Multidisciplinary Design, Analysis, and Optimization Tools Developed at NASA Armstrong Flight Research Center

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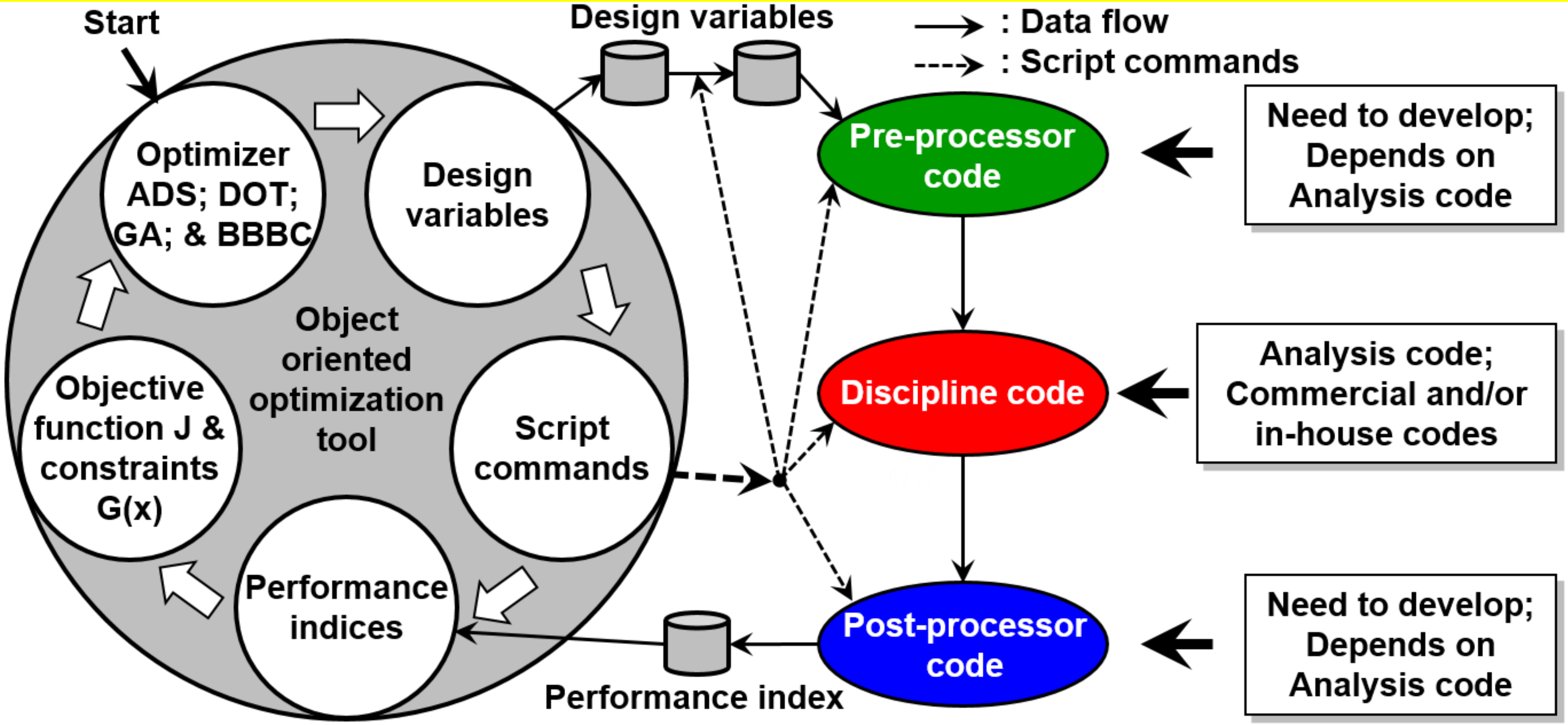
Multidisciplinary Design Optimization

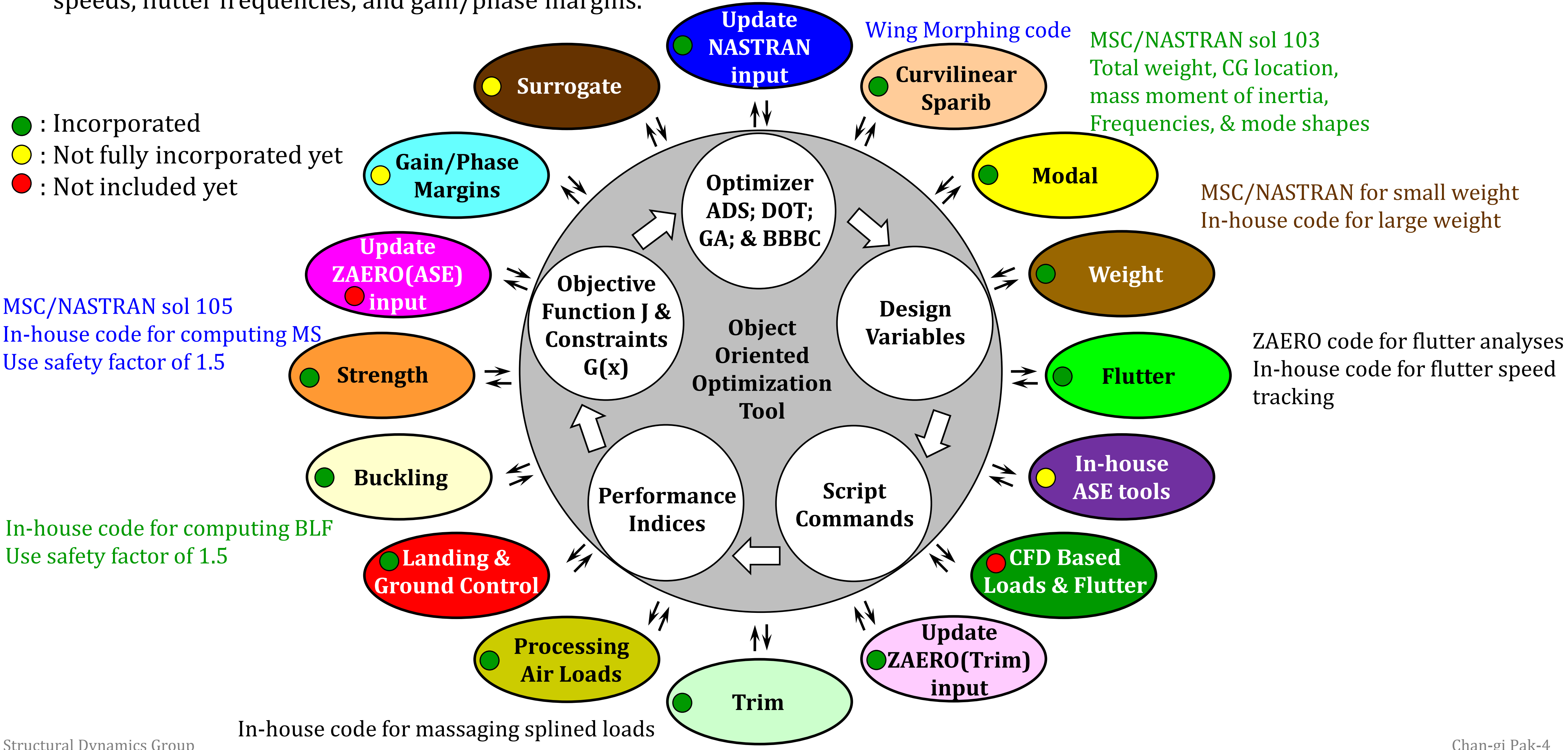
Object-Oriented Optimization Tool

- The object-oriented optimization (O^3) tool is compatible tool with Open MDAO, Model Center, Visual Doc, etc.
  - O^3 tool leverages existing tools and practices, and allows the easy integration and adoption of new state-of-the-art software.
- Interface variables between O^3 tool and discipline modules are design variables and performance index values.
- Detailed instructions for preparing input data cards, DESVAR, DOPTPRM and INDEX, for executing the O^3 tool are explained in the following references.
  - Pak, C.-g.,"Preliminary Development of an Object-Oriented Optimization Tool," NASA/TM-2011-216419.
  - Pak, C.-g. and Truong, S.S., "Extension of an Object-Oriented Optimization Tool: User's Reference Manual," NASA/TM-2015-218733.



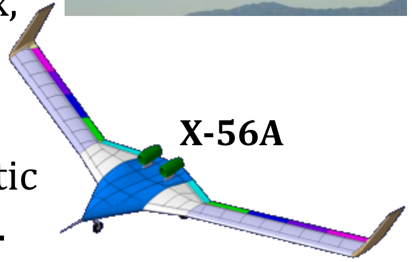
Multidisciplinary Design Optimization tool

- Performs structural optimization with constraints about static margin of safety, buckling load factor, natural frequencies, flutter speeds, flutter frequencies, and gain/phase margins.

