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Transport Weight Reduction through MDO: The Strut-Braced Wing Transonic Transport

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Multidisciplinary Design Optimization (MDO) has been used to investigate the use of a new concept for a transonic transport, the strut-braced wing. The incorporation of a strut into more traditional transonic transport concepts required the application of computational design techniques that had been developed at Virginia Tech over the previous decade. Formalized MDO methods were required to reveal the benefits of the tightly coupled interaction between the wing structural weight and the aerodynamic performance. To perform this study, a suite of approximate analysis tools was assembled into a complete, conceptual-level MDO code. A typical mission of the Boeing 777-200IGW was chosen as the design mission profile. Several single-strut configurations were optimized for minimum takeoff gross weight, with the best single-strut configuration showing a nearly20% reduction in takeoff gross weight, a 29% reduction in fuel weight, a 28% increase in the lift-to-drag ratio, and a 41% increase in seat-miles per gallon relative to a comparable cantilever configuration. The use of aeroelastic tailoring in the design illustrated ways to obtain further benefits. The paper synthesizes the results of the five-year effort, and concludes with a discussion of the effects various constraints have on the design, and lessons learned on computational design during the project.

Introduction

Strut, or truss-braced, wing concepts have been used in the design of many low-speed airplanes. Maurice Hurel used the concept to implement very high aspect ratio wings on aircraft. Using a strut, the aircraft could enjoy the high *L/D* benefits of a high aspect ratio wing without paying a large structural weight penalty. This research resulted in the design and brief success of the HD-31, and later led to the development of the Shorts Skyvan. A summary of this work is available in two references.[1,2]

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The idea of using a truss-braced wing configuration at transonic speeds apparently originated with Werner Pfenninger[3] at Northrop in the early 1950s. Although he was primarily interested in reducing parasite drag through laminar flow control, he realized that to obtain an efficient airplane, the induced drag had to be reduced to a value comparable to the parasite drag at cruise. This led to the need for high aspect ratio wings, and the strut-braced wing concept arose for the same reasons that it was used by Hurel. Other strut-braced wing aircraft investigations followed Pfenninger's work, notably the work at Boeing reported by Jobe et al.[4] and Park[5] from Stanford. The Boeing work is remarkable in that it used many of the methods that appeared later as being fundamental to an MDO toolkit. This included both response surface methodology and variable complexity modeling. Park pointed out explicitly the weight penalty arising from designing the strut to prevent buckling under the negative *g* load condition. Turriziani et al.[6] also considered the advantages of the strut-braced wing concept on a subsonic business jet with an aspect ratio of 25.

The computational design of Strut-Braced Wing Concepts using MDO at Virginia Tech

The tight coupling between aerodynamics and structures required to obtain the full potential of the strut-braced wing concept led Dennis Bushnell at NASA Langley to suggest that the concept be re-examined with MDO methods. Subsequently, the strut-braced wing (SBW) design concept was studied by the Multidisciplinary Analysis and Design (MAD) Center at Virginia Tech for several years (1997 – 2001). We had been developing computational design methodology for MDO for a number of years with both NASA and NSF support. Our initial application focus was the high speed civil transport (HSCT).[7] Based on that work, an appreciation of the design issues and some general guidelines emerged.[8,9] We applied our approaches to the strut-braced wing design. The initial framework for the MDO problem was developed by Grasmeyer.[10,11] The entire team reported all the results in a MAD Center Report.[12] Key components of the methodology specific to the concept included engine out analysis and induced drag of strut braced wings by Grasmeyer,[13,14] and a strut-braced wing bending material weight analysis by Naghshineh-Pour, et al.[15] Strut-wing aerodynamic interference was addressed by Tetrault,[16] and later in more detail by Ko, et al.[17] An examination of the role that constraints play in determining the final design was investigated by Ko.[18,19] The refinements to the design work resulting from collaborative work with Lockheed Martin Aeronautical Systems (LMAS) led to further refinements and substantiation of the results.[20]

The structural issues associated with thin high aspect ratio strut-braced wings were the subject of several investigations, including the effects of wing flexibility.[21,22] Passive load alleviation,[23] flutter,[24] and the strut compression issues[25] were also examined. None of these considerations changed the conclusions on the value of the concept.

