Multidisciplinary Analysis & Design Center for Advanced Vehicles

Multidisciplinary Optimization of Innovative Aircraft using ModelCenter

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General Framework

Physics Based Analysis

- Wing Weight
- Flutter
- Control/Stability

New Aircraft Concepts Analysis

- Ongoing Effort at Virginia Tech
- Improve Conceptual Design Analysis
- Extend Analysis to Non-Conventional Configuration

AIC Conceptual Design Analysis Platform

Multidisciplinary Analysis & Design Center for Advanced Vehicles
Overview

• Multidisciplinary Optimization (MDO) Tool at Virginia Tech
  • Developed over the past two decades

• Application
  • Truss-braced wing (TBW) aircraft MDO research
    • Earlier results – huge benefits of TBW to fuel burn and TOGW reduction as observed through MDO studies
    • Effect of flutter constraint in MDO studies of TBW
    • Aeroelastic benefits of a Novel Control Effector to TBW via a MDO study
    • Preliminary stages of current MDO research for SUGAR III TBW aircraft
  • Tailless supersonic aircraft MDO research
TBW MDO research
VT MDO Framework

- Product of Two Decades Effort
- Analysis Platform: ModelCenter + FLOPS
  - ModelCenter: Connects Analysis Modules, Provides Optimization Algorithms
  - FLOPS: Provides Analysis Methods (Empirical)
- Double Loop Architecture:
  - TOGW Computation
  - Performance Optimization
- Application
  - Conventional
  - SBW and TBW
• Use Multidisciplinary Design Optimization (MDO) to explore the potential for LARGE improvements in subsonic, transport aircraft performance by employing truss-braced wings combined with other advanced technologies.
# Design Load Cases

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## Design Variables

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<td>17</td>
<td>Tip Chord Length</td>
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<tr>
<td>21</td>
<td>Jury Chord Length</td>
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</table>

### Non-geometric Design variables

### Geometric Design variables
Constraints

- Range ≥ 7730 [NM] + 350 [NM] (reserve)/3115 [NM] + 200 [NM] (reserve)
- Initial Cruise ROC ≥ 500 [ft/min]
- Max. $C_l$ (2-D) ≤ 0.8
- Available fuel volume ≥ required fuel volume
- Wing tip deflection ≤ 20.3 [ft.] (fuse. diameter)
- 2\textsuperscript{nd} segment climb gradient (TO) ≥ 2.4\% (FAR)
- Missed approach climb gradient ≥ 2.1\% (FAR)
- Approach velocity ≤ 132.5 [kn.]
- Balanced field length (TO & Land.) ≤ 11,000 [ft.]/ 8,700 [ft.]
- Flutter speed ≥ Flutter boundary
- Roll rate, roll acceleration ≥ required values for projected banking motion in roll
Flight Mission of Transport Vehicle

235-passenger, 7730 NM range, Mach 0.85 dual-aisle transport aircraft (similar to 777)

162-passenger, 3115 NM range, Mach 0.70 single-aisle transport aircraft (similar to 737)
Earlier TBW MDO research
TBW Study Matrix

• Configurations:
  – Cantilever wing
  – Single member TBW: SBW
  – Three members TBW: Jury TBW

• Current Design goals:
  – Min. TOGW
  – Min. Fuel Weight and Emissions
  – Max. L/D

• 2 Friction drag cases:
  – Aggressive laminar:
    Wing Technology Factor = 1 (F-14 Glove exp.)
    Fuselage: riblets and “Flat Plate” Transition \( \text{Re}_x = 2.5 \cdot 10^6 \)
  – Current technology:
    Wing Technology Factor = 0 (Current wings)
    Fuselage: No riblets and “Flat Plate” Transition \( \text{Re}_x = 0.25 \cdot 10^6 \)
Cross Comparison – Long-range Mission “777-like”

- 2% Higher TOGW with 32% less fuel (57[klb] saved fuel weight)
- 112[ft] vs. 214[ft] half span
- 76[klb] vs. 133[klb] wing weight
Previous TBW MDO Study Conclusions

• TBW can improve performance
  – Lower structural weight for the same/higher span
  – Lower fuel weight
  – Lower t/c
  – Increased stiffness – lower deflection