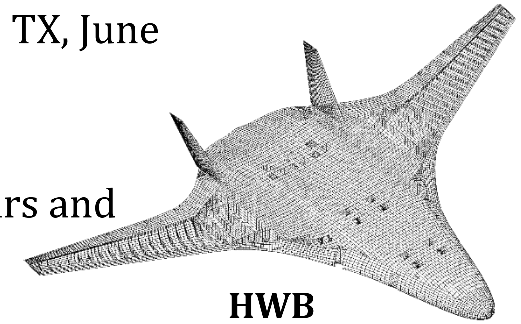


Applications of in-house MDO tool

- Approximate unsteady aerodynamics
  - Pak, C.-g. and Li, W., “Application of Approximate Unsteady Aerodynamics for Flutter Analysis,” AIAA 2010-3085, 51st AIAA/ASME/ASCE/AHS /ASC Structures, Structural Dynamics, and Materials Conference, Orlando, Fl, April 12-15, 2010.
  - Li, W. and Pak, C.-g., “Basis Function Approximation of Transonic Aerodynamic Influence Coefficient Matrix,” 27th International Congress of the Aeronautical Sciences, Nice, France, Sept. 19-24, 2010.
- Ikhana aircraft
  - Pak, C.-g. and Li, W., “Multidisciplinary Design, Analysis, and Optimization Tool Development Using a Genetic Algorithm,” 26th International Congress of the Aeronautical Sciences, Anchorage, Alaska, Sept. 14-19, 2008.
- X-56A aircraft
  - Li, W. and Pak, C.-g., “Aeroelastic optimization study based on X-56A aircraft,” AIAA 2014-2052, AIAA Atmospheric Flight Mechanics Conference, Atlanta, GA, June 16-20, 2014.
  - Li, W. and Pak, C.-g., “Mass Balancing Optimization Study to Reduce Flutter Speeds of the X-56A Aircraft,” *Journal of Aircraft*, Vol. 52, No. 4, 2015, pp. 1359-1365 doi: http://arc.aiaa.org/doi/abs/10.2514/1.C033044
- Supersonic aircraft
  - Pak, C.-g., “Aeroelastic Tailoring Study of an N+2 Low-boom Supersonic Commercial Transport Aircraft,” AIAA 2015-2791, 16th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, Dallas, TX, June 22-26, 2015.
- Hybrid Wing Body aircraft
  - Li, W. and Pak, C.-g., “Aeroelastic Optimization of a Hybrid Wing Body Aircraft using Curvilinear Spars and Ribs,” Abstract submitted for AIAA SciTech, January, 2017.


X-56A


N+2 LSCT


HWB

On going milestones in MDO area

- Develop MSC/NASTRAN and ZAERO based **sensitivity analysis routines** and incorporate these modules into the current in-house MDO tool.
- Demonstration of in-house MDAO tool for aeroelastically tailored aircraft design with **curvilinear spars and ribs**
  - Using a HWB as a optimum design demonstration
- Develop Object-Oriented Optimization (O^3) based MDAO tool with **surrogate modeling capability**
  - Surrogate code was tested, but incorporating code into in-house MDO code was not completed.
- Demonstrate Object-Oriented Optimization (O^3) based MDAO tool for the design of an **aeroservoelastically tailored** aircraft design
  - Demonstrate the MDO tool using HWB with Turbo-electric Distributed Propulsion system
  - Incorporating analytical sensitivity analysis using MSC/NASTRAN and ZAERO codes
- Develop Object-Oriented Optimization (O^3) based MDAO tool with **CFD-based AIC** capability
- Develop an efficient **frequency domain Aeroservoelastic analysis code** and incorporate into in-house MDO tool
  - Use new efficient aerodynamic code using **unstructured** as well as structured panels

MultiDisciplinary Analysis

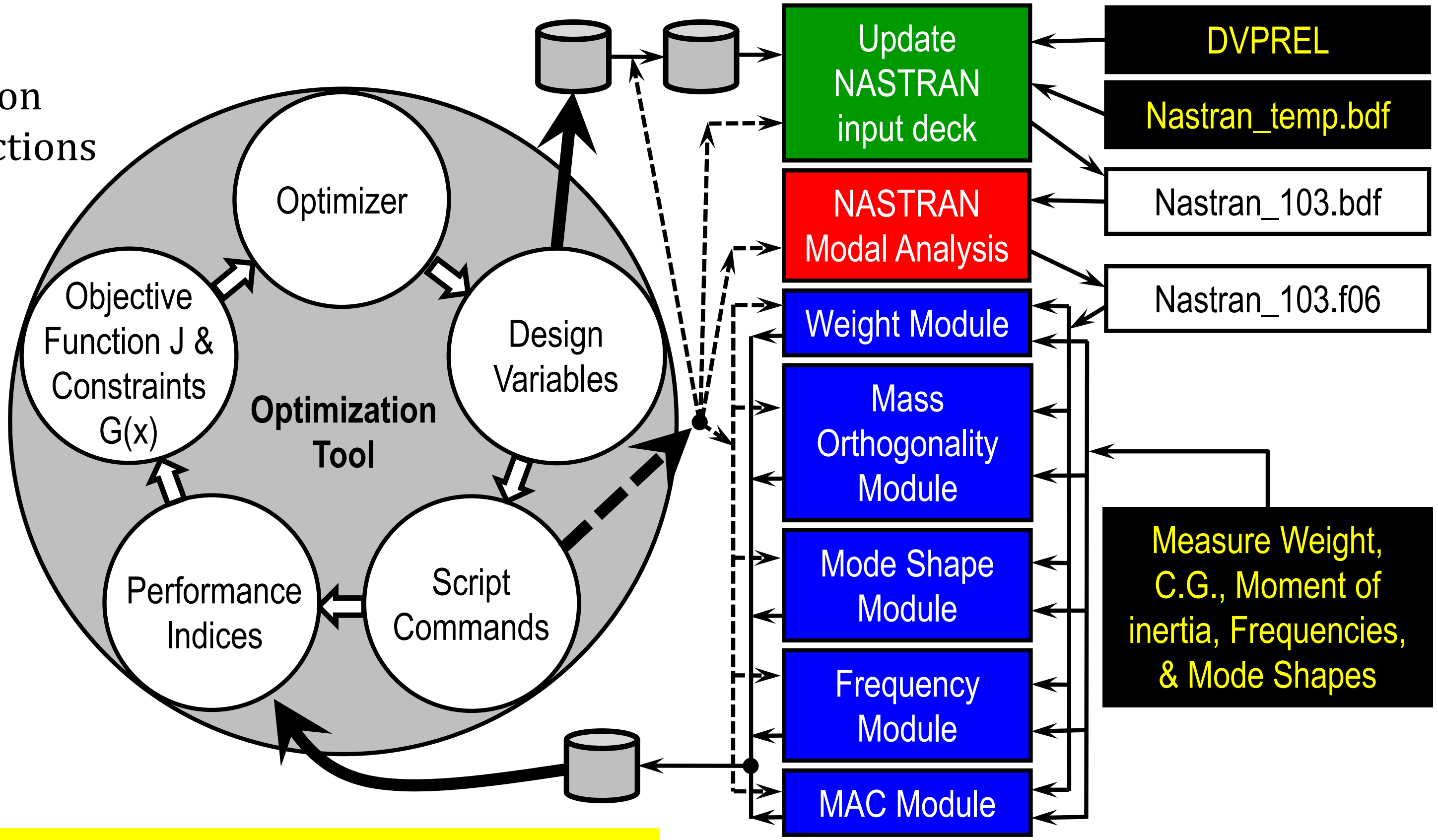
Structural dynamic model tuning tool

Capability

- This tool is used for validation of a structural dynamic finite element model (based on MSC/NASTRAN model) with respect to test data, such as total weight, x & y CG locations, moment of inertia, frequencies, and mode shapes.