In addition to studying concepts with traditional engine locations, wing and fuselage mounted, we also studied tip-mounted engines. Although the engine out problem for a two-engine tip mounted concept is severe, there have been experimental studies that suggest that induced drag can be significantly reduced. The various reports cited above include details. When considering tip-mounted engines, it is necessary to use circulation control on the vertical tail to generate the side force required to control the airplane.[26]

In the work presented here we will consider four cases. They are a reference cantilever design, and for the strut-braced wing concept, we will consider cases with fuselage mounted engines, wing mounted engines, and wingtip mounted engines.

The design problem

The configuration considered was a 7500 nmi range transonic passenger transport aircraft. Essentially, we used the Boeing 777-200IGW mission, with a specified cruise Mach number of 0.85. There were 305 passengers in a three-call configuration. We also studied other mission, but the results for this mission are described in this paper. For this configuration the strut runs between the bottom of the fuselage to around the 67% semi-span location of the wing. The strut is connected to the wing via a pylon to increase the distance between the wing and the strut at the intersection. To avoid buckling, the strut adopts an innovative telescoping sleeve mechanism so that it only carries tension loads. From an aerodynamics standpoint, minimizing the interference drag between the wing, pylon and strut juncture is a key requirement in the aerodynamic design of the strut-braced wing airplane. Figure 1 illustrates the mission.

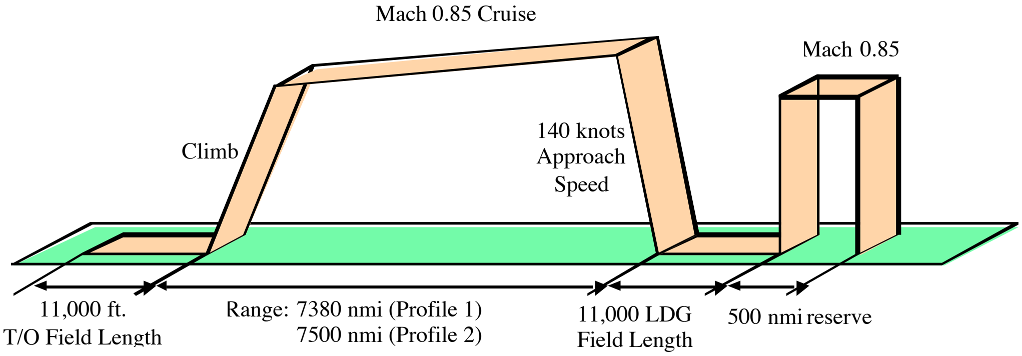


Figure 1. Strut-Braced Wing Mission Profile for Computational Design Using MDO

The MDO Problem Formulation

For the purpose of computational design, we characterize the plane in terms of a number of design variables and constraints. Table 1 provides a list of the design variables.

Table 1: Design variables used in the different configurations.

	Design Variables	Cantilever Optimum	Fuselage Mounted Engines SBW	Wing Mounted Engines SBW	Tip Mounted Engines SBW
1	Spanwise position of wing/strut intersection		✓	✓	✓
2	Wing semispan (ft)	✓	✓	✓	✓
3	Wing sweep (deg)	✓	✓	✓	✓
4	Wing dihedral (deg)		✓	✓	✓
5	Strut sweep (deg)		✓	✓	✓
6	Strut chordwise offset (ft)		✓	✓	✓
7	Strut vertical aerodynamic offset (ft)		✓	✓	✓
8	Wing centerline chord (ft)		✓	✓	✓
9	Wing break chord (ft)	✓			
10	Wing tip chord (ft)	✓	✓	✓	✓
11	Strut chord (ft)		✓	✓	✓
12	Wing thickness to chord ratio at centerline	✓	✓	✓	✓
13	Wing thickness to chord ratio at breakpoint	✓	✓	✓	✓
14	Wing thickness to chord ratio at tip	✓	✓	✓	✓
15	Strut thickness to chord ratio		✓	✓	✓
16	Wing skin thickness at centerline (ft)	✓	✓	✓	✓
17	Strut tension force (lbs)		✓	✓	✓
18	Vertical tail scaling factor	✓	✓	✓	✓
19	Fuel weight (lbs)	✓	✓	✓	✓
20	Required thrust (lbs)	✓	✓	✓	✓
21	Spanwise position of engine		✓		
22	Average cruise altitude (ft)	✓	✓	✓	✓

Table 2 lists the constraints employed in the computational design.

