Multidisciplinary Design Optimization of a Truss-Braced Wing Aircraft with Tip-Mounted Engines

NASA Design

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Problem Statement

Responding to Dennis Bushnell’s challenge:

- Apply MDO methodology to a transonic, truss-braced wing design to seek a major increase in performance
- Minimize Takeoff Gross Weight
- Use the mission profile of the Boeing 777-200IGW
**Technology Integration**

- High aspect ratio via strut bracing
- Laminar flow via low sweep
- Tip-mounted engines

**Special Challenges**

- Wing-strut interference drag
  - CFD Design
- Engine-out condition
  - Circulation control on vertical tail
- Aeroelasticity
  - Load alleviation and active control
Design Mission Profile (777)

Cruise
Range = 7,380 nmi
M = 0.85

Payload = 305 passengers

Reserve = 500 nmi
Objective function: minimize takeoff gross weight

17 design variables
- 12 wing shape variables
- 2 weight variables
- Optimum strut force
- Altitude
- Circulation control

7 constraints
- Weight convergence
- Range
- $C_{L_{\text{max}}}$ at a given approach speed
- Maximum allowable section $C_l$
- Fuel volume
- Engine-out at minimum control speed
- 80 meter gate box limit
Multidisciplinary Approach

- Baseline Design
  - Initial Design Variables
  - Updated Design Variables

- Geometry Definition
  - Loads

- Structural Optimization
  - Weight

- Aerodynamic Analysis
  - Drag

- Performance Evaluation
  - Objective Function, Constraints

- Optimizer

- Induced Drag

- Friction and Form Drag

- Wave Drag

- Interference Drag
  - Offline CFD Interference Drag Analysis
**Interference Drag Approach**

◆ Estimate the Drag Penalty of the Wing-Strut Junction
◆ Use CFD Tools to Generate “Empirical” $\Delta C_D$ Data
  – CFD code: USM3D
  – Inviscid/Euler formulation at this stage
  – Unstructured grid generation with GRIDTOOL
◆ Study Various Configurations
  – Single/Multiple strut designs
  – Arch-shaped strut
◆ Parametrically Vary the Shape of the Strut to Minimize the Drag
Wing-Strut Configuration

$M=0.75, \alpha=0^\circ$
**Structural Optimization**

- Determine the minimum bending material weight for a given configuration
- Piecewise linear beam theory
- Critical load cases
  - 2.5 g’s: strut in tension
  - -1.0 g: strut inactive in compression
  - Strut buckling is the critical design issue
- Future Work
  - Include aeroelastic effects using NASTRAN
  - Create response surface from FEM optimizations
  - Evaluate other load cases such as landing and taxi bump
Baseline and Optimum Configurations

Baseline Cantilever
- Statically Stable
- Completely Turbulent

“Optimum” Cantilever
(Obtained with VT MDO tools)
- Relaxed Static Stability
- Partially Laminar
- Rubber Engine Sizing

Optimum Single-Strut
- Relaxed Static Stability
- Partially Laminar
- Rubber Engine Sizing
- Circulation Control for Engine-Out
## Configuration Comparison

<table>
<thead>
<tr>
<th></th>
<th>Base Cant</th>
<th>Opt Cant</th>
<th>Opt SS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wing Span (ft)</td>
<td>199.9</td>
<td>208.2</td>
<td>232.3</td>
</tr>
<tr>
<td>Wing Area (ft$^2$)</td>
<td>4,607</td>
<td>4,244</td>
<td>3,606</td>
</tr>
<tr>
<td>Aspect Ratio</td>
<td>8.7</td>
<td>10.2</td>
<td>15.0</td>
</tr>
<tr>
<td>Inboard Wing Sweep (deg)</td>
<td>31.6</td>
<td>33.6</td>
<td>25.6</td>
</tr>
<tr>
<td>Outboard Wing Sweep (deg)</td>
<td>31.6</td>
<td>33.6</td>
<td>25.6</td>
</tr>
<tr>
<td>Strut Sweep (deg)</td>
<td>N/A</td>
<td>N/A</td>
<td>14.5</td>
</tr>
<tr>
<td>Inboard Wing t/c</td>
<td>13.0%</td>
<td>12.5%</td>
<td>8.9%</td>
</tr>
<tr>
<td>Outboard Wing t/c</td>
<td>10.9%</td>
<td>10.2%</td>
<td>4.6%</td>
</tr>
<tr>
<td>Strut t/c</td>
<td>N/A</td>
<td>N/A</td>
<td>4.60%</td>
</tr>
<tr>
<td>Cruise L/D / Max L/D</td>
<td>18.6/20.2</td>
<td>21.9/24.3</td>
<td>28.4/30.0</td>
</tr>
<tr>
<td>Specific Range (nmi/1000 lb)</td>
<td>26</td>
<td>34</td>
<td>54</td>
</tr>
<tr>
<td>Seat Miles per Gallon (seats*nmi/gal)</td>
<td>60</td>
<td>76</td>
<td>112</td>
</tr>
<tr>
<td>Wing Weight (lb)</td>
<td>77,701</td>
<td>78,585</td>
<td>58,564</td>
</tr>
<tr>
<td>Takeoff Gross Weight (lb)</td>
<td>636,063</td>
<td>562,080</td>
<td>461,420</td>
</tr>
</tbody>
</table>
Weight Comparison

- Base Cant: 636,063 lbs
  - Fuel: 296,915 lbs
  - Wing and Strut: 261,447 lbs
  - Zero Fuel - Wing: 77,701 lbs

- Opt Cant: 562,080 lbs
  - Fuel: 277,597 lbs
  - Wing and Strut: 205,898 lbs
  - Zero Fuel - Wing: 78,585 lbs

- Opt SS: 461,420 lbs
  - Fuel: 262,856 lbs
  - Wing and Strut: 58,564 lbs
  - Zero Fuel - Wing: 140,000 lbs
Discussion of Results

- Strut alleviates large span weight penalty and allows a reduction of $t/c$
- Increased span reduces induced drag
- Decreased $t/c$ allows some unsweeping of the wing and some reduction in wave drag
- Parasite drag is reduced via increased laminar flow
  - Higher AR means smaller chords and smaller Re
  - Unsweeping wing reduces cross-flow instability
  - Decreasing $t/c$ allows more favorable pressure gradients and delays shock formation
- Result: Synergistic increase in overall aircraft efficiency
**On-screen Visualization**

- Fortran subroutine creates DXF file
- AutoCAD and Infini-D are used to create rendered images and animations

**Rapid Prototyping**

- A solid model is created in I-DEAS
- Fused Deposition Modeling is used to create a plastic model
Current Conclusions

<table>
<thead>
<tr>
<th>% Improvement Over</th>
<th>Baseline Cantilever</th>
<th>Optimum Cantilever</th>
</tr>
</thead>
<tbody>
<tr>
<td>Takeoff Gross Weight</td>
<td>-27%</td>
<td>-18%</td>
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<tr>
<td>Fuel Weight</td>
<td>-46%</td>
<td>-32%</td>
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<tr>
<td>L/D</td>
<td>+53%</td>
<td>+30%</td>
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<tr>
<td>Seat-Miles/Gallon</td>
<td>+87%</td>
<td>+47%</td>
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</table>

- The strut-braced wing configuration achieves a significant increase in performance
- This merits further study
Future Work

◆ Broaden the parameter set to allow optimization of more complex and innovative truss geometries
◆ Refine analyses
  – Create a structural response surface with finite element model optimizations
  – Create a response surface from CFD interference drag analyses
  – Include aeroelastic effects
  – Utilize load alleviation at the critical load cases
◆ Design a wind tunnel model