Technical Background

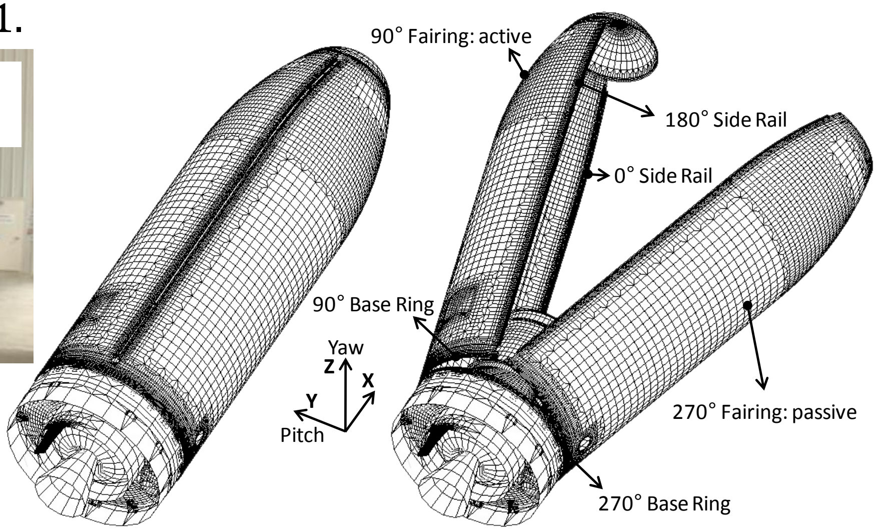
- Optimization Problem Statements
  - Minimize $J = \sum_i w_i J_i$ Such that $J_k \le \varepsilon_k$
    - J : Objective function
    - w_i: Weighting factor for the performance index i
    - J_i: Performance index i selected for objective function
    - J_k: Performance index k selected for constraint functions
    - e_k: Small tolerance value for performance index k



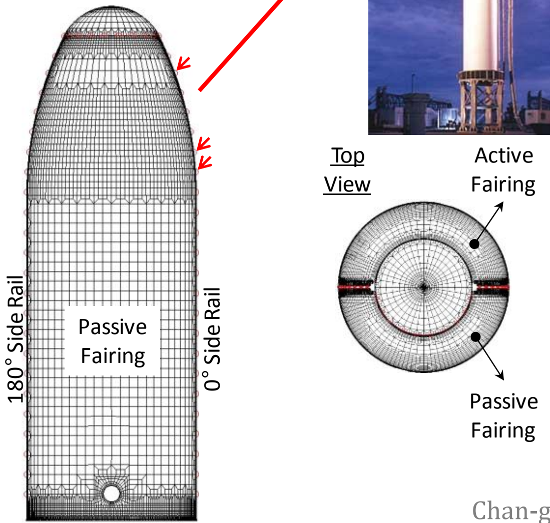
A proven technique can improve the quality of a structural dynamic model.

Applications of in-house structural dynamic model tuning tool

- Quiet Spike Boom
  - Herrera, C. and Pak, C.-g., "Build-up Approach to Updating the Mock Quiet Spike™ Beam Model," AIAA 2007-1776, 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Honolulu, Hawaii, April 23-26, 2007.
- X-37 Drogue Chute Test Fixture
  - Pak, C.-g., "Finite Element Model Tuning Using Measured Mass Properties and Ground Vibration Test Data," *ASME Journal of Vibration and Acoustics*, Vol. 131, No. 1, Feb. 2009. doi: 10.1115/1.2981092.
- Glory Mishap Investigation: Use "Topology Optimization"
  - Pak, C.-g., Peck, J., and Schultz, K., "Dynamic Modeling and Analysis Report: Appendix F.2," Taurus XL T9 Mishap Investigation Report, NASA IRIS Case No. S-2011-063-00001.



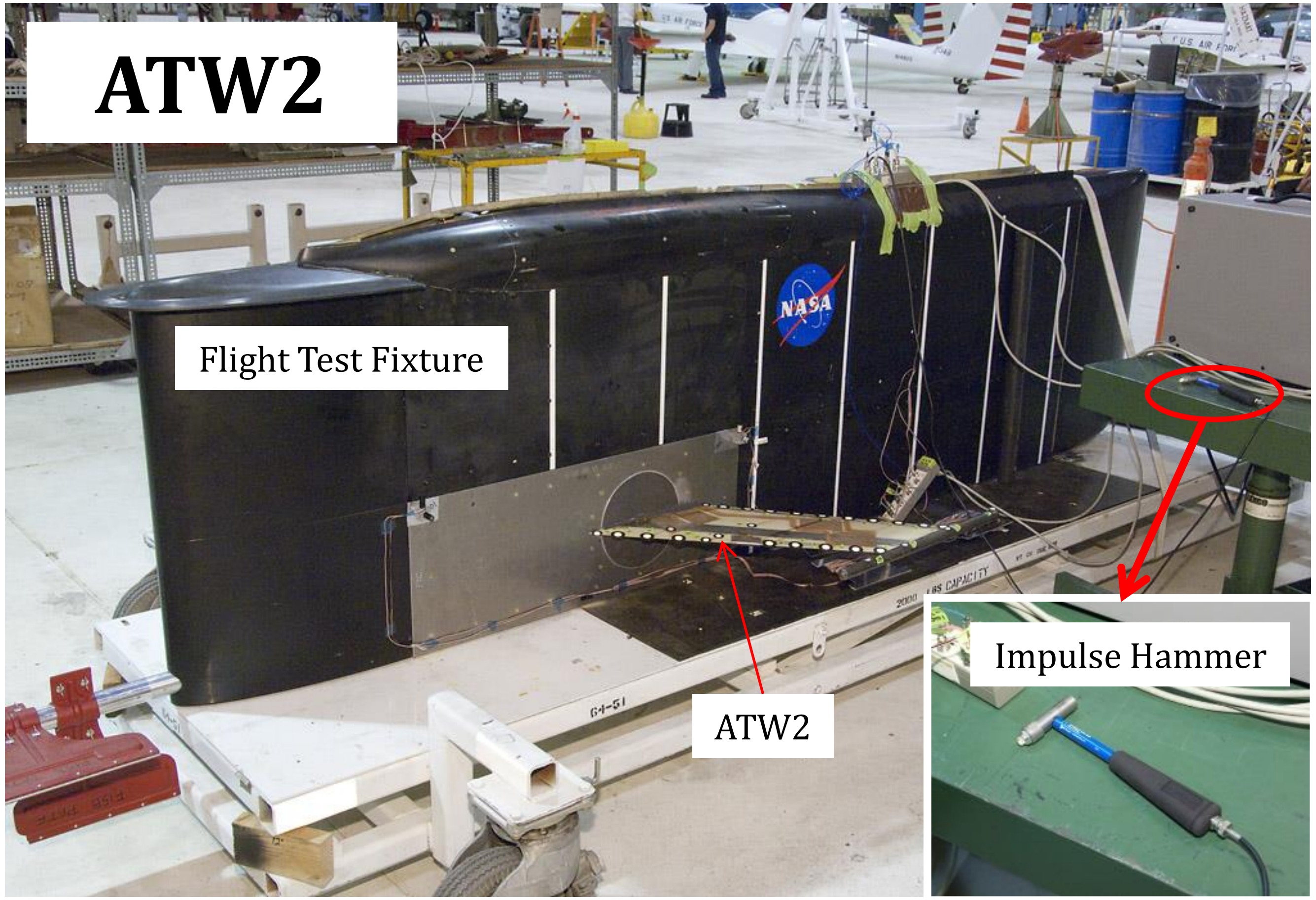
Taurus XL Launch Vehicle (Mishap investigation)



Identification of a Post-Mishap Vehicle Configuration using Topology Optimization Technique

Applications of in-house structural dynamic model tuning tool (continued)

- Aerostructures Test Wing 2
  - Pak, C.-G., and Lung, S.-F., "Flutter Analysis of the Aerostructures Test Wing with Test Validated Structural Dynamic Model," *Journal of Aircraft*, Vol. 48, No. 4, 2011, pp. 1263–1272. doi:10.2514/1.C031257
- X-56A aircraft
  - Pak, C.-g. and Truong, S.S., "Creating a Test-Validated Finite-Element Model of the X-56A Aircraft Structure," *Journal of Aircraft*, Vol. 52, No. 5, September-October 2015, pp. 1644-1667, doi: http://arc.aiaa.org/doi/abs/10.2514/1.C033043



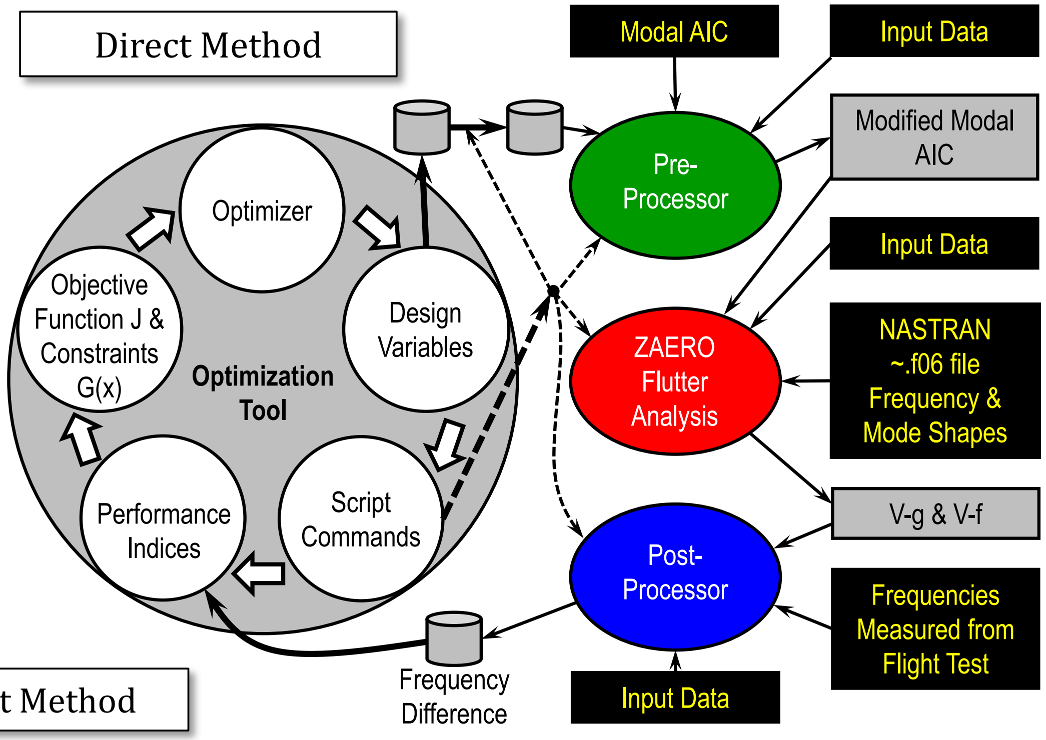
Unsteady aerodynamic model tuning tool

Capability

- ❑ This tool is used for validation of an unsteady aerodynamic model (based on ZAERO model) with respect to test data, such as aeroelastic frequency.