Table 2: Design Constraints

	Description	Constraint
1	Range	Mission + Reserve Range < Calculated Range
2	Initial Cruise Rate of Climb	Initial Cruise ROC > 500 ft/min
3	Max. Allowable Section C_l	Calculated Maximum $C_l <$ Maximum Specified C_l
4	Fuel Capacity	Fuel Weight < Fuel Capacity
5	Engine-out	Required C_n < Available C_n
6	Wing deflection	Wing deflection < 20 ft.
7	Second Segment Climb Gradient	Calculated Gradient > 0.024
8	Balanced Field Length	Balanced Field Length < 11000 ft.
9	Approach Velocity	Approach Velocity < 140 knots
10	Missed Approach Climb Gradient	Calculated Gradient > 0.021
11	Landing Distance	Landing Distance < 11000 ft.
12	Slack Load Factor	0. < Strut Slack Load Factor < 0.8

The design variables and constraints are then used in a framework that is driven by a gradient based optimization algorithm. In this work we use Vanderplaats's DOT Software.[27] The framework is shown in Figure 2.

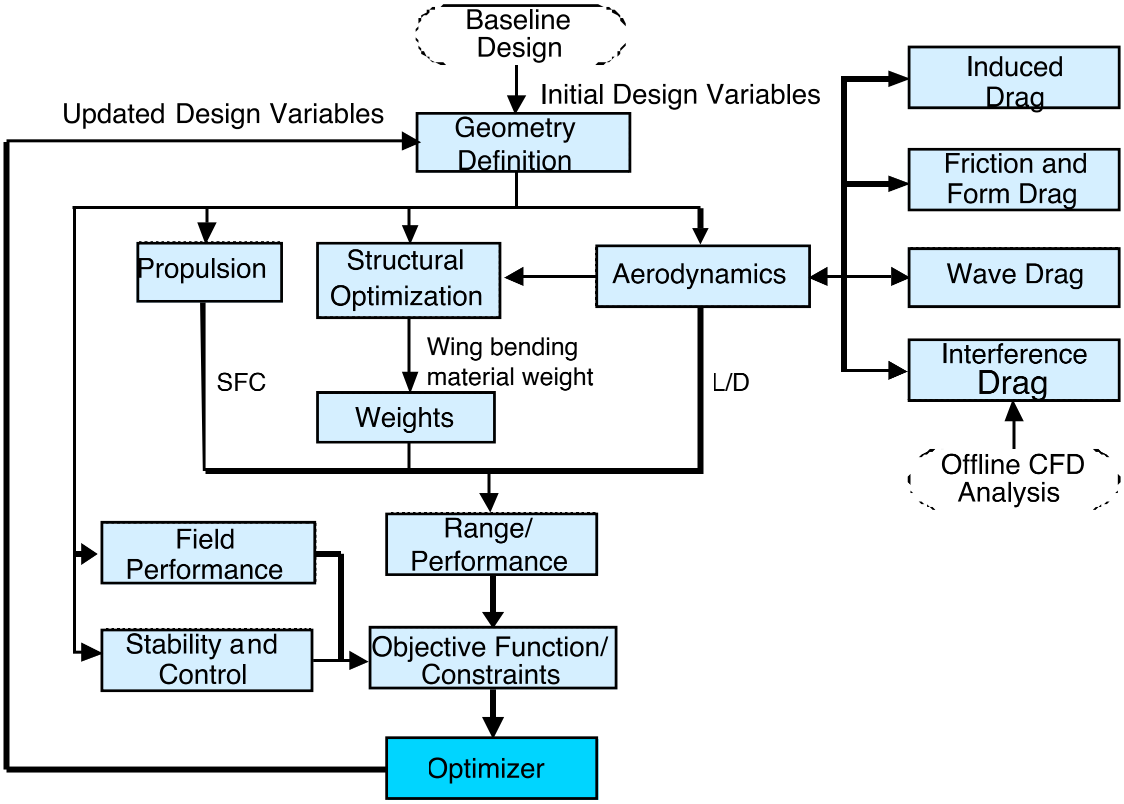


Figure 2. MDO Code Architecture

As described in the introduction, modules for the various disciplines were developed individually, and are described in the appropriate references. It is worth noting that aside from the special wing bending material weight routine, the weights essentially come from FLOPS.[28] Because the results are sensitive to the wave drag model, it is worth noting that our approach[29,30] has been evaluated recently and been found to be slightly optimistic,[31] but valid for the comparison studies presented here. The MDO program was written in Fortran. Today we use ModelCenter by Phoenix Integration to couple disciplinary codes. This has improved our productivity significantly. In addition, our students manually restart the optimization several times from slightly different conditions to avoid local optima.

