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Conceptual Design Studies of a Strut-Braced Wing Transonic Transport

John F. Gundlach, IV,* Philippe-André Tétrault,* Frank H. Gern,† Amir H. Nagshineh-Pour,* Andy Ko,*
Joseph A. Schetz,‡ William H. Mason,§ Rakesh K. Kapania,§ and Bernard Grossman¶
Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061-0203
and
Raphael T. Haftka**
University of Florida, Gainesville, Florida, 32611-6250

Recent transonic airliner designs have generally converged upon a common cantilever low-wing configuration. It is unlikely that further large strides in performance are possible without a significant departure from the present design paradigm. One such alternative configuration is the strut-braced wing (SBW), which uses a strut for wing-bending load alleviation, allowing increased aspect ratio and reduced wing thickness to increase the lift to drag ratio. The thinner wing has less transonic wave drag, permitting the wing to unsweep for increased areas of natural laminar flow and further structural weight savings. High aerodynamic efficiency translates into smaller, quieter, less expensive engines and less pollution. A multidisciplinary design optimization (MDO) approach is essential to realize the full potential of this synergistic configuration caused by the strong interdependence of structures, aerodynamics, and propulsion. NASA defined a need for a 325-passenger transport capable of flying 7500 n miles at Mach 0.85 for a 2010 service entry date. Lockheed Martin Aeronautical Systems (LMAS), as Virginia Polytechnic Institute and State University's (Virginia Tech) industry partner, placed great emphasis on realistic constraints, projected technology levels, manufacturing, and certification issues. Numerous design challenges specific to the strut-braced wing became apparent during the study. Modifications were made to the Virginia Tech formulation to reflect these concerns, thus contributing realism to the MDO results. The SBW configuration is lighter, burns less fuel, requires smaller engines and costs less than an equivalent cantilever wing aircraft.

Nomenclature

b_w = wingspan, ft
C_{Df} = flat-plate friction drag coefficient
C_{Dp} = profile drag coefficient
$C_{d\,wave}$ = wave drag coefficient of strip
C_L = total lift coefficient
C_l = two-dimensional section lift coefficient
$C_{n\,req}$ = required yawing moment coefficient
D_E = drag of inoperable engine, lb
F_F = form factor
L/D = lift-to-drag ratio
M_{crit} = critical Mach number
M_{dd} = drag divergence Mach number
q = dynamic pressure, lb/ft^2
R = range, ft
S = wetted area of component
S_{ref} = reference area (usually S_w), ft^2
S_{strip} = planform area of strip, ft^2
S_w = wing planform area, ft^2
T_E = thrust of operating engine at one engine-out condition, lb
T/W = aircraft thrust-to-weight ratio
t/c = thickness-to-chord ratio
W_f = aircraft weight at the end of the cruise leg
W_i = aircraft weight at initial cruise
Y_E = spanwise distance to engine, ft
γ_2 = second segment climb gradient
κ_a = airfoil technology factor
Λ = wing sweep angle at quarter chord

Introduction

OVER the last half-century transonic transport aircraft have converged upon what appears to be two common solutions. Very few aircraft differ from a low cantilever wing with either underwing or fuselage-mounted engines. Within that arrangement a highly trained eye is required to discern an Airbus from a Boeing airliner or the various models from a single manufacturer (Fig. 1). Although subtle differences such as high-lift device and control system alternatives distinguish the various aircraft, it is unlikely that large strides in performance will be possible without a significant change of vehicle configuration.

Numerous alternative configuration concepts have been introduced over the years to challenge the cantilever wing design paradigm. These include the joined wing, blended wing body, twin-fuselage, and the strut-braced wing, to name a few. This study compares the strut-braced wing (SBW) to the cantilever wing.

The SBW has the potential for higher aerodynamic efficiency and lower weight than a cantilever wing as a result of favorable interactions between structures, aerodynamics, and propulsion (Figs. 2 and 3). The strut provides bending load alleviation to the wing, allowing the wing thickness to be reduced at a given wing weight. Reduced wing thickness decreases the transonic wave drag and parasite drag, which in turn increase aerodynamic efficiency. These favorable drag effects allow the wing to unsweep for increased regions of natural laminar flow and wing structural weight savings.

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*Graduate Research Assistant, Department of Aerospace and Ocean Engineering. Student Member AIAA.

†Research Associate, Department of Aerospace and Ocean Engineering; currently Research Assistant Professor, CIMSS, Blacksburg, VA 24061-0261. Member AIAA.

‡Fred D. Durham Chair, Department of Aerospace and Ocean Engineering. Fellow AIAA.

§Professor, Department of Aerospace and Ocean Engineering. Associate Fellow AIAA.

¶Professor and Department Head, Department of Aerospace and Ocean Engineering. Associate Fellow AIAA.

**Distinguished Professor, Department of Aerospace Engineering, Mechanics, and Engineering Science. Fellow AIAA.

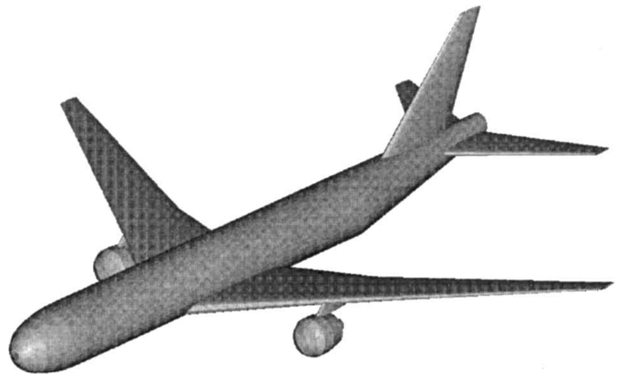

Fig. 1 Conventional cantilever-wing aircraft configuration.

