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

<table>
<thead>
<tr>
<th>Baseline “SUGAR Free” Conventional Configuration</th>
<th>“Refined SUGAR” Conventional Configuration</th>
<th>“SUGAR High” Truss Braced Wing Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>N+3</td>
<td>N+3</td>
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</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 Model Instrumentation

Wing Assembly

Strut Assembly

<table>
<thead>
<tr>
<th>Instrumentation</th>
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<tbody>
<tr>
<td>Z axis accel =</td>
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<tr>
<td>X axis accel =</td>
</tr>
<tr>
<td>Stain gage =</td>
</tr>
<tr>
<td>RVDT =</td>
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<td>Fiber optic cable =</td>
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Fixed Wing Project
Fundamental Aeronautics Program
Transonic Dynamics Tunnel
TBW Modes and Frequencies

Wing 2\textsuperscript{nd} out-of-plane bending mode

Wing 1\textsuperscript{st} 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>1</td>
<td>GVT 5.20</td>
<td>FEM19 5.12</td>
<td>1\textsuperscript{st} out-of-plane wing bending</td>
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<tr>
<td>3</td>
<td>9.08</td>
<td>9.17</td>
<td>2\textsuperscript{nd} out-of-plane wing bending</td>
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<td>4</td>
<td>11.35</td>
<td>11.34</td>
<td>1\textsuperscript{st} wing/nacelle torsion</td>
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<tr>
<td>5</td>
<td>19.56</td>
<td>18.53</td>
<td>wing bending</td>
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<tr>
<td>7</td>
<td>28.44</td>
<td>27.44</td>
<td>wing/nacelle torsion/bending</td>
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</table>
Flutter Boundary Summary

![Graph showing flutter boundary summary with various data points and lines indicating different conditions such as pre-holiday and post-holiday AOA at various dynamic pressures and Mach numbers.](image-url)

Legend:
- Red: Pre-holiday -3° AOA
- Black: Pre-holiday -1° AOA
- Blue: Pre-holiday +1° AOA
- Green: Pre-holiday +3° AOA
- Red: Post-holiday -3° AOA
- Black: Post-holiday -1° AOA
- Blue: Post-holiday +1° AOA
- Green: Post-holiday +3° AOA

Mach Number vs Dynamic Pressure psf plot with various constant dynamic pressure lines (H = 1000, 700, 500, 300, 200) and data points indicating different conditions.

Fixed Wing Project
Fundamental Aeronautics Program
Analysis/Test Comparison

The graph shows the analysis/test comparison for different dynamic pressures and Mach numbers. The dynamic pressure is plotted on the y-axis, and the Mach number is on the x-axis. Lines represent various experimental conditions and simulations, with labels such as 'Experimental post holiday AOA -3°', 'FEM20 AOA -3°', and so on. The graph includes labels for different altitudes (H = 1000, H = 700, H = 500, H = 300, H = 200) to indicate the altitude at which these conditions are observed.

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Fundamental Aeronautics Program
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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
Closed Loop Results, AOA > 0

AOA +1

<table>
<thead>
<tr>
<th>Dynamic Pressure, psf</th>
<th>Mach Number</th>
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<tr>
<td>200</td>
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<tr>
<td>150</td>
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<td>100</td>
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<tr>
<td>50</td>
<td>0.7</td>
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<tr>
<td>H = 1000</td>
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<tr>
<td>H = 700</td>
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AOA +3

<table>
<thead>
<tr>
<th>Dynamic Pressure, psf</th>
<th>Mach Number</th>
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<tr>
<td>200</td>
<td>1.0</td>
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<tr>
<td>150</td>
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<td>100</td>
<td>0.8</td>
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<tr>
<td>50</td>
<td>0.7</td>
</tr>
<tr>
<td>H = 1000</td>
<td></td>
</tr>
<tr>
<td>H = 700</td>
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Closed-loop stable: FEM19 based controller
Closed-loop stable: sysID based controller
Flutter boundary
H = 500
FEM19 Controller OL/CL @ Unstable Condition
Flutter Suppression
OL/CL Gust Response, FEM19 Based Control
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  – Experimental ASE Results
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• Conclusions
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], “Aerelastic 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
- High Speed Aileron
- Low Speed Aileron
- Side-wall Mounted
- Strut
# Boeing Weight Results with Resized FEM

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<tr>
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<td>Config 1</td>
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<td>Delta</td>
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<td>Spurs</td>
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<td>Spar Caps</td>
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<td>Rib Caps</td>
<td>160.9</td>
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<td>Strut</td>
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<td>889.6</td>
<td>102.5</td>
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<td>244.5</td>
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<tr>
<td>Jury</td>
<td>21.4</td>
<td>24.0</td>
<td>2.6</td>
<td>35.7</td>
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<td>14.2</td>
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<td>Gear Pylon 2D</td>
<td>3415.2</td>
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<td>Gear Pylon 1D</td>
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<td>Total</td>
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<td>808.9</td>
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</table>

Updated flutter penalty increases to 809 lb
Dynamically Scaled Model

<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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<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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<th>Velocity</th>
<th>Mass</th>
<th>Acceleration</th>
<th>Force</th>
<th>Stiffness</th>
<th>Frequency</th>
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<table>
<thead>
<tr>
<th>Weight (lb)</th>
<th>Span (ft)</th>
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<th>Dyn Pres (psf)</th>
<th>Density (s/cf)</th>
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<tr>
<td>109.63</td>
<td>12.75</td>
<td>0.820</td>
<td>162.03</td>
<td>0.001597</td>
<td>450.52</td>
<td>5.07E+06</td>
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</table>
Truss-Braced Wing: Wing Weight Uncertainty

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FEM 19 and FEM 20 Differences

v.19 FEM

v.20 FEM

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
NASTRAN Flutter Analysis

Mach, Alpha, Q

Steady Aerodynamic Corrections

SOL144

Force Cards

SOL106
Param LGDISP

Updated Stiffness

SOL145
Restart

Unsteady Aerodynamic Corrections

Typical Linear Analysis
Control Systems
Control Law Design Block Diagram