NAG–1–2217
MULTIDISCIPLINARY DESIGN INVESTIGATION OF TRUSS-BRACED WING AIRCRAFT: PHASE 4

Final Report
April 2000

Principal Investigators:
B. Grossman, R. K. Kapania,
W. H. Mason and J. A. Schetz

Department of Aerospace and Ocean Engineering
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061

Virginia Tech
The subject grant NAG-1-2217 was in effect from 7/1/99 to 10/31/99. The objective of this grant was to complete a strut-braced wing study which began under grant NAG-1-1852, which was in effect from 6/27/96 until 9/15/99. While the initial grant was on-going, we were also under subcontract to Lockheed-Martin, Aerospace Systems Division, Marietta, GA to do additional studies related to the strut-braced wing grant under contract RV28007, "A Structural and Aerodynamic Investigation of a Strut-Braced Wing Transonic Aircraft Concept", 4/1/98-11/15/98. Lockheed-Martin was under contract to NASA Langley under contract NAS1-96014 DA17. Finally the research under this grant has led to a joint proposal from NASA Langley, Lockheed-Martin, Virginia Tech and NASA Dryden to develop a transonic strut-braced wing demonstration aircraft in response to NASA NRA 99-LaRC-3, Flight Research for Revolutionary Aeronautical Concepts (REVCON). This final report summarizes the research done under NAG-1-2217, augmented by the additional concommitant research projects mentioned above.

The transonic truss-braced wing is a highly integrated technology concept that has large potential payoffs including aircraft weight reduction and increased cruise performance. The operational benefits are a higher aspect ratio, lower thickness ratio, and lower wing weight compared to the conventional cantilever wing. The reduction in thickness allows the wing sweep to be reduced without incurring a transonic wave drag penalty and results in a further reduction of the wing weight. The reduced wing sweep also allows a larger percentage of the wing area to achieve natural laminar flow resulting in lower drag.

The basic idea of a transonic strut-braced wing can be traced to early studies conducted from 1954 to 1981, which concluded that although the strut-braced wing concept showed promise, it also required careful technology integration between aerodynamics and structures. Design tools needed to perform the integrated analysis required for this concept were not available. However, when contemporary Multidisciplinary Design Optimization (MDO) techniques are employed to integrate the aerodynamic and structural design requirements, results indicate that not only is take-off gross weight reduced by more than 10-percent, but fuel usage is reduced in excess of 20-percent. This is for the case of fuselage-mounted engines. Significantly larger weight reductions (19% TOGW) are obtained for the wing-mounted engine case. An extensive follow-on industry study additionally found a 42-percent reduction in emissions and a 26-percent reduction in direct operating cost when a strut-braced wing was installed on a 2010 entry advanced transport aircraft compared to a 1995 technology baseline aircraft.

Two key technology issues are critical. These are the aerodynamic interference penalties associated with the wing-strut junction at transonic speeds, and the need for an innovative tension-only strut mechanism to avoid the problem of strut buckling at the negative g loading condition. In previous studies, the need for the strut to be strong enough to avoid buckling under the negative g condition resulted in the transonic strut-braced wing concept actually becoming heavier than the corresponding cantilever wing design.
In the course of our research, three students have completed M. S. theses, Joel Grasmeyer, Amir Naghshineh-Pour and Jay Gundlach, and one student has completed a Ph.D. dissertation, Philippe Tétrault. Another M.S. degree, Andy Ko and another Ph. D. degree, Erwin Sulaeman are in progress. In addition, Dr. Frank H. Gern, working as a Post-Doc participated fully in this research.

On January 11, 2000, Joel Grasmeyer won the Dr. Abe M. Zarem Award for Distinguished Achievement. The award was “presented as a means for students pursuing advanced degrees in aeronautics and astronautics to showcase their talent and work.” Joel’s award was for his master’s level work on “Multidisciplinary Design Optimization of a Truss-Braced Wing Aircraft” and was presented at the 38th AIAA Aerospace Sciences Meeting in Reno NV.