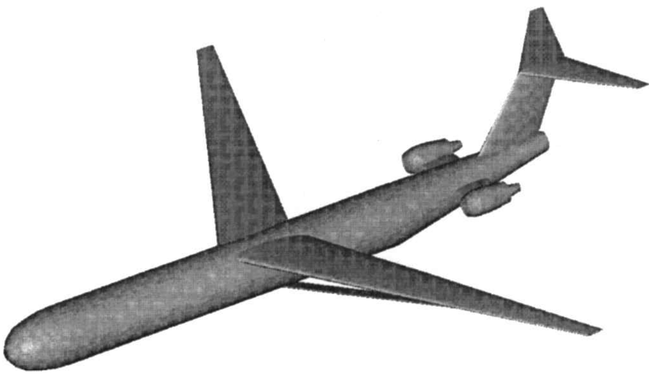

Fig. 2 SBW with fuselage-mounted engines.

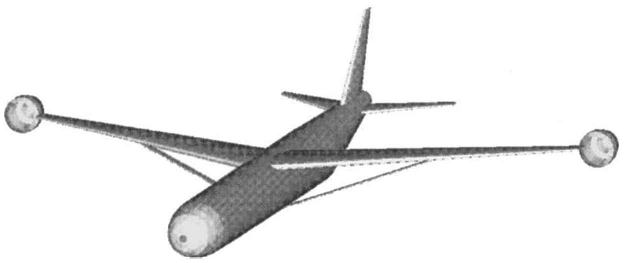

Fig. 3 SBW with tip-mounted engines.

Decreased weight, along with increased aerodynamic efficiency, permits engine size to be reduced. The strong synergism offers potential for significant increases in performance over the cantilever wing. A multidisciplinary design optimization (MDO) approach is necessary to exploit fully the interdependencies of various design disciplines.

Several transonic and aeroelastic SBW design studies have been performed in the past,[1–6] although not with a full MDO approach. Recently, as proposed by Pfenninger, NASA became interested in revisiting the possibility of a strut-braced transonic transport. Grasmeyer et al.[7] describe NASA-sponsored work done by the Multidisciplinary Analysis and Design Center at Virginia Polytechnic Institute and State University (Virginia Tech), which was followed by an industry/university study described by Martin and Kopec.[8] With the concept continuing to show promise, Gern et al.[9] describe many of the structural considerations that have been investigated for this concept.

Performance can be measured by numerous metrics. Certainly range and passenger load are important. Life-cycle cost, takeoff gross weight (TOGW), overall size, noise pollution, and fuel consumption are all candidate figures of merit. In this study TOGW is used as the major figure of merit. Other factors such as passenger acceptance and certifiability are less easy to quantify but can determine the fate of a potential configuration.

This study was funded by NASA with Lockheed Martin Aeronautical Systems (LMAS) as an industry partner. The primary role of the interaction with LMAS was to add practical industry experience to the design study. This was achieved by calibrating the Virginia Tech MDO code to the LMAS sizing code for 1995 and 2010 technology-level cantilever wing transports. LMAS also reviewed aspects of the Virginia Tech design methods specific to the SBW. The first author worked on location at LMAS to upgrade, calibrate, and validate the Virginia Tech MDO code before proceeding with optimizations of conventional cantilever and SBW aircraft.

The primary mission of interest is a 325-passenger, 7500-n mile range, Mach 0.85 transport. An economic mission aircraft that has reduced passenger load and a 4000-n mile range, while still capable of fulfilling the full mission, is also considered. Range effects on TOGW and fuel consumption are investigated. A sensitivity analysis is employed to further understand the differences between 1995 and 2010 technology-level aircraft and to see how the SBW and cantilever configurations exploit these technologies. If the SBW can better harness one set of technologies, then greater emphasis must be placed on these. Also, synergy in technology interactions will become apparent if the overall difference in 1995 and 2010 design TOGW is greater than the sum of the TOGW differences for the individual technology groups.

The Virginia Tech MDO code models SBW aircraft with wing-tip engines, underwing engines, or fuselage-mounted engines with a T-tail. Underwing and tip engines use circulation control on the vertical tail from the auxiliary power unit to counteract engine-out yawing moment. The main landing gear is located within partially protruding pods on the fuselage. The strut intersects the pods at the landing gear bulkhead and the wing at a strut offset pylon that connects to the wing.

Cantilever aircraft may have underwing engines or fuselage-mounted engines with a T-tail. In each case the landing gear is stowed in the wing between the wing box and a kick spar. This paper compares optimum cantilever and SBW configurations using identical methodology, allowing direct comparisons between the two concepts. Although both T-tail fuselage-mounted engine and underwing engine cantilever designs were optimized, the difference was small, and detailed results are presented here for the underwing engine cantilever aircraft only. The complete details of all of the results obtained in this study are contained in Ref. 10.

Methodology

Multidisciplinary Optimization

The Virginia Tech MDO code models aerodynamics, structures/weights, performance, and stability and control of both cantilever and SBW configurations. Design Optimization Tools (DOT) software by Vanderplatts R&D[11] is used to optimize the vehicles with the method of feasible directions. Between 15 and 22 design variables are used in a typical optimization. These include several geometric variables such as wing span, chords, thickness-to-chord ratios, strut geometry, strut force, and engine location, plus several additional variables including engine maximum thrust and average cruising altitude. As many as 17 inequality constraints can be used:

1) Zero fuel weight convergence (These weight formulations are implicit functions and must be converged at the end of the optimization.)