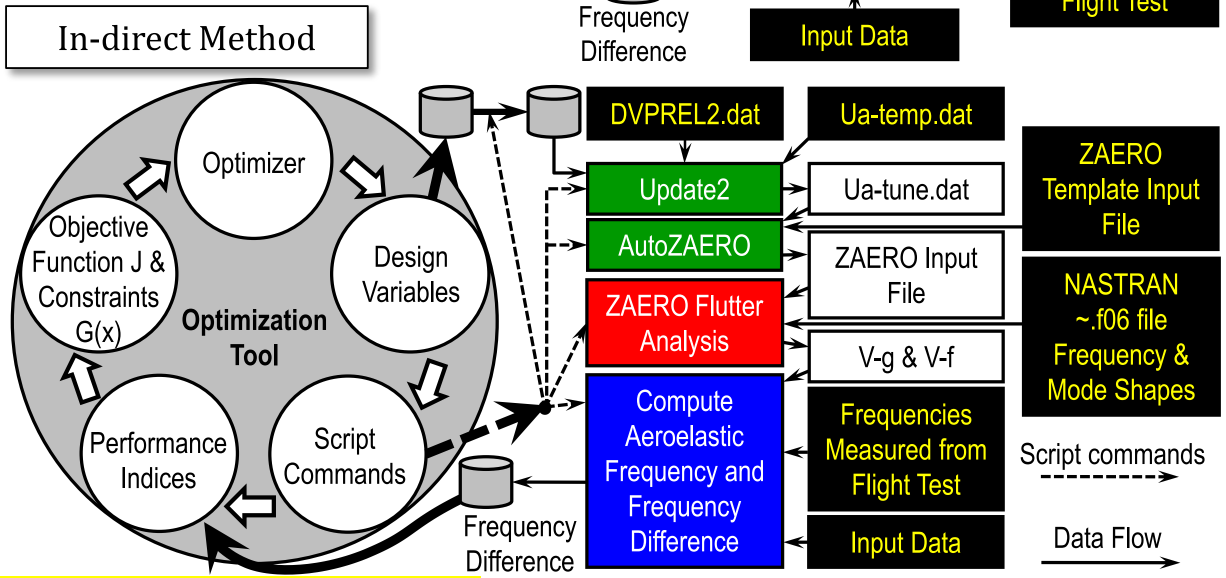
Technical Background

- ❑ Optimization Problem Statements
  - ❖ Minimize J=measured aeroelastic frequency – computed aeroelastic frequency



Approach

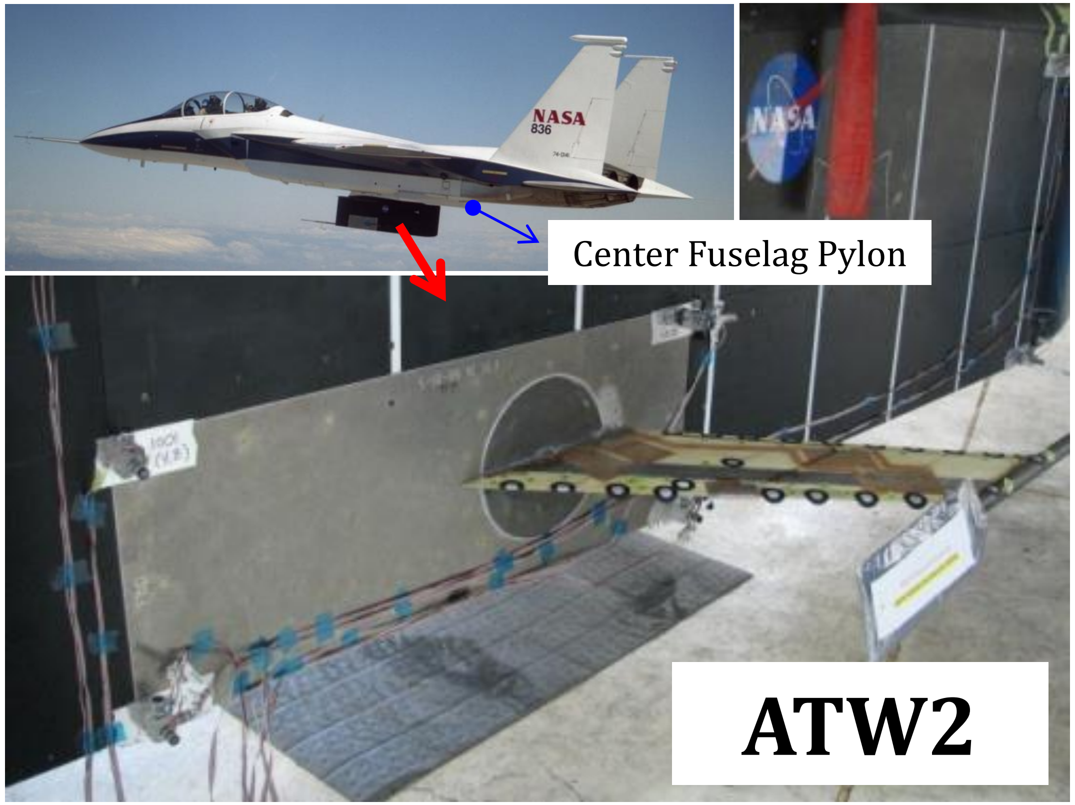
- ❑ Direct Method (**Completed**)
  - ❖ Faster than in-direct method
  - ❖ Update AIC matrices
  - ❖ Design Variables
    - ➢ Scaling factor for each element of AIC matrices
- ❑ In-direct Method (**Not completed**)
  - ❖ Physics based approach
  - ❖ Update AIC matrices through the change of aerodynamic panel geometry
  - ❖ Design Variables
    - ➢ Aerodynamic mesh geometries



Direct method is already developed. In-direct method is being developed.

Applications of in-house unsteady aerodynamic model tuning tool

- ❑ Aerostructures Test Wing 2
  - ❖ Pak, C.-g., “Unsteady Aerodynamic Model Tuning for Precise Flutter Prediction,” *Journal of Aircraft*, Vol. 48, No. 6, 2011, pp. 2178–2184.