The results of our research may be found in the viewgraphs at the end of this report. The research is also reported in Refs. 1–16 below.
REFERENCES


Strut-Breased Wing
Transonic Commercial Transport with a
Multidisciplinary Design Optimization of a
- CFD and Interference Drag
  - Philippe-Andre Tetrault*

- Aeroelasticity
  - Enwin Sulaeman

- Structures
  - Amir Naghshineh-Pour*
  - Dr. Frank H. Gem
  - Joel Grasmeyer*
  - John Gundlach IV*

- Aerodynamics and MDO
  - Andy Ko

- Faculty Members
  - Dr. B. Grossman,
  - Dr. R.K. Kapania
  - Dr. R.T. Haftka
  - Dr. J.A. Schetz
  - Dr. W.H. Mason

*Students that have graduated
Some History

1996: VPI starts MDO work under NASA Support
1978: AFWAL studies include strut concepts
Werner Pfenninger proposes concept by early 1950s

Late 1997/early 1998: Internal LARC study
Results look promising

1998: VPI briefs both Boeing and Lockheed Martin

1998: Both VPI and LMAS do additional work
VPI works as subcontractor to LMAS

1999: LMAS contracted by NASA LARC

1999: NASA/LSMS/VPI Team propose a demonstrator aircraft

• 1999: Both VPI and LMAS do additional work

• 1999: NASA/LSMS/VPI Team propose a demonstrator aircraft
- Higher aspect ratio means smaller chords and smaller Re

- Un-sweeping the wing reduces cross-flow instability

- Parasite drag is reduced via increased laminar flow

- Reduced t/c allows less sweep without wave drag penalty

- Lower weight and increased span reduce induced drag

- Wing t/c reduced without a weight penalty

- The strut increases the structural efficiency of the wing

Advantages

Strut-Braced Wing
MDO Process
Description of the

includes static aerelasticity
Structural Optimization

Drag
Interference
Wave Drag
Form Drag
Friction
Induced

Aerodynamics

Weights
Wing bending
Material weight
SFC

Structural Optimization

Performance
Range/Field

Control
Stability and
Performance

Propulsion

Geometry
Initial Design Variables

Updated Design Variables
Tip Mounted Engines SWB only
Vertical Tail Scaling Factor
Under Wing Engine SWB only
Position of Engine
Altitude
Engine Thrust
Fuel Weight
Wing Centerline Skin Thickness
Wing t/c (3)
Wing Centerline and Tip Chord for SWB
Cantilever Centerline Chord = 52 ft.
Wing Chord
Wing t/4 Chord Sweep
Wing Half Span
Objective: Minimize Takeoff Gross Weight

Statement
MDO Problem
- Slack Load Factor
- Landing Distance
- Missed Approach Climb Gradient
- Approach Velocity
- Balanced Field Length
- Second Segment Climb Gradient
- Wing Deflection
- Engine Out
- Fuel Capacity
- Maximum Section Cl.
- Initial Cruise Rate of Climb
- Range

Constraints

Optimization Method: Method of Feasible Directions (DOT)
- 325 Passengers

- Two GE-90 Class Engines

Design Mission
Fuselage Mounted Engines SWB

Fuel Weight = 190366 lbs. (14.1%)
TGW = 546709 lbs. (10.0%)

Cantilever Optimum

Fuel Weight = 221692 lbs.
TGW = 607656 lbs.
Tip Mounted Engines SWW

Wing Mounted Engines SWW

Fuel Weight = 185159 lbs. (16.5%)
Fuel Weight = 185892 lbs. (16.1%)