2) Range calculated > required range

3) Initial cruise rate of climb > 500 ft/min

4) Cruise section $C_l < 0.7$

5) Fuel volume required < fuel volume available

6) C_n available > C_n required

7) Wing-tip deflection < max wing-tip deflection allowed at taxi bump

8) Wing weight convergence (These weight formulations are implicit functions and must be converged at the end of the optimization.)

9) Maximum body and contents weight convergence (These weight formulations are implicit functions and must be converged at the end of the optimization.)

10) Second segment climb gradient > 2.4%

11) Balanced field length < 11,000 ft

12) Approach velocity < 140 kts

13) Missed approach climb gradient > 2.1%
14) Landing distance < 11,000 ft
15) Econ. mission range calculated > 4000 n miles
16) Econ. mission section $C_{l\,\max} < 0.7$
17) Thrust at altitude > drag at altitude

Side constraints also bound each design variable. TOGW, economic mission TOGW, and fuel weight are examples of objective functions that can be minimized.

The MDO code architecture is configured in a modular fashion such that the analysis consists of subroutines representing various design disciplines. The primary analysis modules include aerodynamics, wing-bending material weight, total aircraft weight, stability and control, propulsion, flight performance, and airfield performance.

Slight differences exist between the analysis methods and design parameters for the cantilever and SBW configurations. The primary difference is in the analysis of the wing/strut bending material weight, as discussed in the structures section. The strut has parasite drag and interference drag at the intersections with the fuselage and wing. Also, there are some geometric differences, such as requiring the minimum root chord for the cantilever wing to allow room for wing-mounted landing gear and kick spar. The SBW configuration uses a purely trapezoidal wing. The SBW configuration has a high wing and fuselage mounted gear. Even though the external geometry of the fuselage for all cases is identical, the fuselage weights will generally be different. This is because the fuselage weight is a function of the overall aircraft weight, tail weights, and engine and landing gear placement, all of which vary for each design.

Mission Profile

The primary mission of interest is a 325-passenger, 7500-n mile range, Mach 0.85 transport. An economic mission with a reduced passenger load is also considered because commercial aircraft seldom operate at the full-load maximum-range design mission. Range effects on TOGW are investigated. A minimum fuel-weight design is also considered.

The economic mission is a 4000-n mile range, reduced passenger load flight profile for an aircraft also capable of flying the 7500-n mile, full passenger load mission. A fixed weight is subtracted from the full mission zero-fuel weight to account for the passenger and baggage weight reduction. Economic range and economic cruise section C_l limit constraints are added to the other constraints. Economic mission fuel weight and cruise altitude are selected by the optimizer such that the economic TOGW is minimized, while meeting all of the appropriate constraints.

Technology Impact Assessment

The sensitivity analysis investigates the relative benefits of several technology groups when applied to baseline 1995 technology level aircraft. A 1995 aircraft represents current technology levels similar to those of the Boeing 777. A technology factor of unity is associated with a metallic 1995 aircraft benchmark. Technology factors are applied to various vehicle component weights, tail volume coefficients, specific fuel consumption, induced drag, and constants for wave drag and laminar flow to study the effects of advances in technology. Groupings were made in the following categories: natural laminar flow, other aerodynamics, structural weights, systems, and propulsion. The other aerodynamics grouping includes the effects of riblets on the fuselage and nacelles, active load management for induced drag reduction, and all moving control surfaces. Systems technologies include integrated modular flight controls, fly-by-light and power-by-light, simple high-lift devices, and advanced flight management systems. Airframe technologies are composite wing and tails and integrally stiffened fuselage skins. Finally, the propulsion technology is reflected in reduced specific fuel consumption.

Aerodynamics

Care was taken to ensure that both the Virginia Tech MDO aerodynamic analysis and Lockheed's analysis produced consistent drag polars at the design conditions. The drag components considered in the Virginia Tech MDO tool are parasite, induced, interference, and wave drag. Unless specified otherwise, the drag model is identical to previous Virginia Tech SBW studies.[7]

To calculate the parasite drag, form factors are applied to the equivalent flat-plate skin-friction drag of all exposed surfaces on the aircraft. The amounts of laminar flow on the wing and tails are estimated by interpolating Reynolds number vs sweep data from the NASA F-14 and 757 glove experiments.[12] The fuselage, nacelle, and pylon transition locations are specified by an input transition Reynolds number. Laminar and turbulent flat-plate skin-friction form factors used LMAS specified formulas. These include form factors for the wing, tails, fuselage, and nacelles. The parasite drag of a component is found by

$$C_{\mathrm{Dp}} = C_{\mathrm{Df}} F_F (S/S_{\mathrm{ref}}) \tag{1}$$

The induced drag module[7] uses a discreet vortex method to calculate the induced drag in the Trefftz plane. Given an arbitrary, noncoplanar wing/truss configuration, it provides the optimum load distribution corresponding to the minimum induced drag. This load distribution is then passed to the wing structural design subroutine. An additional lift-dependent parasite drag component was added to correlate with LMAS drag polars at off-design conditions. The induced drag is reduced for the wing-tip-mounted engine case.[7]

The interference drag between the wing-fuselage and strut-fuselage intersections is estimated using Hoerner[13] equations based on subsonic wind-tunnel tests. The wing-strut interference drag is based on Virginia Tech computational fluid dynamics (CFD) results and is found to vary inversely with the strut vertical aerodynamic offset from the wing at the intersection. The CFD methodology used is described by Tétrault et al.[14]