• Min. TOGW design exhibits good structural/fuel weight compromise

• VT showed (results obtained without applying a flutter constraint)
  – up to 8% reduction in TOGW and 18% reduction in fuel burn for long-range mission with TBW/SBW over conventional cantilever
  – up to 3.6% reduction in TOGW and 9% reduction in fuel burn for medium-range mission for TBW/SBW over conventional cantilever
Effect of flutter constraint in MDO studies of TBW
Min TOGW Flutter Results – Medium-range

<table>
<thead>
<tr>
<th></th>
<th>POINT 1</th>
<th>POINT 2</th>
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<tbody>
<tr>
<td>TOGW (lbs.)</td>
<td>138,400</td>
<td>140,600</td>
</tr>
<tr>
<td>Fuel wt. (lbs.)</td>
<td>26,600</td>
<td>26,500</td>
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<tr>
<td>Struct wt. (lbs.)</td>
<td>24,500</td>
<td>27,500</td>
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<tr>
<td>Wing/strut semi-span (ft.)</td>
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<td>78.8/50.9</td>
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<tr>
<td>Root Chord (ft.)</td>
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<td>9.6</td>
</tr>
<tr>
<td>Strut-wing junc. chord (ft.)</td>
<td>8.8</td>
<td>12.0</td>
</tr>
<tr>
<td>Tip Chord (ft.)</td>
<td>4.0</td>
<td>5.8</td>
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<tr>
<td>Strut chord (ft.)</td>
<td>5.9</td>
<td>5.3</td>
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<tr>
<td>Jury chord (ft.)</td>
<td>2.4</td>
<td>3.1</td>
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<tr>
<td>Root t/c</td>
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<td>0.051</td>
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<tr>
<td>Strut-wing junc. t/c</td>
<td>0.100</td>
<td>0.118</td>
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<tr>
<td>Tip t/c</td>
<td>0.107</td>
<td>0.050</td>
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<tr>
<td>Strut t/c</td>
<td>0.100</td>
<td>0.090</td>
</tr>
<tr>
<td>Jury t/c</td>
<td>0.090</td>
<td>0.095</td>
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</tbody>
</table>

Flutter Margin (%): -17.60, 1.30
Speed (KEAS): 367.2, 427.6
Freq. (Hz.): 4.25, 5.76

1.5% penalty on TOGW
1.15 \( V_D \)

TOGW vs Flutter Margin

Designs

Virginia Tech
Multidisciplinary Analysis & Design Center for Advanced Vehicles
Min Fuel Flutter Results – Medium-range

- **Fuel wt. (lbs.):**
  - POINT 1: 23,700
  - POINT 2: 24,900

- **TOGW (lbs.):**
  - POINT 1: 141,000
  - POINT 2: 142,500

- **Struct wt. (lbs.):**
  - POINT 1: 30,400
  - POINT 2: 29,800

- **Wing/strut semi-span (ft.):**
  - POINT 1: 97.4/49.6
  - POINT 2: 85.6/48.6

- **Root Chord (ft.):**
  - POINT 1: 14.4
  - POINT 2: 14.6

- **Strut-wing junc. chord (ft.):**
  - POINT 1: 8.9
  - POINT 2: 8.2

- **Tip Chord (ft.):**
  - POINT 1: 3.4
  - POINT 2: 4.1

- **Strut chord (ft.):**
  - POINT 1: 3.6
  - POINT 2: 4.0

- **Jury chord (ft.):**
  - POINT 1: 3.0
  - POINT 2: 3.2

- **Root t/c:**
  - POINT 1: 0.107
  - POINT 2: 0.111

- **Strut-wing junc. t/c:**
  - POINT 1: 0.136
  - POINT 2: 0.122

- **Tip t/c:**
  - POINT 1: 0.063
  - POINT 2: 0.092

- **Strut t/c:**
  - POINT 1: 0.083
  - POINT 2: 0.115

- **Jury t/c:**
  - POINT 1: 0.098
  - POINT 2: 0.083

- **Flutter Margin (%):**
  - POINT 1: -15.30
  - POINT 2: 0.01

- **Speed (KEAS):**
  - POINT 1: 372.6
  - POINT 2: 417.2

- **Freq. (Hz.):**
  - POINT 1: 3.25
  - POINT 2: 4.26
Aeroelastic benefits of Novel Control Effector to TBW via MDO study
Background

Motivation
• Minimizing fuel burn (major objective - NASA N+3 Fixed Wing) results in flexible aircraft with large-aspect ratio (like truss-braced wing)
• Flexible truss braced wing (TBW) aircraft prone to control reversal and aeroelastic instabilities especially as span increases

