Flutter and Aeroservoelastic Testing of the Boeing SUGAR Truss Braced Wing Aircraft

Presented by Robert Bartels

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Outline

• Phase I Findings, Phase II Objectives

• Experimental Validation, TDT Test
  – Test Objectives
  – Wind-Tunnel Model Design
  – Transonic Dynamics Tunnel
  – “Configurations” – GVT and FE Analyses
  – Experimental Flutter Results
  – Experimental ASE Results

• Phase II Findings

• Conclusions
**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

| Baseline “SUGAR Free” Conventional Configuration | **N** |
| “Refined SUGAR” Conventional Configuration | **N+3** |

| “SUGAR High” Truss Braced Wing Configuration | **N+3** |

**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
TBW Model Instrumentation

Wing Assembly

Strut Assembly

<table>
<thead>
<tr>
<th>Instrumentation</th>
<th>Count</th>
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<tr>
<td>Z axis accel</td>
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<td>X axis accel</td>
<td>4</td>
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<td>10</td>
</tr>
<tr>
<td>RVDT</td>
<td>2</td>
</tr>
<tr>
<td>Fiber optic cable</td>
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Transonic Dynamics Tunnel
TBW Modes and Frequencies

Wing 2nd out-of-plane bending mode

Wing 1st torsion mode

<table>
<thead>
<tr>
<th>Mode</th>
<th>Pre-Holiday (Hz)</th>
<th>Post-Holiday (Hz)</th>
<th>Description</th>
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<tr>
<td></td>
<td>GVT</td>
<td>FEM19</td>
<td>GVT</td>
</tr>
<tr>
<td>1</td>
<td>5.20</td>
<td>5.12</td>
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<td>3</td>
<td>9.08</td>
<td>9.17</td>
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<tr>
<td>4</td>
<td>11.35</td>
<td>11.34</td>
<td>11.14</td>
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<tr>
<td>5</td>
<td>19.56</td>
<td>18.53</td>
<td>18.62</td>
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<tr>
<td>7</td>
<td>28.44</td>
<td>27.44</td>
<td>27.57</td>
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</table>
Flutter Boundary Summary

![Diagram showing flutter boundary summary with dynamic pressure vs. Mach number.](image)
Analysis/Test Comparison

![Graph showing Analysis/Test Comparison with dynamic pressure on the y-axis and Mach number on the x-axis. The graph includes lines for different altitudes (H = 1000, 700, 500, 300, 200) and various angle of attack (AOA) settings. The legend indicates lines for Experimental post holiday AOA -3°, Experimental post holiday AOA -1°, Experimental post-holiday AOA +1°, Experimental post holiday AOA +3°, FEM20 AOA -3°, FEM20 AOA -1°, FEM20 AOA +1°, and FEM20 AOA +3°.](image)
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ASE and CL Testing

- **Open Loop System ID**
  - Sine sweeps to control surfaces for ASE model verification and system ID
  - Dwell/Decay for estimating modal damping
- **Flutter Suppression Control Laws**
  - LQR based control law for each ASE model
  - System ID based control law (2)
    - Derived from two experimental data points
      - Linear sine sweeps to each surface at two stable tunnel conditions
      - AOA = -3°
  - FEM 19 based control laws (18)
    - ASE models derived from version 19 of NASTRAN FEM
    - 18 ASE models used, including OL stable and unstable
      - Control laws were scheduled based on Mach and dynamic pressure
- **Gust Response**
  - Back to back OL and CL data points acquired with AOS frequency sweep
Closed Loop Results, AOA < 0

AOA -3

AOA -1
Fixed Wing Project
Fundamental Aeronautics Program

Closed Loop Results, AOA > 0

AOA +1

AOA +3
FEM19 Controller OL/CL @ Unstable Condition
Flutter Suppression
OL/CL Gust Response, FEM19 Based Control
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Conclusions

• **Open-Loop Flutter Boundaries Established**
  – Flutter Boundaries a Function of Aerodynamic Loading (Angle of Attack)
  – Boeing NASTRAN/MDO Approach Validated/Improved
    • Importance of Static Nonlinear Effects Established
    • The TBW Configuration Remains A Viable Concept For Reducing Transport Aircraft Energy Consumption

