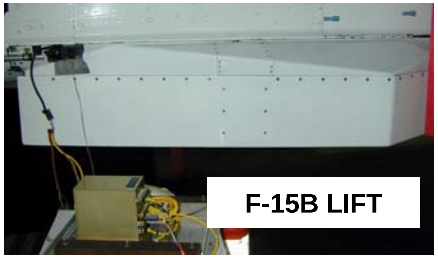


ATW2



F-15B Quiet Spike

AAW



F-15B LIFT

F-15 IFCS

Project Supports & Researches (FY02 - FY04)

- Helios Mishap Investigation
  - Structural Dynamic & Flutter Analyses
- X-43A Ship1
  - Independent Mishap Investigation
  - Closed-Loop Flutter Analysis
- X-43A Ship2 & Ship3
  - B-52B Captive Carry Flutter Clearance
- X-37 ALTV, Pylon, and DCF
  - B-52H Captive Carry Flutter Clearance
- ALTAIR (UAV)
  - Structural Dynamic & Flutter Analyses
- F-15B CDE
  - Flutter Clearance
- ATW1
  - Flutterometer Research
- X-45A (UCAV)
  - GVT


Helios


X-43A Ship 1


X-43A Ship 2 & 3


X-37 ALTV, Pylon, & DCF


ALTAIR


F-15B CDE


ATW1


X-45A