The wave drag is approximated with the Korn equation, modified to include sweep using simple sweep theory.[15] This model estimates the drag divergence Mach number as a function of airfoil technology factor, thickness-to-chord ratio, section lift coefficient, and sweep angle by

$$M_{\mathrm{dd}} = \frac{\kappa_a}{\cos\Lambda} - \frac{t/c}{\cos^2\Lambda} - \frac{c_l}{10\cdot\cos^3\Lambda} \tag{2}$$

The airfoil technology factor κ_a was selected by Lockheed to agree with their estimates. Using Lock's relation for drag rise,[16]

$$c_{d\,\mathrm{wave}} = 20(M - M_{\mathrm{crit}})^4 \tag{3}$$

the critical Mach number can be found from Eq. (2) using the definition of M_{dd} ($\mathrm{d}C_D/\mathrm{d}M = 0.1$) to be

$$M_{\mathrm{crit}} = M_{\mathrm{dd}} - (0.1/80)^{\frac{1}{3}} \tag{4}$$

The aircraft wave drag is then found by integrating the Lock wave drag across the span.

The drag polars used in the Virginia Tech MDO formulation and the LMAS formulation agree within 1% on average for cantilever wing designs.

Structures and Weights

The aircraft weight is calculated using two different methods. The majority of the weights equations come from NASA Langley's Flight Optimization System (FLOPS).[17] Many of the FLOPS equations were replaced with those suggested by LMAS. However, differences between the aircraft weight components from either set of weight equations are minor, thus leading to very similar aircraft configurations during the optimization. Neither one of the methods have the option to analyze an SBW with the desired fidelity, and so a piecewise linear beam model was developed at Virginia Tech to estimate the bending material weight.[18]

The piecewise linear beam model represents the wing-bending material as an idealized double plate with upper- and lower-wing box covers. A vertical offset member was added to the wing/strut intersection to help reduce the interference drag. The structural offset length is the length of the exposed aerodynamic offset plus the internal distance from the lower-wing surface to the neutral axis of bending. The offset must take both bending and tension loading. The offset member weight increases rapidly with increasing length, but the interference drag decreases. The offset length is a design variable, and the optimizer selects its optimum value. Fortunately, the vertical offset imposes bending moment relief on the wing at the intersection, and the overall influence on the TOGW is negligible. A 10% weight penalty is applied to the piecewise linear beam model to approximately account for nonoptimum loading and manufacturing constraints. An additional 1% bending material weight increase is added to the SBW to approximately address the discontinuity in bending moment at the wing/vertical offset intersection.[9,10]

Earlier studies[7] have shown that the critical structural design case for the single strut is strut buckling at $-1g$ loading. To alleviate this stringent requirement, a telescoping sleeve mechanism arrangement is employed such that the strut will engage under a positive load factor, and the wing will act essentially as a cantilever wing under negative loading. This mechanism further allows the selection of the strut load at the critical $2.5g$ pull-up maneuver. The strut load is one of the MDO design variables. A weight estimate for the telescoping sleeve mechanism is based on landing gear component data. Also, the SBW analysis must include the $-2g$ taxi bump case, where the strut is also inactive.

Weights calculated in the transport optimization code are identical to FLOPS with the exception of nacelle, thrust reverser, passenger service, wing, fuselage, and tail weights. Weight technology factors are applied to major structural components and systems to reflect advances in technology levels from composite materials and advanced electronics.

Traditionally, aircraft weight equations are implicit functions, and internal iteration loops are required for convergence. However, utilizing the optimizer for zero fuel weight convergence is more efficient and provides smoother gradients. DOT also selects the fuel weight so that the range constraint is not violated. Other weights such as the maximum body and contents weight and wing weight converge efficiently using values from preceding iterations.

Stability and Control

The horizontal and vertical tail areas are first calculated with a tail volume coefficient sizing method.[19] The tail volume coefficients were determined based on statistical data. The planform shape is maintained while the area varies. The tail moment arm is also assumed to be constant for a given configuration.

A vertical tail sizing routine was developed to account for the one-engine inoperative condition.[7,20] The engine-out constraint is met by constraining the maximum available yawing moment coefficient to be greater than the required yawing moment coefficient. The aircraft must be capable of maintaining straight flight at 1.2 times the stall speed, as specified by FAR requirements. The operable engine is at its maximum available thrust. Circulation control is used on the vertical tail for the tip-mounted engine case, resulting in vertical tail lift coefficient augmentation and greater available yawing moment. The maximum change in lift coefficient caused by blowing is assumed to be 1.0 as a conservative but adequate limit.[21]

The engine-out yawing moment coefficient required to maintain straight flight is given by

$$C_{n\,\mathrm{req}} = \frac{(T_E + D_E)Y_E}{q S_W b_W} \tag{5}$$

The lateral force of the vertical tail provides most of the yawing moment required to maintain straight flight after an engine failure.

The maximum available yawing moment coefficient is obtained at an equilibrium flight condition with a given bank angle and a given maximum rudder deflection. FAR 25.149 limits the maximum bank angle to 5 deg, and some sideslip angle is allowed. Stability and control derivatives are estimated using empirical methods of Roskam[19] as modified by Grasmeyer.[20]

To allow a 5-deg aileron deflection margin for maneuvering, the calculated deflection must be less than 20–25 deg. If the calculated available yawing moment coefficient is less than the required yawing moment coefficient, the vertical tail area is scaled up by the optimizer.