• **Flutter Suppression Control Laws Designed & Demonstrated**
  – Control Laws Designed using ASE Models Derived From Both Open-Loop Experimental Data and the NASTRAN FEM
  – Close Loop Dynamic Pressures of at Least 25% Above the Open Loop Boundary Were Demonstrated
  – Viability of Flutter Suppression for TBW N+3 Concept Established
  – Flutter Suppression Controllers Provide Small Gust Load Alleviation Benefit

• **Model Status**
  – Survived Several Hard Flutter Points
  – NASA Retained Ownership, Available for Future Testing

• **Documentation**
  – SciTech 2014 (2)
  – Contractor Reports (2)
  – SciTech 2915 Special Session
  – Aviation 2015 (1)
Backup Slides
Truss-Braced Wing: Wing Weight Uncertainty

**PROBLEM**
Conceptual design of Truss-Braced Wing (TBW) configuration during the N+3 phase 1 study showed significant potential of this technology to contribute to meeting NASA N+3 goals, but also highlighted a significant uncertainty in the wing weight estimate.

**OBJECTIVE**
Refine the TBW configuration and reduce the uncertainty in the potential benefits with specific focus on reducing the uncertainty of the wing weight.

**APPROACH**
Create a detailed finite element model (FEM) of the TBW configuration to provide a higher fidelity weight estimate of the concept; validate the FEM via a transonic aeroservoelastic (ASE) test in the NASA Transonic Dynamics Tunnel (TDT).

**RESULTS**
A high fidelity weight estimate was completed which showed favorable wing weights and significant improvement in fuel burn. The ASE test was used to validate and update the wing weight estimate which increased 463 lbs (12,577 lb wing).

**SIGNIFICANCE**
The TBW configuration remains a viable concept for reducing transport aircraft energy consumption. The validated detailed FEM enables credible weight and fuel burn estimates that justify further investigations of the TBW concept. Based on these results, an aerodynamic performance test and evaluation is going forward that will show that high-order aerodynamic design and analysis tools can be used to predict the performance of a low-interference truss braced wing.
Contractor Final Reports


AIAA Conference papers


FY15 Documentation

• Contractor Final Report -> submit for publication as a NASA CR
• AIAA SciTech, January 2015
  – Bradley, M., “Final Results of the Subsonic Ultra Green Aircraft Research (SUGAR) Study”
  – Special Session Sponsored by SDTC & GEPC
    1. Allen, Timothy J. [The Boeing Company], "SUGAR Truss Braced Wing Full Scale Aeroelastic Analysis and Dynamically Scaled Wind Tunnel Model Development"
    2. Scott, Robert C. [NASA], "Aeroservoelastic Wind-Tunnel Test of the SUGAR Truss Braced Wing Wind-Tunnel Model"
    4. Zhao, Wei [Virginia Tech], "Nonlinear Aeroelastic Analysis of SUGAR Truss-Braced Wing (TBW) Wind-Tunnel Model (WTM) under In-plane Load"
    5. Mallik, Wrik [Virginia Tech], “Aeroelastic Analysis and Optimization of Truss-Braced Wing Aircraft with Novel Control Effectors”
    6. Chen, P. C. [ZONA], "Low-Weight Low-Drag Truss-Braced Wing Design using Variable Camber Continuous Trailing Edge Flaps”
• AIAA Aviation, June 2015
  – Bartels, R., Scott, R., and Funk, C. “Analysis of Limit Cycle Oscillation Data from the Aeroelastic Test of the Boeing SUGAR Vehicle”
Flow Through Nacelle and Active Control Surfaces