Engineering Innovation

Before presenting the results, it is important to identify the role of engineering innovation in obtaining benefits of the strut concept. Two features of our design were not the result of computations. To avoid the weight penalty associated with the strut under compressive loading, we allow for the use of a mechanism that unloads the strut, similar to a landing gear shock absorber. Consultation with numerous engineers in the industry confirmed our thinking. Thus we assume a weight penalty for this mechanism, and have the wing support the negative 1*g* load as a cantilever beam. The second innovation was the use of an offset pylon to allow for aerodynamic design of the strut-wing juncture without a drag penalty. Subsequent computational aerodynamic design provided insight into the flowfield physics of the juncture, and how to shape the surfaces to achieve a drag-free intersection.[17]

Results

The results presented here are from Ko,[18] and represent the culmination of the refinements to the technique. His thesis, available on the web, should be consulted for a detailed description of the refined methodology. Figure 3 provides the MDO results for the baseline cantilever wing configuration.

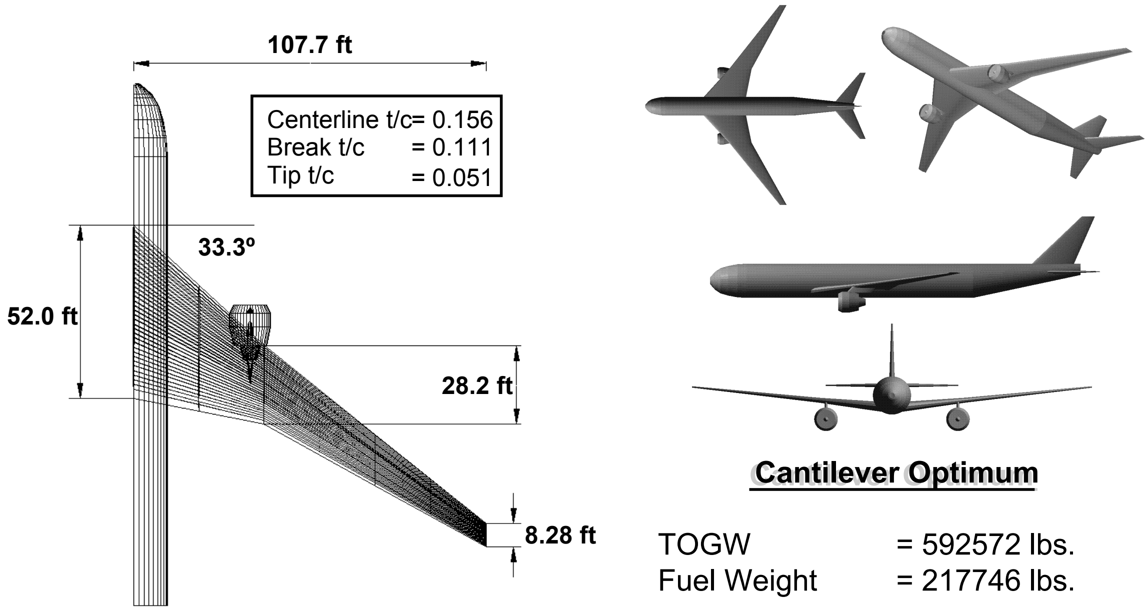


Figure 3. Baseline optimization: the pure cantilever wing transonic transport.