TOW = 523563 lbs. (13.8%)
TOW = 521023 lbs. (14.3%)
<table>
<thead>
<tr>
<th>Wing Loading (lb/ft²)</th>
<th>Thrust to Weight Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.251</td>
<td></td>
</tr>
<tr>
<td>0.227</td>
<td></td>
</tr>
<tr>
<td>0.195</td>
<td></td>
</tr>
<tr>
<td>0.164</td>
<td></td>
</tr>
<tr>
<td>0.131</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Wing Lc</td>
</tr>
<tr>
<td>32.1</td>
</tr>
<tr>
<td>31.5</td>
</tr>
<tr>
<td>31.0</td>
</tr>
<tr>
<td>29.5</td>
</tr>
<tr>
<td>19.4</td>
</tr>
<tr>
<td>10.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Aspect Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.0</td>
</tr>
<tr>
<td>3.5</td>
</tr>
<tr>
<td>3.0</td>
</tr>
<tr>
<td>2.5</td>
</tr>
<tr>
<td>2.0</td>
</tr>
<tr>
<td>1.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reference Area (ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4620.2</td>
</tr>
<tr>
<td>4369.6</td>
</tr>
<tr>
<td>4077.5</td>
</tr>
<tr>
<td>3820.2</td>
</tr>
<tr>
<td>3563.1</td>
</tr>
<tr>
<td>3351.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wing Half-Span (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>101.8</td>
</tr>
<tr>
<td>106.6</td>
</tr>
<tr>
<td>110.8</td>
</tr>
<tr>
<td>114.4</td>
</tr>
<tr>
<td>118.2</td>
</tr>
<tr>
<td>122.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero Tuel Weight (lb)</td>
</tr>
<tr>
<td>38942</td>
</tr>
<tr>
<td>18582</td>
</tr>
<tr>
<td>7946</td>
</tr>
<tr>
<td>52203</td>
</tr>
<tr>
<td>55554</td>
</tr>
<tr>
<td>33513</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fuel Weight (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18582</td>
</tr>
<tr>
<td>7946</td>
</tr>
<tr>
<td>52203</td>
</tr>
<tr>
<td>55554</td>
</tr>
<tr>
<td>33513</td>
</tr>
<tr>
<td>15343</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wing Weight (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18582</td>
</tr>
<tr>
<td>7946</td>
</tr>
<tr>
<td>52203</td>
</tr>
<tr>
<td>55554</td>
</tr>
<tr>
<td>33513</td>
</tr>
<tr>
<td>15343</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Calculated Takeoff Weight (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>607656</td>
</tr>
<tr>
<td>546709</td>
</tr>
<tr>
<td>522072</td>
</tr>
<tr>
<td>52203</td>
</tr>
<tr>
<td>55554</td>
</tr>
<tr>
<td>33513</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Weights</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBW Engines Mounted</td>
</tr>
<tr>
<td>Tip</td>
</tr>
<tr>
<td>Wing</td>
</tr>
<tr>
<td>Fuselage</td>
</tr>
<tr>
<td>Canarder</td>
</tr>
</tbody>
</table>

Mission Profile:

- 7500 nmi. Range + 500 nmi. Reserve
- 325 Passengers

Design Comparisons
<table>
<thead>
<tr>
<th>Thrust to Weight Ratio</th>
<th>Performance (%)</th>
<th>Average Wing Uc</th>
<th>Aspect Ratio</th>
<th>Reference Area</th>
<th>Wing Half-Span</th>
<th>Geometry (%)</th>
<th>Zero Fuel Weight</th>
<th>Wing Weight</th>
<th>Fuel Weight</th>
<th>Takeoff Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>-5.6</td>
<td>-2.8</td>
<td>-22.8</td>
<td>-5.4</td>
<td>-10.2</td>
<td>-117</td>
<td>21.6</td>
<td>10.5</td>
<td>-21.7</td>
<td>-7.7</td>
<td>-9.6</td>
</tr>
<tr>
<td>-3.3</td>
<td>-3.3</td>
<td>-21.6</td>
<td>-11.7</td>
<td>-117</td>
<td>-11.2</td>
<td>21.7</td>
<td>10.5</td>
<td>-16.1</td>
<td>-16.1</td>
<td>-14.3</td>
</tr>
<tr>
<td>-2.8</td>
<td>-2.8</td>
<td>-21.6</td>
<td>-11.7</td>
<td>-117</td>
<td>-11.2</td>
<td>21.7</td>
<td>10.5</td>
<td>-12.3</td>
<td>-16.5</td>
<td>-13.8</td>
</tr>
<tr>
<td>-4.2</td>
<td>-4.2</td>
<td>-21.7</td>
<td>-5.5</td>
<td>-6.5</td>
<td>-8.4</td>
<td>21.7</td>
<td>10.5</td>
<td>-12.3</td>
<td>-16.5</td>
<td>-13.8</td>
</tr>
</tbody>
</table>
Wing

- Stiff imposes compressive forces on the inboard

Wing buckling •

Optimization process

- Incorporation of passive load alleviation into

Flexible wing sizing •

Double deck fuselage design

- Need to know the sensitivity of the designs with

Constraint studies •
Lagrange multipliers used to calculate sensitivities

- Strut slack load factor
- Approach velocity
- Balanced field length
- Second segment climb gradient
- Wing deflection
- Engine out
- Section Cl max
- Range

Considered constraints

Need to determine the sensitivity of designs towards design
| Rank | Sections | Load Factor | Upper Strut Stack | Wing Deletion | Second Segment | Climb Gradient | Second Segment | Upper Strut Stack | Length | Balanced Field | Climb Gradient | Second Segment | Approach Velocity | Section CI Max | Section CI Max | Range | Range | Range | Engine Out | Balanced Field | Balanced Field | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engines SBW | Engineers
The SWB is generally less sensitive than the cantilever optimum.