Propulsion

A GE-90 class high-bypass-ratio turbofan engine is used for this design study. Analytic models for specific fuel consumption and maximum thrust as a function of altitude and Mach number were developed using regression analysis.[10] The general forms of the equations are identical to those found in Mattingly et al.[22] for high-bypass-ratio turbofan engines, but the coefficients and exponents are modified. The engine size is determined by the maximum thrust required to meet the most demanding of several constraints. These include thrust at average cruise altitude, rate of climb at initial cruise altitude, balanced field length, second segment climb gradient, and missed approach climb gradient. The engine weight is assumed to be proportional to the engine thrust. The specific fuel consumption model is independent of engine scale. A specific fuel consumption technology factor is applied to reflect advances in engine technology.

Flight Performance

The range is calculated using the Breguet range equation including a fuel reserve leg:

$$R = [V(L/D)/sfc]\,\ln(W_i/W_f) - R_{\mathrm{reserve}} \tag{6}$$

The L/D, flight velocity, and specific fuel consumption are determined for the average cruising altitude and fixed Mach number. The initial weight is 95.6% of the TOGW to account for fuel burned during climb to the initial cruise altitude. A reserve range of 500 n miles is used as an approximation to the FAR reserve fuel requirement.

Airfield Performance

Takeoff and landing performance uses methods found in Lan and Roskam.[23] The field performance subroutine calculates the second segment climb gradient, balanced field length, missed approach climb gradient, and the landing distance. All calculations are done for hot day conditions (83°F at sea level).

Reference drag polars for the aircraft at takeoff and landing were used. Trends are the same for both the SBW and cantilever configurations. The actual drag polars use correction factors based on total aircraft wetted area and wing aspect ratio. It was assumed that, for the modest level of fidelity of this systems study, the high-lift characteristics of the vehicles may be tailored such that the corrected drag polars can be attained.

The second segment climb gradient is the ratio of rate of climb to the forward velocity at full throttle while one engine is inoperative and the gear is retracted. The second segment climb gradient γ_2 is found by

$$\gamma_2 = T/W - 1/(L/D) \tag{7}$$

The ground roll lift coefficient is the minimum of the C_L associated with $V_2 = 1.2V_{\mathrm{stall}}$ and the C_L for the tail scrape angle. Normally, the tail scrape C_L is the most critical.

Lan and Roskam methods[23] are also used to determine the landing distance. Three legs are defined: the air distance from clearing the 50-ft object to the point-of-wheel touchdown, which includes the flare distance, the free roll distance between touchdown and application of brakes, and finally, the distance covered while braking. The lift coefficient on landing approach is the minimum C_L associated with either $V = 1.3V_{\mathrm{stall}}$ or the C_L to meet the tail scrape requirement. The drag coefficient is calculated with gear down.

The missed approach climb gradient is calculated in the same way as the second segment climb gradient with a few exceptions. First, the weight of the aircraft at landing is assumed to be a fraction of the TOGW. Second, all engines are operational. Third, a landing drag polar distinct from the takeoff drag polar is used. The FAR minimum missed approach climb gradient constraint was never violated in this study.

Table 1 Minimum TOGW designs (2010 technology)

Parameter	Cantilever wing	SBW w/fuselage engines	SBW w/tip engines
Span, ft (m)	223.2 (68.0)	227.0 (69.2)	199.8 (60.9)
S_w, ft^2 (m^2)	5,120 (475.7)	4,233 (393.3)	4,114 (382.2)
Aspect ratio AR	9.73	12.17	9.70
Root t/c	14.50%	14.28%	14.37%
Tip t/c	7.80%	6.15%	6.56%
Wing $\Lambda_{1/4}$, deg	33.3	29.9	30.6
Strut $\Lambda_{1/4}$, deg	——	20.1	22.8
Spanwise strut position	——	68.9%	57.2%
Spanwise engine position	37.0%	——	100.0%
Max thrust, lbs (kN)	75,133 (334.2)	59,572 (265.0)	58,326 (259.4)
Cruise altitude, ft (m)	41,160 (12546)	40,322 (12290)	39,996 (12191)
L/D	23.34	25.40	25.01
Wing weight, lb (kg)	63,774 (28927)	60,745 (27554)	45,104 (20459)
Bending weight, lb (kg)	48,076 (21807)	43,326 (19652)	27,671 (12551)
Fuel weight, lb (kg)	184,948 (83891)	159,883 (72522)	159,930 (72543)
TOGW, lb (kg)	**535,643 (242964)**	**492,332 (223318)**	**486,750 (220786)**
% TOGW improvment	——	8.1%	9.1%
% fuel improvment	——	13.6%	13.5%
% thrust reduction	——	20.7%	22.4%
Section C_l limit	ACTIVE	ACTIVE	ACTIVE
2nd segment climb	ACTIVE	ACTIVE	——
Balanced field length	——	ACTIVE	ACTIVE
Engine out	ACTIVE	——	——

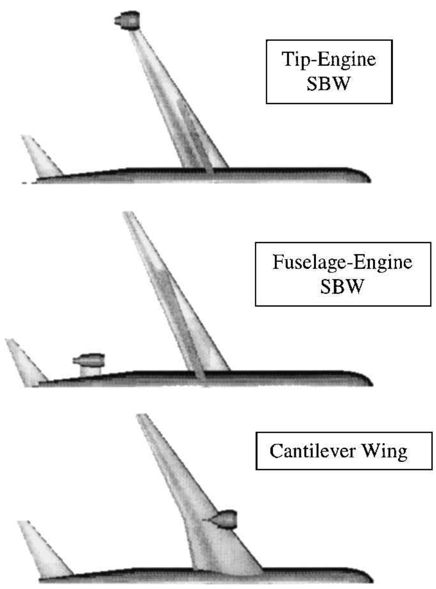

Fig. 4 Minimum TOGW designs.