Figures 4 and 5 provide the results for the fuselage-mounted and wing-mounted engines strut-braced wing concepts. Each figure also contains the percentage reduction in takeoff gross weight compared to the reference cantilever design. The wing-mounted engine case results in a 19% reduction in TOGW, a truly remarkable result. The strut allows for an increase in aspect ratio, and a reduction in *t/c*. The reduction in *t/c* allows the wing to unsweep. Thus the wing weight is reduced while the aspect ratio is increased. The balance between the structural and aerodynamic design is only possible using an integrated design approach: MDO.

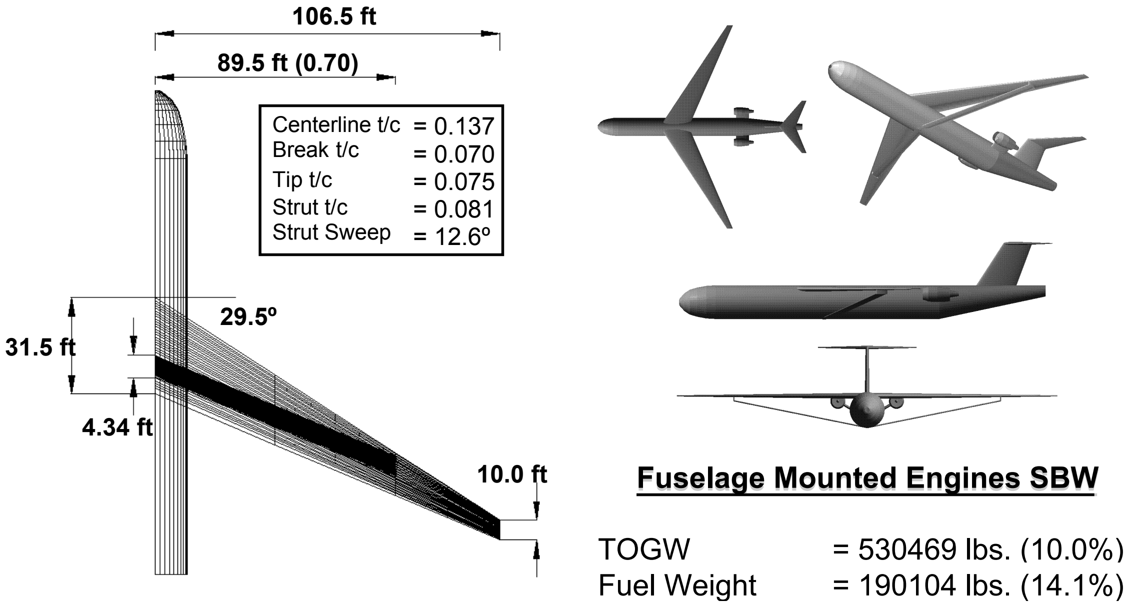


Figure 4. The optimized fuselage-mounted engines strut-brace wing case.