Sensitivities are valid within 5% of the optimum design.

<table>
<thead>
<tr>
<th>Unscaled Sensitivities (lbs/ft)</th>
<th>Constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unscaled Sensitivities (lbs)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SBW Engines Mounted Tip Wing</th>
<th>SBW Engines Mounted Tip Wing</th>
<th>SBW Engines Mounted Tip Wing</th>
<th>SBW Engines Mounted Tip Wing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Seark Slack Factor (0.8)</td>
<td>Approach Velocity (140 Kts)</td>
<td>Balanced Field Length (11000 ft)</td>
<td>Second Segment Climb Grad (lbs/deg)</td>
</tr>
<tr>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>2.52520.49</td>
</tr>
<tr>
<td>0.00</td>
<td>1.52520.49</td>
<td>6.34</td>
<td>2.52520.49</td>
</tr>
<tr>
<td>2.52520.49</td>
<td>1.335883.33</td>
<td>4.57766.67</td>
<td>1.518637.50</td>
</tr>
<tr>
<td>-1.197.90</td>
<td>-630.55</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>469357.89</td>
<td>65.92</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>41.22</td>
<td>40.53</td>
<td>41.62</td>
<td>41.62</td>
</tr>
<tr>
<td>57.74</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Second Segment Climb Grad (0.024) Winging Deflection (20 ft) Engine Out Section CI Max (0.8) Range (7500 nmi)
A double bubble design was adopted giving an extra 5 ft of wing strut separation.

- Determine dimensions of the fuselage and cargo layout was investigated
to larger wing strut separation
- Probable improvement in TCGW savings due
Recalculation of wing weight from flexible wing

Method

Calculation of wing deformation

Lift redistribution due to wing deformation (2.5g)

Inaccurate results for maneuver, maneuver, maneuver, maneuver, maneuver.

Wing sizing from rigid lift redistribution gives
- Validated with several standard test cases
- Consideration of panel twist and dihedral
- Analysis or optimization mode (Vortex lattice method)
- 40 spanwise and 1-10 chordwise vortex panels (single)
- Aerodynamic model
  - Validated with Lockheed C-5B and Boeing 747-100 data
  - Piecewise linear load representation
  - High accuracy (based on Lockheed wing sizing experience)
  - Stringers, and skins
  - Optimized area/thickness ratios for spar webs, spar caps
  - Hexagonal wing box with
- Structural wing model

Flexible Wing Sizing
Nondimensional wing span

Flexible wing (stiff at front spar)
Flexible wing (stiff in elas. axis)
Rigid wing

Further load alleviation

Flexible load is due to reduced wing box
SBW load alleviation

Flexible load was due to

Aerodynamic loads are

Upward bending (wash-out)
Angles of attack due to

Reduction of outboard wing

Desing

Fuselage mounted engine

Maneuver Load Allivation

For Advanced Vehicles
C\textsuperscript{L} at Wing Root - Convergence History

Spanload

LMA Configuration (Strut at Wing-Box Front Spar)

Weight Calculation

Flexible Wing

Virginia Tech
Convergence
Wing bending weight

Wing deformation at 2.5g
Strut offset
Fuselage mounted engine design (Influence of chordwise

Maneuver Load Alllevation

For Advanced Vehicles

Multi-disciplinary Analysis and Design
Flexible Wing Sizing

Significance of

Weights for tip-mounted engines SBW

But: flexible wing sizing indicates higher wing

underwing mounted engines SBW

for canard/wing, fuselage mounted and

Rigid wing sizing gives conservative results

Impact on MDO results is comparably small

Wing sizing using flexible wing loads is more

accurate
- Increased outboard wing loading (wash-in)
- Downward deflection of the outboard wing sections