Table 2 Minimum fuel optimum designs (2010 technology)

Parameter	Cantilever wing	SBW w/fuselage engines
Span, ft (m)	256.2 (78.1)	262.3 (79.9)
S_w, ft^2 (m^2)	5,800 (538.8)	4,694 (436.1)
Aspect ratio AR	11.32	14.65
Root t/c	13.06%	12.37%
Tip t/c	5.31%	5.29%
Wing $\Lambda_{1/4}$, deg	32.3	28.3
Strut $\Lambda_{1/4}$, deg	——	21.2
Spanwise strut position	——	66.6%
Max thrust, lb (kg)	70,919 (315.5)	57,129 (254.1)
Cruise altitude, ft (m)	43,826 (13358)	42,248 (12877)
L/D	26.13	29.08
Wing weight, lb (kg)	89,373 (40539)	86,260 (39127)
Bending weight, lb (kg)	74,846 (33950)	68,543 (31091)
Fuel weight, lb (kg)	**176,646 (80125)**	**150,147 (68106)**
TOGW, lb (kg)	554,963 (251727)	509,881 (231278)
% TOGW improvement	——	8.1%
% fuel improvement	——	15.0%
Shock C_l	ACTIVE	ACTIVE
2nd segment climb	ACTIVE	——
Balanced field length	——	ACTIVE

Results

Detailed comparisons are given for SBW and cantilever wing optimum designs for both minimum TOGW and minimum-fuel cases for 2010 technology factors. For the minimum TOGW case both tip-mounted and fuselage-mounted engine SBW cases are presented. For the minimum fuel case only the fuselage-mounted engine SBW results are presented. Planforms are compared for several different cases, and the results of the economic mission optimization results are discussed. Next the effect of varying mission range on the difference between the cantilever and SBW concepts is presented. Finally, the effects of incrementally including advanced technologies in the MDO process is presented, illustrating the relative importance of various advanced technologies on the cantilever and SBW design concepts.

Table 1 and Fig. 4 show the results for TOGW minimization, and Table 2 shows minimum fuel weight results. A comparison of cantilever and SBW wings for various objective functions can be seen in Fig. 5. Note that the cantilever wing has a trailing-edge break to permit landing gear stowage. In general, the SBW aircraft have less wing area, higher aspect ratio, and less sweep than their cantilever counterparts.

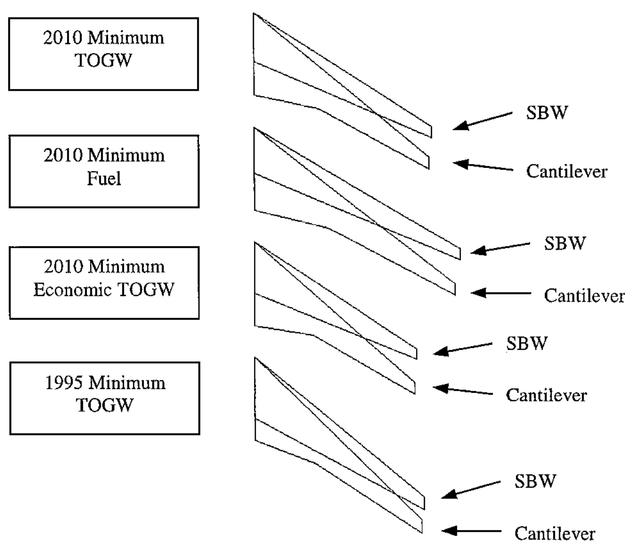

Fig. 5 Optimum cantilever and SBW designs.

For minimum TOGW and minimum-fuel cases the SBW is superior for the selected objective functions. Although the SBW has an 8.1% decrease in TOGW, the savings in fuel consumption are even more impressive. An SBW has a 13.6% lower fuel burn than a cantilever configuration when optimized for minimum TOGW, and a 15% lower fuel weight when both are optimized for minimum fuel weight.

The minimum-fuel SBW has a higher wing span to increase the L/D and fly at higher altitudes. The minimum-fuel-SBW TOGW is 8.1% lighter than an equivalent cantilever design and 3.6% heavier than the minimum-TOGW-SBW. The SBW L/D increases from 25.4 to 29.1 going from the minimum TOGW to the minimum-fuel case and from 21.7 to 26.1 for the cantilever configuration. This improved aerodynamic efficiency is achieved by increasing the wing span and reducing wing thickness, and therefore comes at the expense of an increased wing weight.

Fuel burn is likely to be an increasingly important factor in aircraft design from two perspectives. First, as the Earth's petroleum resources are depleted, the cost of aviation fuel will rise. A reduction in fuel use will be even more important if the fuel price becomes a larger part of the life-cycle cost. Second, strict emissions regulations stemming from environmental concerns and resulting treaties will limit the amount of pollutant discharge permitted. Beyond engine design, reducing the overall amount of fuel consumed for a given flight profile by improved configuration design will reduce the emissions.

Airport noise pollution can limit the types of aircraft permitted to use certain urban airfields and impose operational restrictions on those that do. Minimizing engine size can also be expected to reduce the noise generated if the engine is of similar design. Minimum TOGW SBW engine thrust is reduced by 20.7% over the equivalent cantilever design.

The economic mission optimization resulted in a configuration with a similar TOGW to the minimum TOGW case (Fig. 5). It is important to realize that the economic aircraft must also be capable of performing the full mission. Aside from the similarity in TOGW, the two optima have little in common. The economic mission aircraft have 20 ft less span (Fig. 5), cruise at lower altitudes and have a lower L/D than the full mission equivalents for both the SBW and cantilever cases. By decreasing the wing span at a reduced passenger and fuel load, the wing-bending material weight is lower and so is the economic TOGW. Apparently, the L/D decrease associated with the span reduction at the full mission scenario adversely affects the full mission TOGW for the minimum economic TOGW optimum. The TOGW at the 4000- or 7500-n mile range is slightly increased (0.1–0.8%) for those vehicles not optimized for that range and passenger load.

