The Boeing SUGAR Truss-Braced Wing Aircraft: Wind-Tunnel Data and Aeroelastic Analyses

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NASA Ames Applied Modeling and Simulation Seminar
April 16, 2015
Outline

• Context and objectives
• Wind tunnel testing and validation data
• Analyses
  – Structural Models
  – Aerodynamic Modeling
  – Mode Shape Transfer Between Dissimilar CSD/CFD Models
  – Results
    • Flutter Simulations with Linear Aerodynamics
    • Sensitivity to structural model and angle of attack
• Conclusions
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TBW Context in Fixed Wing Project

**Research Theme 2: Higher Aspect Ratio Optimal Wing**
Future wings will be of higher aspect ratio, lighter, more flexible, and have varying degrees of laminar flow to reduce drag and improve performance.

**Technical Challenge 2.1 Higher Aspect Ratio Wing**
Enable a 1.5-2X increase in the wing aspect ratio with safe structures and flight control (TRL 3)

<table>
<thead>
<tr>
<th>Goals Metrics (N+3)</th>
<th>Noise</th>
<th>Emissions (LTO)</th>
<th>Emissions (cruise)</th>
<th>Energy Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage 4 – 52 dB cum</td>
<td>CAEP6 – 80%</td>
<td>2005 best – 80%</td>
<td>2005 best – 60%</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FY09</th>
<th>FY10</th>
<th>FY11</th>
<th>FY12</th>
<th>FY13</th>
<th>FY14</th>
<th>FY15</th>
<th>FY16</th>
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</thead>
<tbody>
<tr>
<td>Phase I, started April 2008</td>
<td></td>
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</tr>
</tbody>
</table>

- **Phase II, 4 years**
  - Truss Braced Wing Concept refinement
  - Update FEM
  - TBW model & TDT test
  - Aero Perf. Test, task ends April 2016

Boeing, LaRC, Boeing
TBW Phase I Findings, Phase II Objectives

**Phase I** – Design Study of TBW Configuration

- Large uncertainty in wing weight estimates prevent concluding whether TBW is viable/beneficial concept

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Block Fuel/Seat (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>20</td>
</tr>
<tr>
<td>Baseline “SUGAR Free”</td>
<td>30</td>
</tr>
<tr>
<td>“Refined SUGAR”</td>
<td>40</td>
</tr>
<tr>
<td>Conventional</td>
<td>50</td>
</tr>
<tr>
<td>“SUGAR High”</td>
<td>60</td>
</tr>
<tr>
<td>Truss Braced Wing</td>
<td>70</td>
</tr>
<tr>
<td>“Refined SUGAR”</td>
<td>80</td>
</tr>
<tr>
<td>Conventional</td>
<td>90</td>
</tr>
</tbody>
</table>

**Phase II** - Includes High Fidelity FEM to Refine Weight Estimate and Experimental Validation via ASE Wind-Tunnel Test in the TDT
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Wind-Tunnel Test Objectives

• Determine Experimental Flutter Boundaries

• Investigate Active Flight Controls
  - System ID
  - Flutter Suppression
  - Assess Effects of FS on Gust Response
TBW Aeroelastic Wind-Tunnel Model

Full-Scale Design Point:
- Mach = 0.82
- Altitude = 15,915 ft
- Span = 170 ft
- Weight = 143,164 lb

Spar Pod Construction
- Wing, Strut, Pylon Scaled
- High Bandwidth Control Surfaces:
  - 2 Trailing Edge
- Designed for Side Wall Mount
  - Fuselage 13.4 ft (reduced from 18.7 ft)
- Span = 12.75 ft (to centerline)
- Standoff = 2.25 in
- Weight = 500 lb

Model Scale Factors:
- Length = 0.15
- Frequency = 3.470

Predicted Flutter Boundary

Model Design Point
- Gas = R134a
- Scaled Weight = 109.63 lb
- Mach = 0.82
- Q = 162 psf