Wing shape & aerodynamic load sensing from measured strain

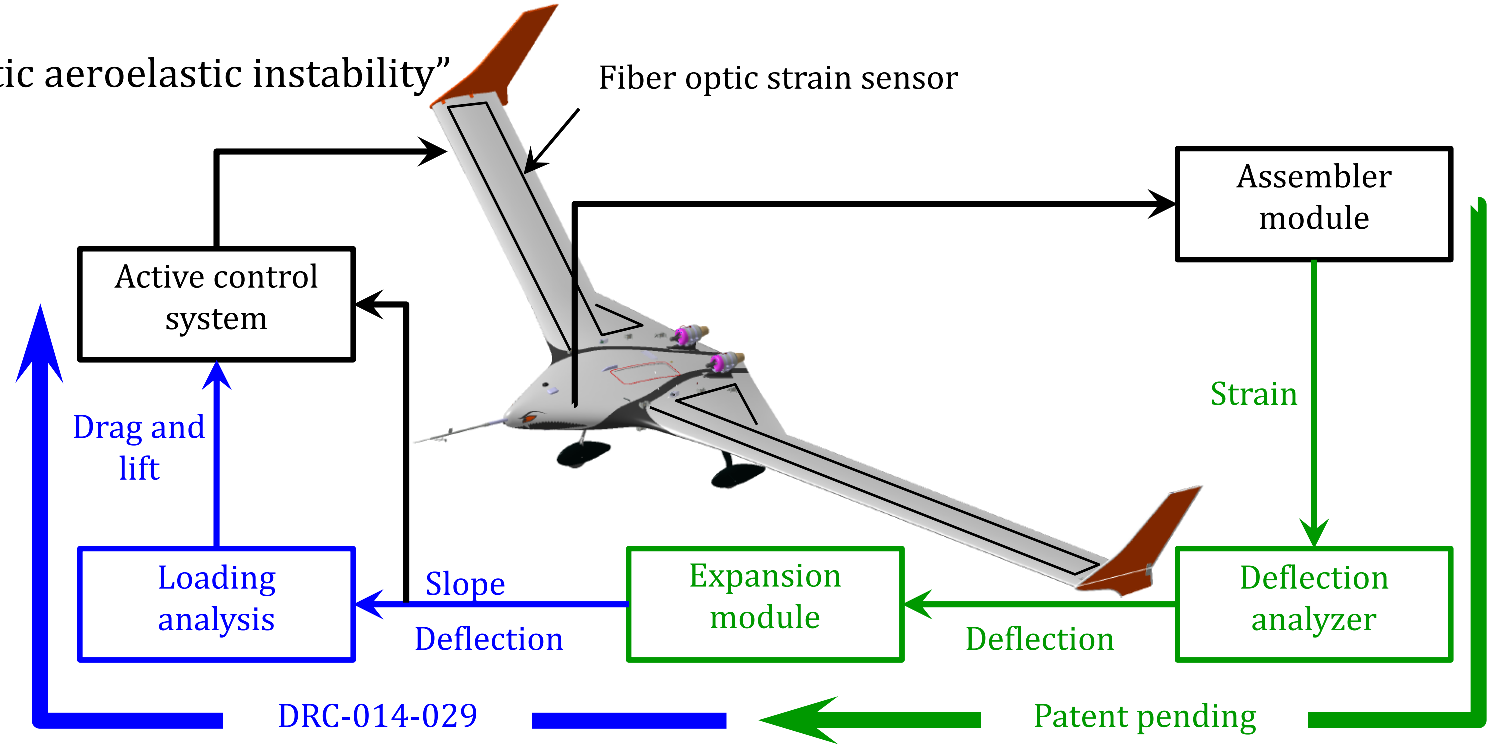
Capability

- ❑ This tool is used to compute unsteady wing/aircraft deformation, velocity, acceleration, and aerodynamic drag and lift forces from measured unsteady strain data.

Potential Applications

- ❑ Aerospace Structures
  - ❖ <u>Active flexible motion control and drag reduction</u>
    - ➢ High as well as "**low**" aspect ratio wings and aircraft
    - ➢ Detailed drag load computation during flight will be available.
      - ✓ Active drag reduction
    - ➢ Active flexible motion control due to "static aeroelastic instability"
      - ✓ Wing divergence control
      - ✓ Steady state wing shape control
  - ❖ Real-time virtual display of structural motion
    - ➢ aeroelastic health monitoring

Active induced drag control to reduce fuel consumption



Applications of wing shape & aerodynamic load sensing from measured strain

- Patent Filed
  - Pak, C.-g., "System and Method for Monitoring the Deflection and Slope of a Three-dimensional Structure such as a Wing using Strain Measurements at Discrete Locations," Patent Application No. 14/482784
- Deformation computation
  - Pak, C.-g., "Wing Shape Sensing from Measured Strain," AIAA Journal, Vol. 54, No. 3, 2016, pp. 1068-1077, DOI: 10.2514/1.J053986
- Velocity and acceleration computation
  - Pak, C.-g., and Truax, R.A., "Acceleration and Velocity Sensing from Measured Strain," AIAA 2016-1229, AIAA Infotech@ Aerospace Conference, San Diego, California, January 4-8, 2016.
- Unsteady aerodynamic force computation
  - Pak, C.-g., "Unsteady Aerodynamic Force Sensing from Measured Strain," 30th Congress of the International Council of the Aeronautical Science, Daejeon, South Korea, September 25-30, 2016
  - Submitted for a journal publication
    - Author: Chan-gi Pak
    - Title: Unsteady Aerodynamic Force Sensing from Strain Data

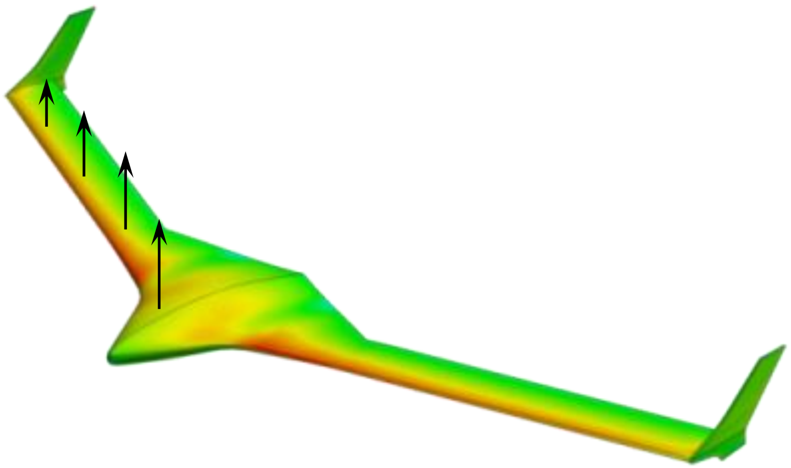
CFD based flutter analysis tool

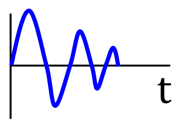
Capability

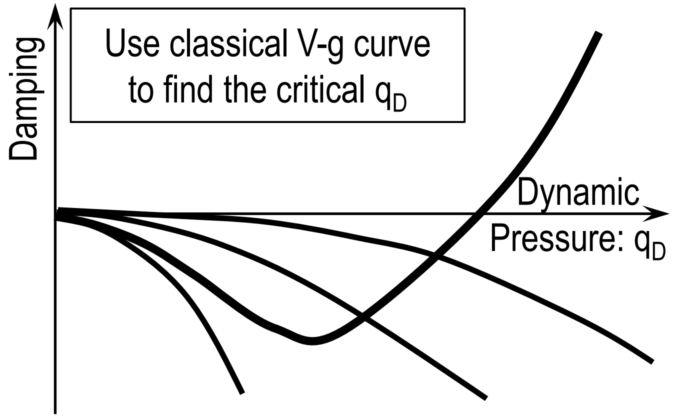
- This tool is used to compute critical dynamic pressure (corresponds to flutter speed) from time histories of CFD computations. From current CFD analysis, this code will predict critical dynamic pressure value which can be used for determination of dynamic pressure for the next CFD simulations

<u>New Technology pursuing Non-provisional Patent</u>

- Title of technology: CFD Based Flutter Analysis Tool.
  - Case number: DRC-013-002
  - Potential licensees
    - During market research by Fuentek, the following three companies expressed some level of interest in the technology.
      - ✓ MathWorks, Inc.
      - ✓ CFD Research Corporation
      - ✓ Exa Corporation







Use classical flutter analysis technique with time-domain aeroelasticity.

Applications of CFD based flutter analysis tool

- Cantilevered rectangular wing
  - Pak, C.-g., and Lung, S.-f., “New Flutter Analysis Technique for Time-Domain Computational Aeroelasticity,” accepted for presentation at AIAA SciTech 2017 Conference, Grapevine, Texas, January 9-13, 2017.