Conventional solution to aeroelastic problems
• increase in wing weight, additional control surfaces
• reduction in aerodynamic efficiency due to larger thickness ratio and chord, limited span

Alternative solution
• Aim – retain sufficient aileron effectiveness for roll control either conventionally or in reversal
• Develop a novel control effector (NCE) – a wing tip with variable sweep
• Use VT MDO to search a large number of probable good fits for the NCE
### MDO results – TBW (Fuel weight v flutter margin)

#### Design Parameters

<table>
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<tr>
<th></th>
<th>TBW Design 1</th>
<th>TBW Design 2</th>
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<tbody>
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<td>Fuel wt. (lbs.)</td>
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<tr>
<td>TOGW (lbs.)</td>
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<td>476,700</td>
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<tr>
<td>Wing/strut semi span (ft.)</td>
<td>121.35/71.68</td>
<td>130.64/71.39</td>
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<td>Root chord (ft.)</td>
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<td>Root chord (ft.)</td>
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<td>Root t/c</td>
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<td>Flutter margin</td>
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Roll motion of TBW designs

- TBW not sufficiently flexible to achieve required bank angle
- NCE wing-tip required
TBW designs with NCE wing-tip

- Various forward and backward sweep angles NCE wing-tip (~15% of span) applied to the TBW
- Swept wing-tip labels
  - sf5: swept forward 5 degrees relative to wing sweep
  - sb10: swept back 10 degrees relative to wing sweep
  - as-is: no sweep relative to wing

TBW Design 1:
- (a) sf5 – 5 deg forward
- (b) as-is
- (c) sb10 – 10 deg backward

TBW Design 2:
Flutter & bank angles for TBW design 1 with NCE

NCE tip helps TBW design 1 to meet the required bank angles and also helps to meet the required flutter margin.
Flutter and bank angles for TBW design 2 with NCE

NCE tip helps TBW design 2 to meet the required bank angles and also helps to meet the required flutter margin.
Comparison of cantilever with NCE aided TBW

<table>
<thead>
<tr>
<th>Design parameters</th>
<th>Cantilever</th>
<th>TBW Design 1 no NCE</th>
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<td>Critical bank angle at cruise (degs.)</td>
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<td>12 (&lt;&lt; 30)</td>
<td>Constraint satisfied</td>
<td>18(&lt;30)</td>
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Conclusion
- NCE wing-tip helps TBW design 1 to meet required roll control capabilities and reduce fuel burn by 5.1%
- NCE wing-tip helps TBW design 2 to almost meet the roll control requirement and aid in flutter avoidance – reduces fuel burn 12.1%
Tailless supersonic aircraft
MDO research
Motivation

- Bring physics based analyses forward into conceptual design stage
  - Traditionally rely on empirically based methods
  - Advantages of physics-based methods
    - Identifies problems/issues that could show up later in design
    - Produces overall better designs
    - Multi-fidelity analyses can be used to quickly explore large regions of design space with minimal computational cost
    - Reduces late stage costs
Aircraft MDO Framework ($N^2$)

- Developed a multi-disciplinary, multi-fidelity design, analysis, and optimization framework for aircraft conceptual design
- Each module (discipline) can be either an analysis or an optimization within itself

Medium-Fidelity Tailless Supersonic $N^2$ Diagram

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<td>Configuration: Mach #, Alt.</td>
<td>Cowl, Aft deck</td>
<td>Configuration</td>
<td>Tank and engine locations</td>
<td>Wing area</td>
<td>Noise shielding factor</td>
<td>Configuration, Avail. fuel vol.</td>
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<td>FLOPS Structures</td>
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<td>FLOPS Mission Performance</td>
<td>Detailed take-off parameters</td>
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<td>FLOPS Noise</td>
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<td>Constraints</td>
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<tr>
<td>Thrust, Altitude, Mach #, BPR, etc.</td>
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<td>Optimization</td>
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</table>
Propulsion Module

- **Low-fidelity**
  - Flight Optimization System (FLOPS)
    - Based on Navy NASA Engine Program
    - Calculates engine analysis: thrust, fuel flow, etc. at given atmospheric flight conditions
    - Limitations
      - Thrust related to type of aircraft
      - Weight estimate
      - No dimensions

- **Medium/High Fidelity**
  - Numerical Propulsion System Simulations (NPSS) & WATE++
    - Performs engine analysis
    - Produces better (more accurate) estimate of weight
    - Calculates dimensions
Virginia Tech Class-Shape Transformation (VT-CST)