2.5g maneuver

2.5g (engine C.G. in el. axis)
Tip mounted engine

Fuselage mounted engine

Normalized lift coefficients $C_l/C_{ave} = 2.59$

Lift Distribution

Flexible Wing

Rigid Wing

Flexible Wing (stall at front spar)
Flexible Wing (stall in el. axis, engue at clp)
Flexible Wing (stall in el. axis, engue in el. axis)
Rigid Wing
Engine offset = f. Cip

Reduction of wing loading using chordwise engine and strut position

Weight
Wing Bending Material

Virginia Tech

Center for Advanced Structures and Design
Higher Weight Configuration
Lowest Weight Configuration

2.5g Maneuver Spanload Convergence
Lowest weight configuration

2.5g maneuver wing deformation

Higher weight configuration
to strut force
Investigation of inboard wing buckling due
Inboard wing compressive loading
Very high horizontal strut force component
Sharp angle between wing and strut

Inboard Wing Buckling
- Comparison with NASTRAN
- Validation of the finite element code
- Sensitivity and optimization for the buckling case
  is based on the variational principle approach
- The geometric stiffness matrix for buckling analysis
  elements to increase the accuracy and CPU time
- Analytical formulation for non-prismatic beam
- MDO code
- The code should be fast enough as part of the
  developed a finite element code

---

Analysis
SBW Wing Buckling

Virginia Tech
\[ f = 8, m = 1 \]
\[ \left\{ \frac{EI}{\rho} \right\}_{0}^{0} = (c) \]

**Cantilever Beam**

**Validation 1:**
<table>
<thead>
<tr>
<th>Rz</th>
<th>Ry</th>
<th>Rx</th>
<th>Tz</th>
<th>Ty</th>
<th>Tx</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>5</td>
<td>6</td>
<td>8</td>
<td>7</td>
<td>4</td>
</tr>
</tbody>
</table>

**Frame Validation 4:**

**Deformations at Point 1**

The — CBEM Element 26

Number of elements used to model
Present FEM: $p = 21.40 \times 9327708195$

NASTRAN: $p = 21.405$ (16 elements)

$r = 8$

$E\ell = E\ell^0 (1 + r x/L)$

Tapered beam

Buckling Analyses

Validation 7
\[
\left\{ (x)\eta \varphi + (x)\eta - \frac{d\eta}{dx} \varphi + \frac{d\eta}{dx} (x + a - b) - \frac{p_{\text{mu}}}{\eta} \varphi (x - \gamma) \left( w - bw + \frac{\gamma}{100\eta} b \right) + (x - \gamma)(1 - b)w \right\} \\
\times \frac{(x)\eta \varphi}{x^d g} = (x)\eta
\]

\[
\zeta (1 - \zeta)(\zeta - b) - \left\{ \eta \varphi - (1 - b)\eta \varphi + (1 - \zeta)(1 - b) \zeta \right\} \frac{\zeta}{(1 - \zeta)} = \lambda
\]

The optimum buckling load

\[
\frac{\zeta I}{EI} \lambda = \text{optimum load}
\]

The optimum load

\[
\frac{E}{dp} = \zeta q
\]

\[
\frac{d\eta}{dp} = \frac{100\eta}{\zeta x + 100\eta} = \rho
\]

\[
(1 - \zeta) = \mu
\]

\[
\eta = 1
\]

\[
\frac{E}{\varphi} = \text{optimum}
\]

Stiffness Distribution

Optimum Beam
buckling load

- strut increases the
silliness matrix of the

- additional geometric

- inboard

- the junction moves

- as buckling increases as

- wing silliness

- does not change the

- position silliness

- wing/strut junction

- changes of the

- Assume that the

**Strut Junction Position**

Variation of the
the fuselage wing and the diameter of between the strut and is related also to the slope buckling.

- The change of the P
  h reference = h actual = 2.2 ft
  h = the offset beam length + 2.5 g maneuver + 0.5 ft.
  Contig. SF opt 8 ft.
Position Effects

Offset Length and
Spanwise Position of the Junction

Move Inboard

For Advanced Vehicles
MAE Center

Intelligent Manufacturing Analysis and Design

Virginia Tech
$20 million
- Phase 2: 3 years
- $300,000
- Phase 1: 9 months
- Program phases
- Years

Concept demonstrator within the next three years

REVCON involves building and testing a
REVCON ( Revolutionary Concepts) project

We have submitted a proposal together with

Future Work