NextGen Aeronautics
TBW Wind-Tunnel Model Wing Tip Accelerations

AOA -1 degree

Dynamic pressure ~ psf

Mach number

Hard flutter boundary

8 g
7 g
6 g
5 g
4 g
3 g
9 g
TBW Wind-Tunnel Model Wing Tip Accelerations

AOA +1 degree

![Graph showing dynamic pressure vs. Mach number with various acceleration levels and hard flutter boundary.](image-url)
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Structural Models

Beam-Rod v.19 and v.20 FEMs

- V.19 FEM was updated with *before-test* ground vibration test (GVT) data.
- V.20 FEM was updated with *after-test* GVT data.
  1. Correlation of mode 3 was improved by decreasing bending stiffness on the strut attachment beam and on certain wing elements.
  2. Correlation of mode 4 was improved by adjusting torsional stiffness on inner wing elements.
Structural Models

Modes 3 and 4 coalesce to produce flutter/LCO
Structural Models

- Cases at zero degrees AoA use unloaded structural modes.
- Cases at +1 and -1 degree AoA use structural modes derived from a nonlinear loaded static solution. i.e., modes derived from a geometrically non-linear structure.
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Aerodynamic Modeling

- Vortex-lattice aerodynamics for static aeroelastic solutions.
- Doublet-lattice for flutter solutions.
- The Navier-Stokes grid has 4.5 million nodes.
- The wind-tunnel wall is treated as a symmetry plane.
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Mode Shape Transfer Between Dissimilar CSD/CFD Models

Final (blue) and initial (gray) surfaces
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Results – Linear Aerodynamics

- Flutter simulations with linear aerodynamics
- Conditions at which Navier-Stokes simulations are performed
- All conditions in this figure are at -1 or +1 degree AoA.
- Static wing and strut loading influences the dynamic pressure at which flutter occurs.
- Note that experimental conditions are also included for reference.
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Results – Comparison of v.19 and v.20 FEM

- Time step and sub-iterative convergence of RANS solutions was studied in Bartels et al. (2014).
- Comparison is made between the v.19 and v.20 TBW FEMs at 0 AoA.
- Flutter occurs for the v.20 FEM at a higher dynamic pressure due to larger separation of mode 3 and 4 frequencies.
- The shape of the v.20 flutter onset above Mach 0.80 is different than the v.19 FEM flutter onset.
Results – Comparison, AoA -1, 0 and +1 deg
Results – Comparison, AoA -1 and +1 deg

<table>
<thead>
<tr>
<th>Mach no.</th>
<th>Dyn press. (psf)</th>
<th>Analysis/Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.70</td>
<td>85</td>
<td>RANS, v.20</td>
</tr>
<tr>
<td>0.70</td>
<td>100</td>
<td>RANS, v.20</td>
</tr>
<tr>
<td>0.75</td>
<td>80</td>
<td>RANS, v.20</td>
</tr>
<tr>
<td>0.75</td>
<td>100</td>
<td>RANS, v.20</td>
</tr>
<tr>
<td>0.78</td>
<td>75</td>
<td>RANS, v.20</td>
</tr>
</tbody>
</table>
Results – Comparison, AoA -1 and +1 deg

Mach 0.75, 80 psf

Mach 0.78, 75 psf
Conclusions

- Conclusions that can be clearly made:
  1. Angle of attack and model sensitivity is predicted well with linear aerodynamics and a static nonlinear structural model.
  2. LCO is predicted with nonlinear aerodynamics (Navier-Stokes) and linear dynamic structural model.
  3. Flutter and LCO onset are quite sensitive to the mass and/or stiffness distribution of the wing.
  4. Force/displacement transfer between fluid and structure meshes requires algorithms that can accommodate complex beam structures models and fine CFD mesh spacing.

- Somewhat tentative conclusions:
  1. A better refined CFD mesh may enable better correlation of simulated LCO onset with experiment.