Flow Through Nacelle

Jury

Side-wall Mounted

High Speed Aileron

Strut

Low Speed Aileron
## Boeing Weight Results with Resized FEM

<table>
<thead>
<tr>
<th></th>
<th>Pre Test</th>
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<th>Post Test</th>
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<tr>
<td></td>
<td>Config 1</td>
<td>Config 1</td>
<td>Delta</td>
<td>Config 1</td>
</tr>
<tr>
<td>No Flutter</td>
<td></td>
<td>1.15VD</td>
<td></td>
<td>1.15VD</td>
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<tr>
<td>Skins</td>
<td>5557.8</td>
<td>5689.1</td>
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<tr>
<td>Spars</td>
<td>765.8</td>
<td>828.4</td>
<td>62.6</td>
<td>814.1</td>
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<tr>
<td>Ribs</td>
<td>705.4</td>
<td>718.3</td>
<td>12.9</td>
<td>724.2</td>
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<tr>
<td>Spar Caps</td>
<td>229.6</td>
<td>250.0</td>
<td>20.4</td>
<td>230.3</td>
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<tr>
<td>Rib Caps</td>
<td>160.9</td>
<td>174.2</td>
<td>13.3</td>
<td>170.1</td>
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<tr>
<td>Strut</td>
<td>787.1</td>
<td>889.6</td>
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<tr>
<td>Jury</td>
<td>21.4</td>
<td>24.0</td>
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<tr>
<td>Gear Pylon 2D</td>
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<tr>
<td>Gear Pylon 1D</td>
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<td>Total</td>
<td>11768.4</td>
<td>12114.0</td>
<td>345.6</td>
<td>12577.3</td>
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Updated flutter penalty increases to 809 lb
Dynamically Scaled Model

### Full-Scale Data - Full Span Values

<table>
<thead>
<tr>
<th>Weight (lb)</th>
<th>Span (ft)</th>
<th>Mach</th>
<th>Vel (KEAS)</th>
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<tbody>
<tr>
<td>143164</td>
<td>170</td>
<td>0.82</td>
<td>400</td>
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</tbody>
</table>

### Full-Scale Data - Half Span Values

<table>
<thead>
<tr>
<th>Weight (lb)</th>
<th>Span (ft)</th>
<th>Mach</th>
<th>Altitude (ft)</th>
<th>Dyn Pres (psf)</th>
<th>Density (s/cf)</th>
<th>Velocity (fps)</th>
<th>Re</th>
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<tr>
<td>29630</td>
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### Basic Scale Factors

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<th>Length</th>
<th>Density</th>
<th>Velocity</th>
<th>Mass</th>
<th>Acceleration</th>
<th>Force</th>
<th>Stiffness</th>
<th>Frequency</th>
<th>Dyn Pres</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.150</td>
<td>1.1000</td>
<td>0.5211</td>
<td>0.003713</td>
<td>1.8103</td>
<td>0.006721</td>
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</table>

### Derived Scale Factors

R134a

### Model-Scale Data

<table>
<thead>
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<th>Weight (lb)</th>
<th>Span (ft)</th>
<th>Mach</th>
<th>Altitude (ft)</th>
<th>Dyn Pres (psf)</th>
<th>Density (s/cf)</th>
<th>Velocity (fps)</th>
<th>Re</th>
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<tbody>
<tr>
<td>109.63</td>
<td>12.75</td>
<td>0.82</td>
<td>162.03</td>
<td>0.001597</td>
<td>450.52</td>
<td>5.07E+06</td>
<td></td>
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</tbody>
</table>
**Truss-Braced Wing: Wing Weight Uncertainty**

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FEM 19 and FEM 20 Differences

Modes 3 and 4 coalesce to produce flutter/LCO
Skin / Pod Design

- Skin created from carbon \ epoxy matrix
- Segmented into pods to prevent stiffness addition to spar
- Attached to spar via ribs, which provide support along the entire chord
- Additional optional skin reinforcement provided by stiffener tubes, located at leading and trailing edges
Wind-TunModel FEMs

Modes 3 and 4 coalesce to produce flutter/LCO

FEM 19 “Pre Holiday”
FEM 20 “Post Holiday”
Pre-Holiday Flutter w/ NASTRAN Analyses
Control Systems

\[ \delta_{\text{position}} \]
\[ \text{Mach} \]
\[ q \]
\[ \text{Excitation} \]
\[ \text{Model Signals} \]

\[ \text{Flight Control} \]

\[ \delta_{\text{Cmd.}} \]

\[ \text{dSpace2} \]

\[ \text{Servo Control PID} \]

\[ \delta_{\text{Cmd.}} = 0 \]

\[ \text{Snub Logic} \]

\[ \text{WatchDog} \]

\[ \text{Enable} \]

\[ \text{Bypass} \]

\[ \text{To Model: Servovalves} \]
Control Law Design Block Diagram