The SBW becomes increasingly desirable as the design range increases. Figures 6 and 7 show the effects of range on TOGW and fuel

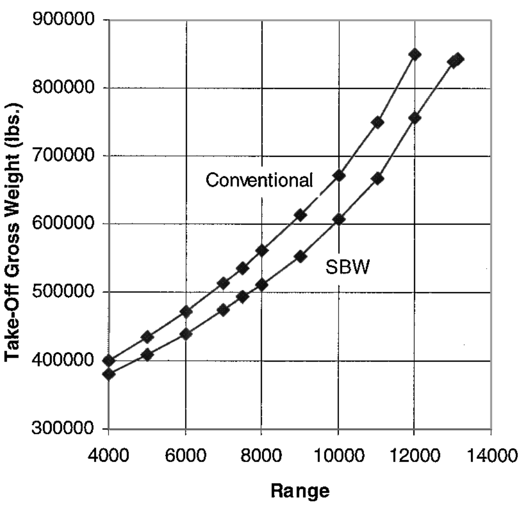

Fig. 6 Effect of range on TOGW for cantilever-wing and fuselage-mounted engines SBW.

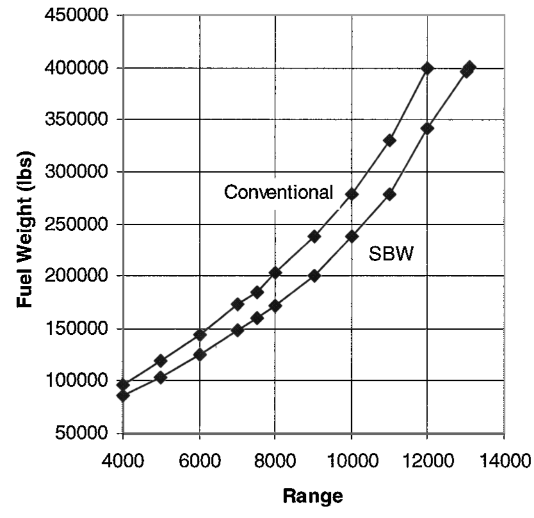

Fig. 7 Effect of range on fuel weight for cantilever-wing and fuselage-mounted engines SBW.

weight. The TOGW reduction relative to the cantilever configuration steadily improves from 5.3% at a 4000-n mile range up to 10.9% at 12,000 n miles. The fuel weight savings fluctuates within about 11–16%, but it generally improves as the design range increases. These results are for minimum TOGW designs. Greater fuel burn improvements occur for SBW aircraft optimized for minimum fuel weight. Maximum fuel weight is set at 400,000 lb. At 12,000 n miles an aircraft can reach any destination on Earth. The SBW maximum range is 13,099 n miles at this fuel weight, whereas the cantilever configuration can only reach 11,998 n miles, or the SBW has 8.4% greater maximum range. In other words, the SBW can either have a reduced fuel weight for a given range or an increased range for a given fuel weight relative to the cantilever configuration.

The tip-mounted engine SBW is 5582 lb lighter than the fuselage mounted engine SBW, caused in part to the induced drag alleviation at takeoff. Similar drag reductions are applied to lift-dependent drag terms of the field performance drag polars as are applied to the cruise-induced drag for the tip-engine case. It has been found that the field performance largely dictates the wing and engine sizing so that any reduction in these penalties can reap large benefits. The tip-mounted engine case has the advantage of inertia relief on the wing for reduced wing-bending material weight. Although the tip-mounted engine case is the lightest of the SBW cases, it is currently considered the highest risk case, which is because of the severity of the engine-out condition, the need for a circulation control system on the vertical tail, and the need for detailed structural analysis with the engine mounted on the wing tip.

An examination of the active constraints for the optimum designs is informative. In every optimum presented here, the cruise section lift coefficient constraint is active. This indicates that the aircraft do not fly at the altitude for best L/D and are thus penalized. Typically, the engines are sized by either balanced field length or second segment climb rather than drag at cruise or initial cruise rate of climb.

One of the early concerns regarding the SBW configuration is the large increase in wing span compared to cantilever wings seen in early studies. More refined modeling of the wing structure and added realism brought about through work with LMAS has lessened the earlier trend. Indeed, now the fuselage-mounted engines SBW has a mere 1.7% increase in span over the cantilever configuration for the minimum TOGW case and a 2.4% increase for the minimum fuel design. In either case the optimum spans fall well within the FAA 80-m gate box limitation.

The relative contribution of the individual technologies to the decrease in TOGW between the cantilever and SBW concepts was also examined. Starting from current (1995) levels, the impact of individual technologies was found by incorporating them individually in the MDO procedure and finding the new TOGW. This is termed

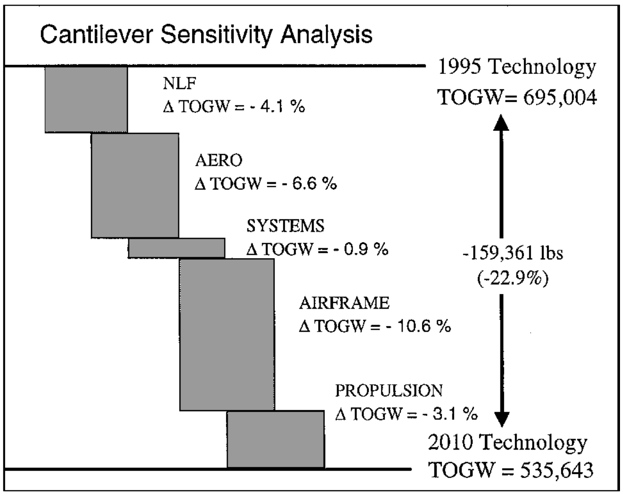

Fig. 8 Cantilever technology sensitivity analysis.