- Parametric mathematical model to describe the outer mold-line shape of an aircraft
  - Based on Kulfan CST developed at Boeing
  - Equations (Bernstein polynomials) are analytic and can represent a variety of common shapes
    - Airfoil
    - Wing
    - Cowl
    - Ramp
    - Fuselage
  - Shapes can be combined to form overall water-tight object
  - Geometry model easily extensible to handle a variety of aircraft configurations
    - Multiple wings
    - Multiple fuselages
    - Multiple engines
  - Code written in object-oriented C++ and is platform independent
Aerodynamics Module

- **Low-fidelity**
  - WingDes
    - 2D panel method - can only represent clean wing
    - Lift and induced drag coefficients
  - Friction
    - Viscous and pressure drag coefficients
  - AWAVE
    - Wave drag coefficient

- **Medium-fidelity**
  - Zonair
    - 3D panel method for entire aircraft geometry to generate aerodynamic information at both subsonic and supersonic speeds
    - Can represent control surfaces and calculate stability

- **High-fidelity**
  - Computational Fluid Dynamics
    - This capability is currently in development
  - Wind Tunnel Testing
    - Rapid prototyping (3D-printing) can be used to quickly generate models that are used for wind tunnel tests
    - This capability is currently in development
Weight Estimate Module

- **Low-fidelity: Empirical estimate**
  - FLOPS Weight Generator
    - An empirical weight estimate of structural and nonstructural mass based on ultimate and maneuvering load factor

- **Medium-fidelity: Structural Finite Element Analysis (under development)**
  - Automatic Generation of a structural model for finite element analysis
    - Geometry module utilized to develop mesh based on input parameters
      - Number and locations of bulkheads, spars, ribs
      - Material properties
      - Non-structural weight information, e.g. fuel, payload, etc.
      - This information currently must be generated through empirical models

  - Finite Element Analysis in NASTRAN
    - Analyses: static aeroelasticity, flutter, buckling

  - Structural Optimization
    - Optimize structural configuration (layout and thicknesses) to minimize weight subject to constraints on stresses, buckling, flutter modes, etc.
Flight Performance and Mission Analysis Module

- **FLOPS**
  - **Mission is specified:**
    - Take off and landing field lengths, speed, etc.
    - Each leg of flight in terms of distance and altitude
  - **Code determines fuel burned (required within the aircraft) based on:**
    - Weight information from Weight Estimate Module
    - Volume of fuel tanks from Geometry Module
    - Aerodynamic information (lift and drag coefficients) from Aerodynamics Module
    - Power available and fuel burn rates from Propulsion Module
Other Analysis Modules

- **Embedded Engine Exhaust-washed Structures (EEWS)**
  - Identified early as a critical analysis – large impact on later design stages
  - Topology optimization of structures subject to mechanical and thermal loading

- **Noise**
  - Noise calculations performed by FLOPS mission analysis
MDO enabled designs – Medium Fidelity Framework

- **Overall optimization**
  - Two successive genetic algorithms
    - Genetic algorithms: NSGA-II

- **Result**
  - Trapezoidal aircraft configuration similar to Northrop YF-23 or Boeing concept F/A-XX
Future Work

- **Currently under development**
  - **Stability Analysis**
    - Rigid stability analysis developed, but not integrated into framework at present
    - Flexible stability analysis under development
  - **Physics based weight estimate**
    - Structural MDO – finite element analysis and aeroelasticity
  - **High-fidelity aerodynamics**
    - CFD
    - Rapid Prototyping and Wind Tunnel Testing

- **Repeat optimization with new modules included**
Benefits/ Drawbacks of ModelCenter

- **Benefits - Excellent multidisciplinary environment**
  - Readily available plug-ins - Matlab, ANSYS, NASTRAN, ABAQUS
  - Flexible plug-in (wrapper) – JAVA or Python scripts
  - User can develop in-house executables and use them
  - Links – Connects analysis to nodes each other or to optimization nodes
  - Several legacy optimizers available
  - Popular optimizers available with purchased license
  - Prompt customer service (proximity of Phoenix@VT CRC)

- **Needed Improvements– A LINUX version, and robust parallel processing framework**

- **ModelCenter is only Windows – Linux based HPC nodes can be connected but via complicated route**
  - Improved memory management for legacy optimizers
  - More documentation, currently has only simple examples - far from real life complicated examples which require parallel processing