Adaptive/Active Controls with Aeroservoelastic System Uncertainties

Problem

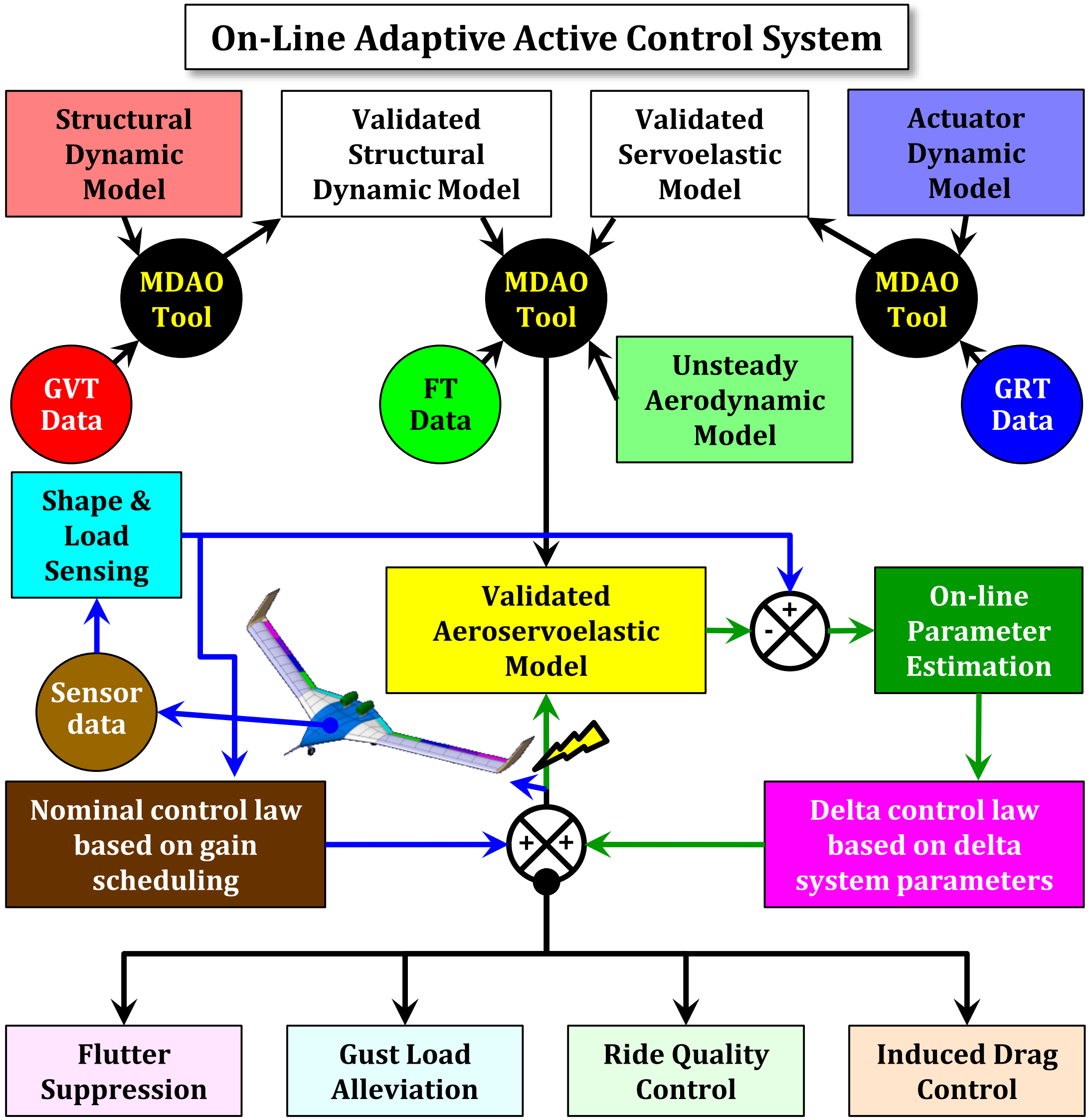
- ❑ The increased flexibility, due to weight reduction, creates an aircraft that is more susceptible to aeroelastic phenomena such as flutter, divergence, buzz, buffet, and gust response.
- ❑ Uncertainties are existed in aeroservoelastic system even with the test validated aeroservoelastic model due 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.
- ❑ 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.



Tool development was not completed.

Application of delta adaptive control technique

- Hashemi, K.E., Pak, C.-g., and Akella, M.R., “Delta Adaptive Flexible Motion Control for the X-56A Aircraft,” AIAA-2015-2244, Proceedings of the AIAA Atmospheric Flight Mechanics Conference, Dallas, TX, June 22-26, 2015.

- Hashemi, K.E., Akella, M.R., and Pak, C.-g., “Tracking Error Convergence for Multi–Input Multi–Output Model Reference Adaptive Control with Known Nonminimum Phase Zeros,” 54th IEEE Conference on Decision and Control, Osaka, Japan, December 15-18, 2015.

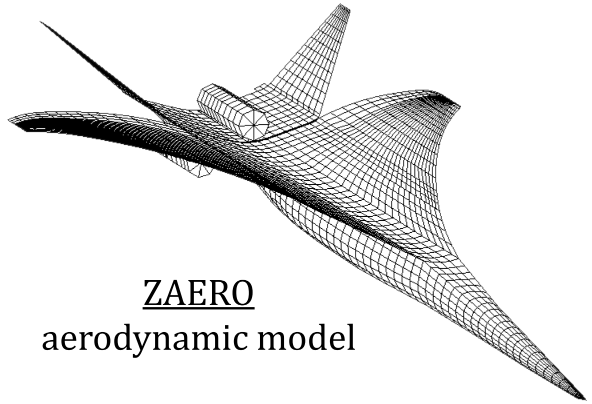
On going milestones in MDA area

- Develop unsteady aerodynamic model tuning tool based on **in-direct method**
- Applications of wing shape & aerodynamic load sensing technique using **measured** strain data
- Perform adaptive active **flexible motion control** and active **induced drag control** using wing shape & aerodynamic load sensing technique
- Applications of CFD based flutter analysis tool for control surface Buzz analysis using NASP wing model
- Incorporate **adaptive control capability** into **CFL3D code** with aerodynamic load sensing from measured strain
- Develop an efficient **time-domain Aeroservoelastic analysis** code

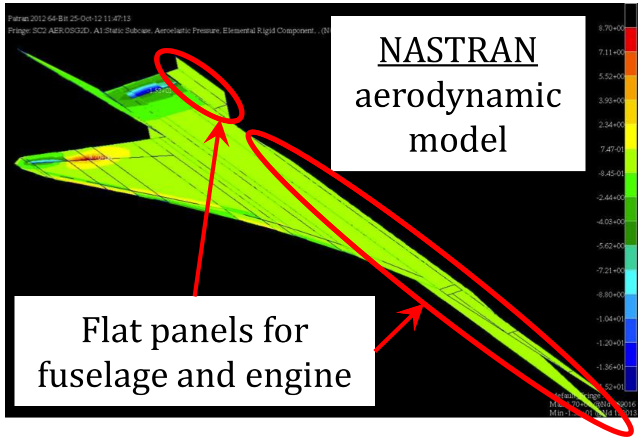
Backup Slides

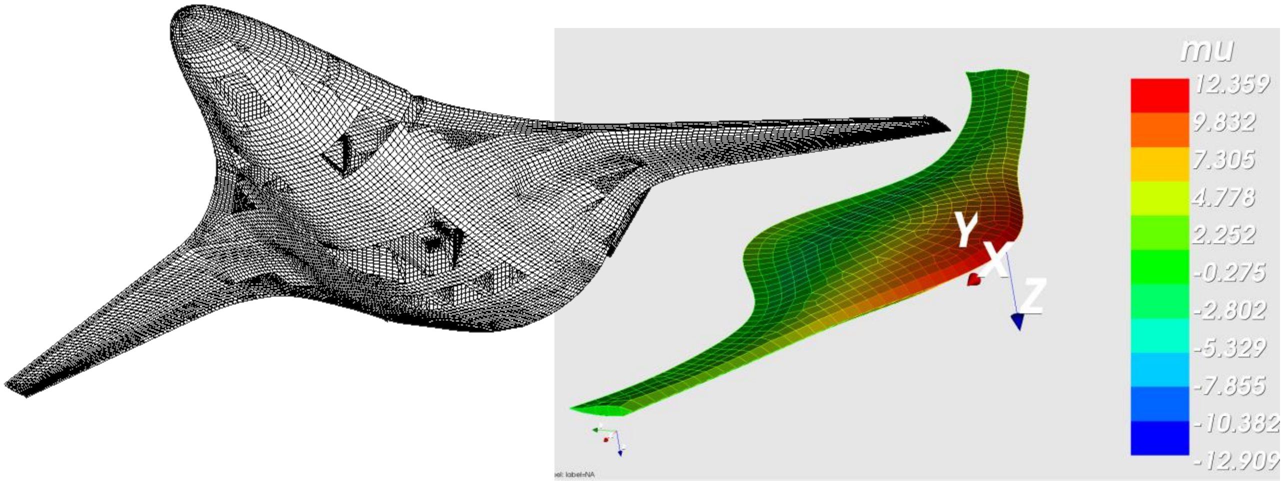
Develop an efficient frequency domain Aeroservoelastic analysis code

- ❑ Incorporate into in-house MDAO tool. Publish paper of this tool.



ZAERO
aerodynamic model





<u>Problem statements</u> **On going**

- ❑ Aerodynamic simulation codes known as “panel codes” have been the backbone of aeroelastic analysis, design, and certification for practically all aircraft developed over 45 years.
  - ❖ Frequency-domain; Low fidelity
  - ❖ Model preparation for them can be time consuming. (Modeling issue)
    - ➢ A structured panels are required.
    - ➢ Wings, tails, and canards, are modeled as infinitesimally thin.
    - ➢ Thickness effect cannot be captured.
    - ➢ Issues with <u>three-dimensional body shapes</u>.
      - ✓ Aerodynamic loads not usable for fuselage design
- ❑ CFD simulations are still sensitive to modeling details and numerical implementation even at low angles of attack.
  - ❖ Time-domain; High fidelity
  - ❖ Expensive to be used in conceptual design as well as industry “production-runs”.