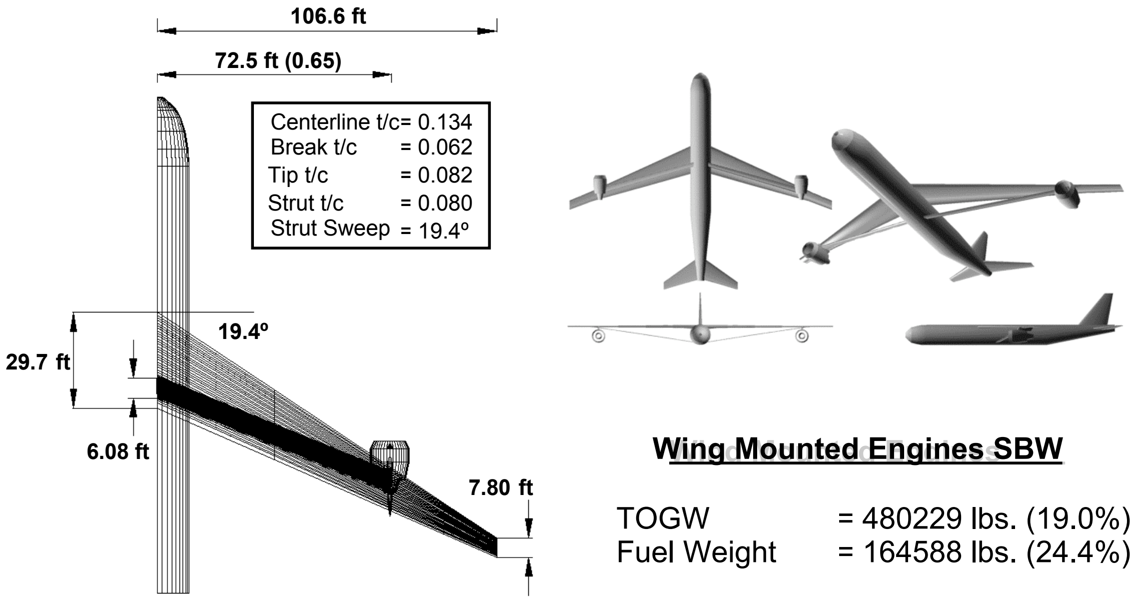


Figure 5. The optimized wing-mounted engines strut-brace wing case.

Even though we take advantage of induced drag reduction using wing-tip mounted engines, Figure 6 shows that the savings in TOGW is not as large as for the wing-mounted engine case. A comparison of the detailed designs is presented in Table 3, and reveals where the savings are found compared to the reference cantilever design.