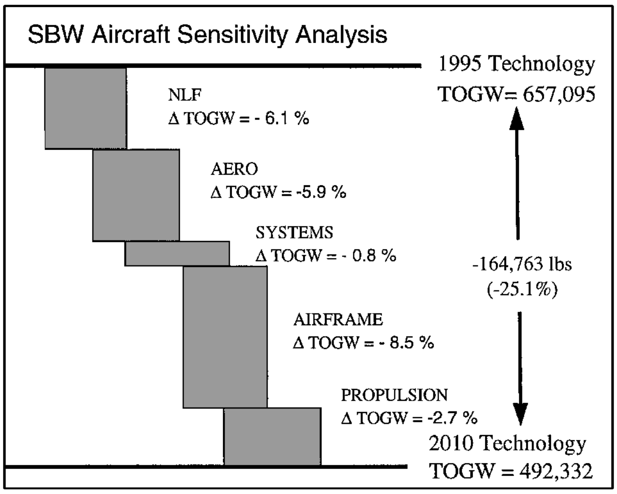

Fig. 9 Fuselage-mounted engines SBW technology sensitivity analysis.

technology sensitivity analysis. The results are shown in Fig. 8 for the cantilever wing concept and Fig. 9 for the SBW concept. The figures show that the SBW takes more advantage of natural laminar flow than the cantilever concept. In both cases the total aerodynamic technology and the structures technology (essentially composites) advances are about equal contributors to the reduction in TOGW. Using MDO, a new design is found for each combination of advanced technologies to ensure that the integration of technologies is optimal.

Conclusions

Virginia Tech transport studies have shown the potential of the SBW over the traditional cantilever configuration. After much added realism by a major airframe manufacturer, the MDO analysis shows that the SBW still demonstrates major improvements over the cantilever wing configuration. Significant reductions in TOGW were found, but the greatest virtues of the SBW can be its improved fuel consumption and smaller engine size. These results indicate that the SBW will cost less, limit pollutant discharge, and reduce noise pollution for urban airports. Advantages of the SBW increase with range, suggesting that this configuration may be ideal for larger, long-range transports.

The SBW exhibits a strong sensitivity to aerodynamic technologies and has favorable synergism overall, unlike the cantilever configuration. This implies that greater emphasis should be placed on laminar flow, transonic wave drag reduction, and other aerodynamic gains than on other systems and technologies in the development of the SBW. Structures, systems, and aerodynamics technologies interact more favorably, yielding greater gains per technology investment.

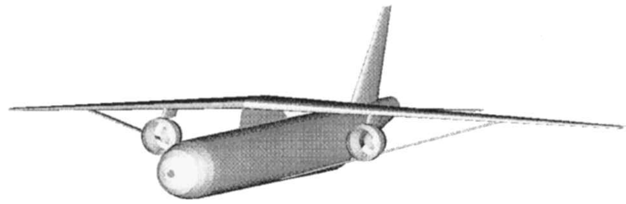

Fig. 10 Parasol SBW layout.

The cooperation with LMAS focused on adding realism to the SBW design effort for direct comparisons with the cantilever design concept. Realism took the form of weight penalties and additional performance constraints. These additional considerations did not alter the earlier conclusions concerning the advantages of the SBW concept. Presently efforts are underway to identify technologies and strut/truss arrangements to further exploit the advantages of the strut. Some possible design modifications are discussed in the recommendations section.

Recommendations for Further Study

One can envision a number of extensions to the general SBW layout studied here, with some ideas more daring than others. Such concepts include variations of configuration or mission. This limited study demonstrates only a few of the advantages of the strut-braced wing.

Configuration changes may allow the SBW to exhibit further benefits. The strut vertical offset thickness has been assumed to be identical to that of the strut. However, the strut offset must take much greater bending loads. Imposing drag penalties as a function of offset thickness but also allowing the thickness to vary will likely yield lower total weights.

One possible way to counter the engine-out problem for the tip-mounted engine configuration would be to have a more powerful engine on the centerline. If one of the tip engines fail, the other can be shut off, and the centerline engine would provide the necessary thrust for the critical cases. This may raise unique dilemmas when attempting to certify this configuration because it is essentially a twin-engine aircraft from an engine failure point of view, but there are physically three engines.

The vertical distance between the strut and the wing at the fuselage plays a significant role in strut effectiveness. As the vertical separation increases, a smaller component of the strut force causes compression on the main wing. This reduces the wing skin thickness required to counteract buckling and reduces the overall wing weight. A double-deck fuselage would increase the vertical separation of the wing and strut at the fuselage. Other means of achieving a greater separation include using a parasol wing (Fig. 10) or attaching the strut to downward-protruding landing gear pods. These arrangements may facilitate underwing engines inboard of the strut/wing intersection without unwanted exhaust interference effects with the strut.

Locating engines above the wings can add inertia relief without interfering with the strut. Blowing over the upper-wing surface will help decrease the takeoff distance. Furthermore, inboard engines will not demand exotic schemes like vertical tail blowing to meet the engine-out constraint.

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