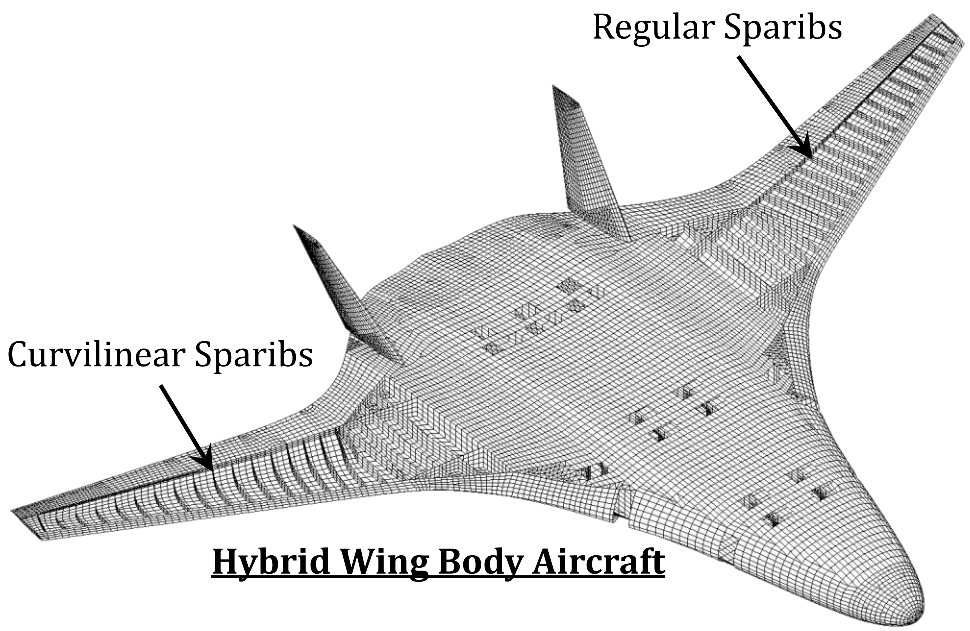
<u>Objectives</u>

- ❑ Time to develop a new efficient aerodynamic code using unstructured as well as structured panels
  - ❖ Frequency-domain; Medium fidelity
  - ❖ They can model complete 3D configurations.
  - ❖ Work with structured and unstructured surface mesh grids

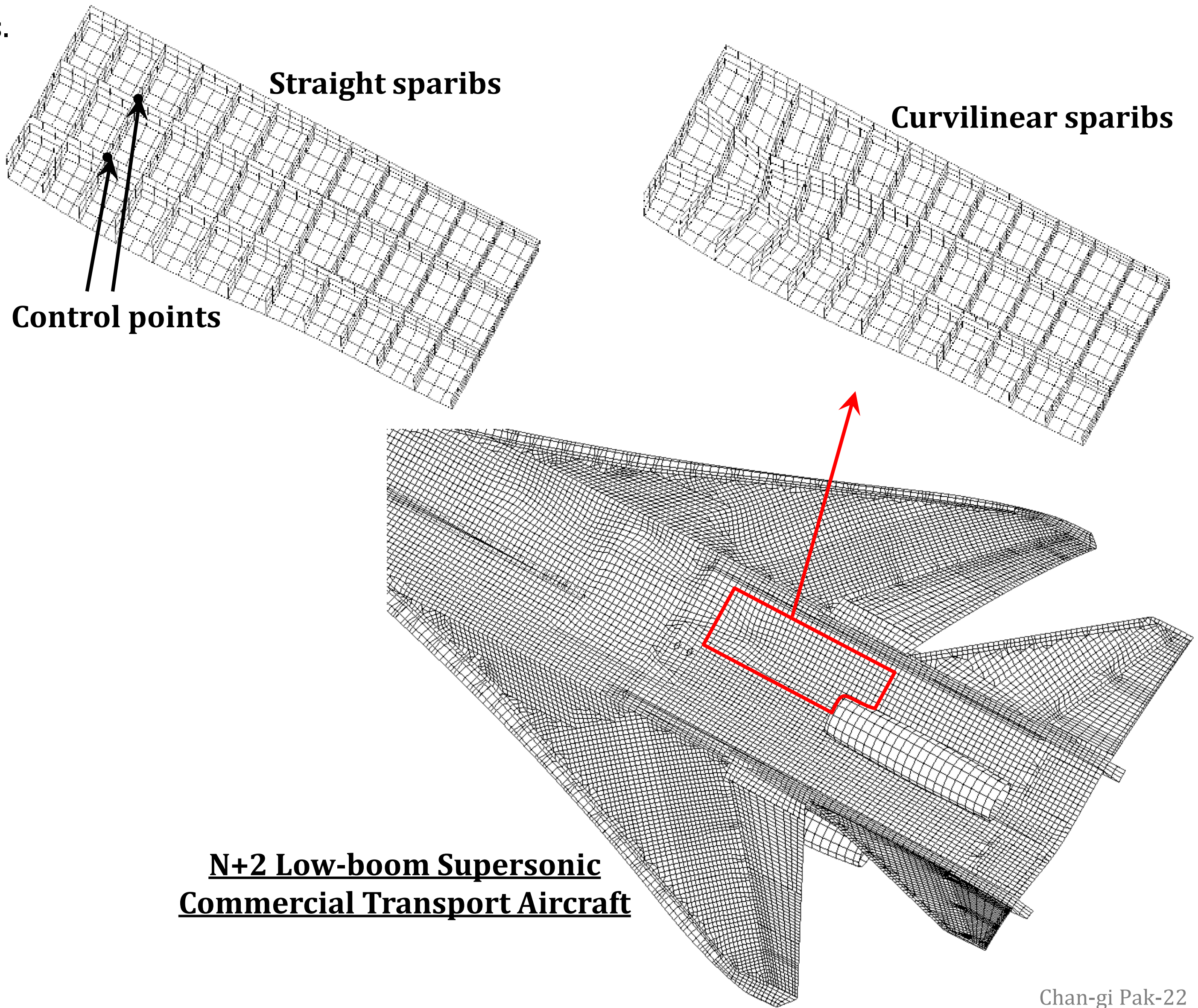
Develop Object-Oriented Optimization (O3) based MDAO tool with curvilinear sparib capability

- Curvilinear sparib code integrated into Object-Oriented Optimization (O3) based MDAO tool
  - A morphing code developed through the STTR is used.
  - Design variables will be x & y movements for control points.

Completed



Hybrid Wing Body Aircraft



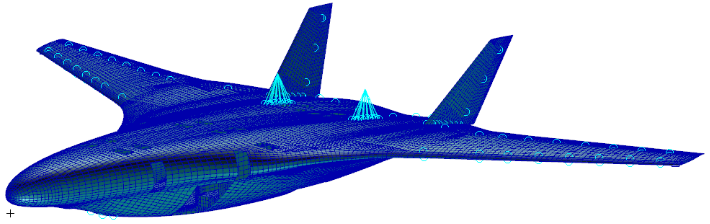
N+2 Low-boom Supersonic Commercial Transport Aircraft

Demonstration of in-house MDAO tool for Aeroelastic Tailored aircraft design with curvilinear

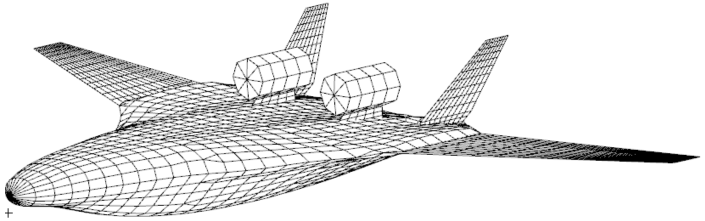
On going

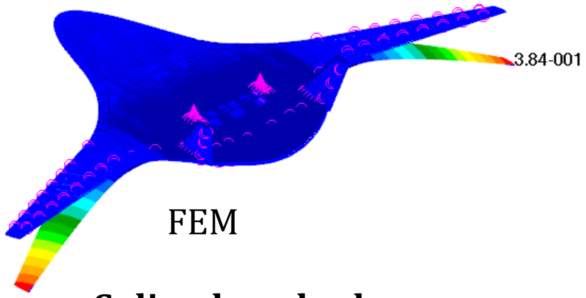
- Design an aeroelastic tailored aircraft and assess performance benefits (e.g. increased margin and/or reduced structural mass)
- Li, W. and Pak, C.-g., "Aeroelastic Optimization of a Hybrid Wing Body Aircraft using Curvilinear Spars and Ribs," **abstract submitted** to AIAA SciTech 2017 conference.
  - Completed structural and aero model.
  - Currently working on trim and flutter analyses.
  - Man power issue