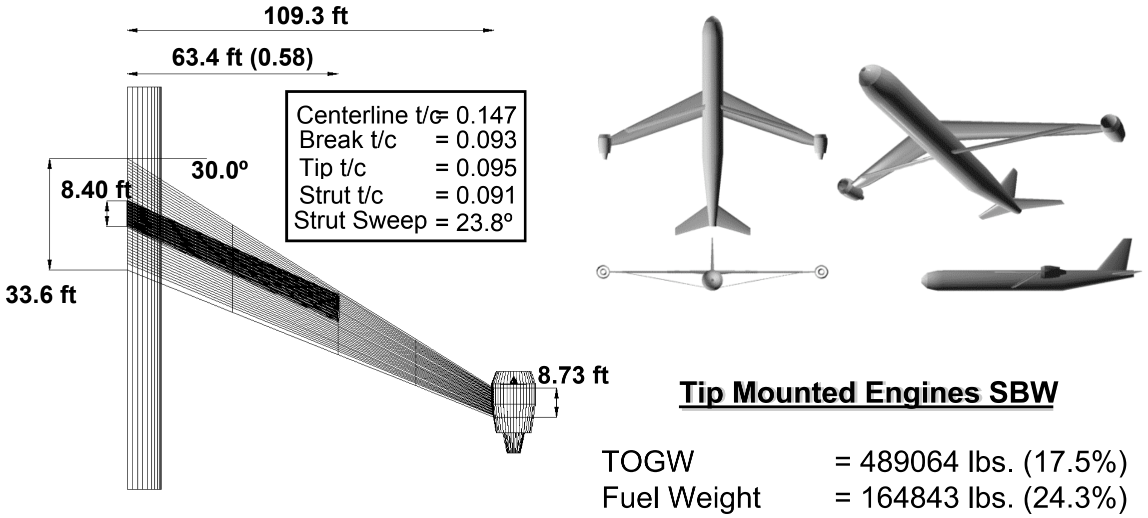


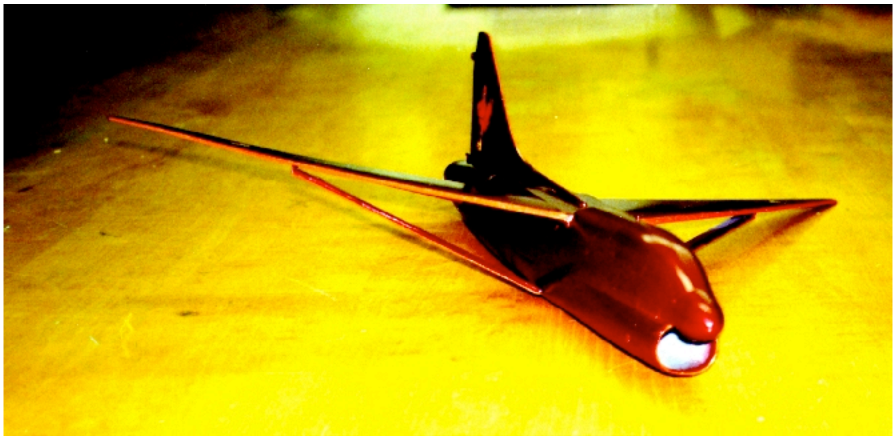
Figure 6. The optimized wing tip-mounted engines strut-brace wing case.

Table 3. Configuration comparison

	Cantilever Wing Optimum	Fuselage Mounted Engines SBW	Wing Mounted Engines SBW	Tip Mounted Engines SBW
Wing Span (ft)	215.4	213.0	213.2	218.6
Reference Area (ft2)	4938.1	4420.6	4001.9	4625.4
Aspect Ratio	9.23	10.3	11.4	10.3
Wing 1/4-Chord Sweep (deg)	33.3	29.5	19.4	30.0
Strut 1/4-Chord Sweep (deg)	N/A	12.6	19.4	23.8
Wing t/c at the Centerline	0.156	0.137	0.134	0.147
Wing t/c at the Chord Breakpoint	0.111	0.07	0.062	0.093
Wing t/c at the Tip	0.051	0.075	0.082	0.095
Strut t/c	N/A	0.081	0.080	0.091
Cruise L/D	21.79	22.58	23.93	24.60
Engine Thrust (lbs)	81568.7	69697.5	60069.8	62226.1
Fuel Weight (lbs)	217746	190104	164588	164843
Wing Weight (lbs)	78072	70440	57171	62962
Takeoff Gross Weight (lbs)	592572	530469	480229	489064

The REVCON Activity

In 1999 the strut-braced wing concept was proposed by NASA Langley as a candidate for the Revolutionary Vehicle Concept program REVCON. It was proposed to convert an A-7 to have a strut braced wing to demonstrate that the strut junction could be designed to be interference free using CFD, and that the strut compressive load could be handled without an excessive weight penalty. As part of this effort, a senior aircraft design team at Virginia Tech used this concept as their project. The model they made is shown in Figure 7.



a) model showing the strut and pylon

b) model view showing the planform

Figure 7. A-7 modified for a strut-brace wing.

Lessons Learned

The combination of computational design and innovative thinking can lead to significant advances in flight vehicles. Advanced design needs both. This educational aspect of having graduate students (and faculty) work as a team can not be underestimated. Students that have worked on this project have gotten very good jobs, and are employing the approaches learned here on the job. Even though the strut-braced wing concept has been identified as being in the category of revolutionary air vehicles,[32] it has not been adopted by the major US airframe manufacturers.

Conclusion

The strut-braced wing transonic transport concept can provide a significant weight reduction compared to existing transonic transport concepts. The design problem is tightly coupled between aerodynamics and structures. Thus, to achieve the advantages of the concept, computational design using MDO was required. The synergy between aerodynamic drag and structural weight associate with wing *t/c*, sweep, and span can only be found with the computational design approach described here. However, several other innovations were also adopted to address possible drawbacks to the concept. The results obtained during the course of the work were so significant that several other design teams reviewed our work. In all cases they verified that our conclusions were substantially correct. An important consideration is that the concept scales to all sizes of transonic airplanes. To date, only airframe manufactures outside North America have shown interest in pursuing the concept.

Acknowledgments

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Note: The papers and reports references for which the authors hold the copyright or have permission to distribute are available electronically from http://www.aoe.vt.edu/~mason/Mason_f/MRpubs.html. Some of the theses are available at http://www.aoe.vt.edu/~mason/Mason_f/MRthesis.html

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