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

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Multidisciplinary Design Optimization

NASA
The object-oriented optimization (O³) tool is compatible tool with Open MDAO, Model Center, Visual Doc, etc.

- O³ tool leverages existing tools and practices, and allows the easy integration and adoption of new state-of-the-art software.
- Interface variables between O³ 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 O³ tool are explained in the following references.

- Pak, C.-g., “Preliminary Development of an Object-Oriented Optimization Tool,” NASA/TM-2011-216419.
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.

- MSC/NASTRAN sol 103
  - Total weight, CG location, mass moment of inertia, frequencies, & mode shapes

- MSC/NASTRAN for small weight
- In-house code for large weight
- ZAERO code for flutter analyses
- In-house code for flutter speed tracking
- In-house code for computing MS
- Use safety factor of 1.5
- In-house code for computing BLF
- Use safety factor of 1.5

- In-house code for massaging splined loads

- : Incorporated
- : Not fully incorporated yet
- : Not included yet

- Objective Function J & Constraints G(x)
- In-house Optimization Tool
- Design Variables
- Script Commands
- Performance Indices
- Optimizer
- ADS; DOT; GA; & BBBC

- Surrogate
- Gain/Phase Margins
- Update NASTRAN input
- Curvilinear Sparib
- Wing Morphing code

- Strength
- Buckling
- Landings & Ground Control
- Processing Air Loads
- Trim
- Updates ZAERO input

- Weight
- Flutter
- In-house ASE tools
- CFD Based Loads & Flutter

- Use safety factor of 1.5

- In-house code for computing MS
- Use safety factor of 1.5
- In-house code for computing BLF
- Use safety factor of 1.5

- In-house code for massaging splined loads
Applications of in-house MDO tool

- Approximate unsteady aerodynamics

- Ikhana aircraft

- X-56A aircraft

- Supersonic aircraft

- Hybrid Wing Body aircraft
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 an optimum design demonstration
- Develop Object-Oriented Optimization (O³) 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 (O³) 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 (O³) 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
**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 \( J = \sum w_i J_i \)  
  - Such that \( J_k \leq \varepsilon_k \)

  - \( J \): Objective function
  - \( w_i \): Weighting factor for the performance index \( i \)
  - \( J_i \): Performance index \( i \) selected for objective function
  - \( J_k \): Performance index \( k \) selected for constraint functions
  - \( \varepsilon_k \): 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

- X-37 Drogue Chute Test Fixture

- Glory Mishap Investigation: Use “Topology Optimization”
Applications of in-house structural dynamic model tuning tool (continued)

- Aerostructures Test Wing 2

- X-56A aircraft
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
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
  - Active flexible motion control and drag reduction
    - 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

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**Diagram:**
- Fiber optic strain sensor
- Assembler module
- Deflection analyzer
- Loading analysis
- Drag and lift
- Slope Deflection
- Expansion module
- DRC-014-029
- Patent pending
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

- Velocity and acceleration computation

- Unsteady aerodynamic force computation
  - 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.

**New Technology pursuing Non-provisional Patent**
- 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
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


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

Problem statements
- 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 three-dimensional body shapes.
      - 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”.

Objectives
- 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
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.

- Curvilinear Sparibs
- Regular Sparibs

Control points

- Straight sparibs
- Curvilinear sparibs

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

- Design an aeroelastic tailored aircraft and assess performance benefits (e.g. increased margin and/or reduced structural mass)
  - Completed structural and aero model.
  - Currently working on trim and flutter analyses.
  - Man power issue

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

- Surrogate modeling capability 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)

Surrogate model 10 samples  
Surrogate model 20 samples  
Surrogate model 40 samples  
Surrogate model 50 samples  
Surrogate model 70 samples  

- Sample points 

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

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

**Analytical sensitivity analyses using MSC/NASTRAN and ZAERO codes**

**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)