FEM



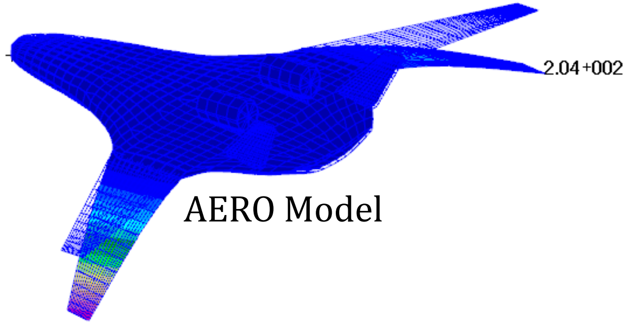
AERO Model



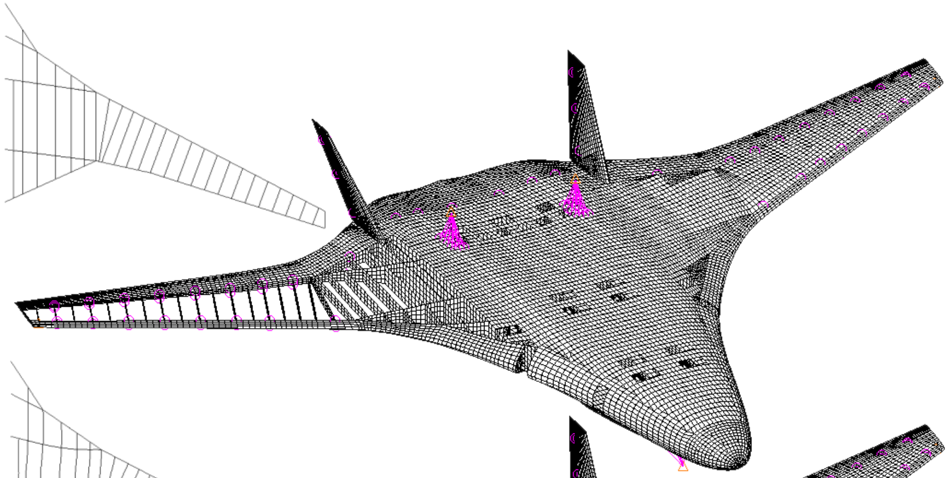


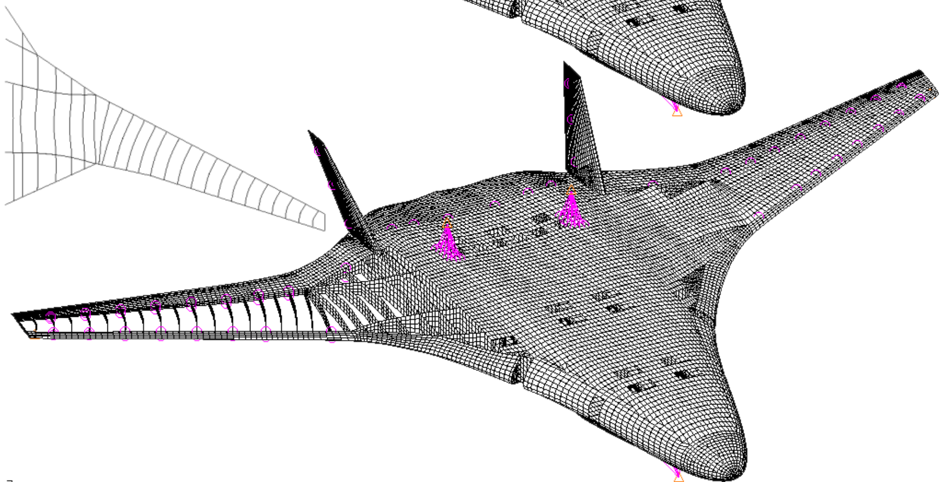
FEM

Splined mode shape



AERO Model



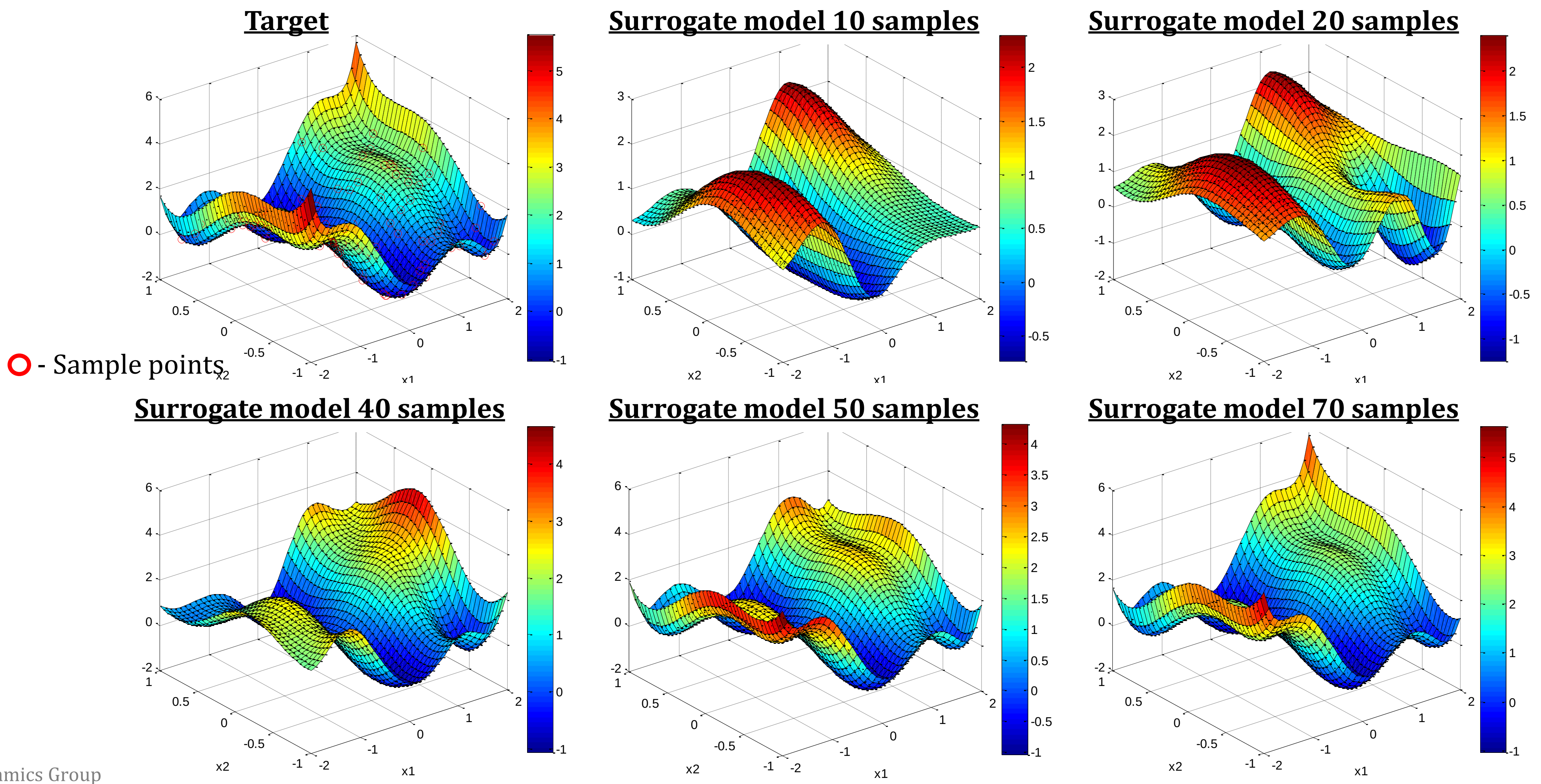


Mode	Baseline (Hz)	After (Hz)
1	1.4799	1.4809
2	2.0137	2.0148
3	4.8542	4.8543
4	4.9303	4.9303
5	6.1364	6.1432
Total weight	206,250.5 lb	206,269.9 lb

Develop Object-Oriented Optimization (O3) based MDAO tool with surrogate modeling capability

On going

- Surrogate modeling capbility integrated into Object-Oriented Optimization (O3) based MDAO tool
- The surrogate module based on Kriging code was tested using a “Rosenbrock” test function. In the figures shown below, the accuracy of the surrogate models was based on the number of samples.
- The surrogate module has not incorporated into the MDO tool yet. (Man power issue)



Demonstrate Object-Oriented Optimization (O3) based MDAO tool for the design of an aeroservoelastically tailored aircraft design

On going

- ❑ Design an aeroservoelastically tailored aircraft using O3 based MDAO tool on one of following configurations:
  - ❖ Turbo-electric Distributed Propulsion system
  - ❖ Low-boom supersonic
  - ❖ HWB

<u>Analytical sensitivity analyses using MSC/NASTRAN and ZAERO codes</u>

Objective

Develop MSC/NASTRAN and ZAERO based sensitivity analysis routines and incorporate these modules into the current in-house MDO tool.

Approach

- ❑ Develop sensitivity analysis routines for the following performance indices:
  - ❖ Total weight (MSC/NASTRAN)
  - ❖ C.G. locations (MSC/NASTRAN)
  - ❖ Mass moment of inertias (MSC/NASTRAN)
  - ❖ Frequencies (MSC/NASTRAN)
  - ❖ Mode shapes (MSC/NASTRAN)
  - ❖ System mass matrix (MSC/NASTRAN)
  - ❖ Margin of safety (MSC/NASTRAN)
  - ❖ Buckling load factor (MSC/NASTRAN)
  - ❖ Flutter speed (ZAERO)
  - ❖ Flutter frequency (ZAERO)
  - ❖ Gain and phase margins of aeroservoelastic system (ZAERO)