Aerodynamic Design Optimization of a Transonic Strut-Braced-Wing Regional Aircraft Based on the RANS Equations

The 7th UTIAS International Workshop on Aviation and Climate Change

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Introduction

Motivation

Environmentally sustainable aviation will likely require contributions from both **alternative fuels** and advances in **aircraft and engine technology**

- Sustainable Aviation Fuel (SAF) and hydrogen fuel can provide a path to 80% and 100% CO_2 emissions reductions, respectively
  - Challenges: high cost, low availability, competition with food production – long term solution
- Advances in aircraft and engine technology offer near and long term solutions
  - Advanced aerodynamic technologies
  - Advanced structures and materials
  - Advanced propulsion technologies
- One major contribution is anticipated to come from unconventional aircraft configurations that have the potential to provide major savings in fuel burn, relative to the conventional tube and wing design

Unconventional Aircraft Configurations

Photo credits: *NASA* (BWB), *Aurora Flight Sciences* (D8), *Lockheed Martin* (Box Wing), *Boeing* (Truss-Braced Wing)

Strut- and Truss-Braced Wings

Advantages

- Significantly lower induced drag due to larger wing span
- Higher structural efficiency due to truss topology
  - Supports higher wing bending loads
  - Enables thinner wings
  - Lowers structural weight

Aerodynamic Design Challenges

- Shock formation in truss region due to flow acceleration in small enclosed space(s)
- Flow interference + skin friction drag penalties from strut members

Aerodynamic design challenges must be addressed at Mach 0.78-0.80 to obtain a **credible estimate for the fuel burn advantage** of the configuration.

*Strut-braced wing = main strut only, truss-braced wing = main strut + jury strut(s)

Photo credits: *Boeing*

Aerodynamic Shape Optimization

- Aerodynamic shape optimization automates the design process through specified objective functions, design variables and constraints, eliminating the need for extensive *a priori* design experience

- Aerodynamic shape optimization based on the Reynolds-averaged Navier-Stokes (RANS) equations:
  - Captures shock formation, boundary-layer separation, and nonlinear interference effects
  - Accurately captures and enables tradeoffs between induced drag and viscous drag

$\boxed{M = 0.78,\ Re = 20 \times 10^6}$

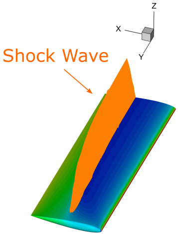
Initial

$\alpha = 1.00°$

$L/D = 8.7$

$C_L = 0.09$

$C_D = 0.0107$



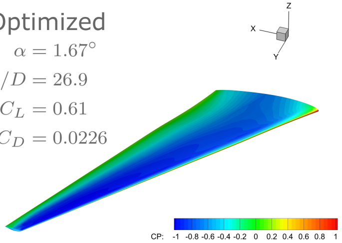
Optimized

$\alpha = 1.67°$

$L/D = 26.9$

$C_L = 0.61$

$C_D = 0.0226$



Questions to Address

1. Can we mitigate shock wave formation within the wing-strut junction at high transonic Mach numbers using high-fidelity aerodynamic shape optimization?

2. How much of a fuel burn benefit can be obtained in the regional jet class through the strut-braced-wing configuration relative to the dominant configuration with current technology levels?

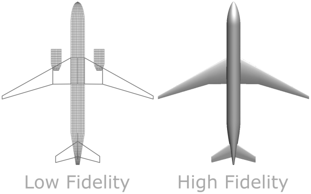
This work will attempt to answer these questions through the application of **Aerodynamic Shape Optimization based on the Reynolds-averaged Navier-Stokes (RANS) equations**.

Methodology

Aircraft Design Methodology

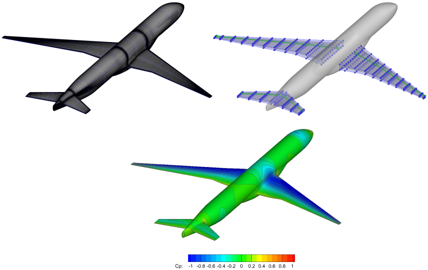
Conceptual Design (Faber)

- Low-order multidisciplinary design optimization framework
- System-level analysis, sizing, and optimization
- Top level aircraft requirements
- Interdisciplinary tradeoffs



Aerodynamic Shape Optimization (Jetstream)

- High-fidelity aerodynamic shape optimization framework
- Design point optimization
- Nonlinear aerodynamics via the Reynolds-averaged Navier-Stokes (RANS) equations



Conceptual Design

Design Requirements: Missions and Sizing

Reference aircraft: **Embraer E190-E2**

- Maximum payload = 30,200 lb
- Design payload = 104 passengers
- Design range = 3,100 nmi
- Nominal range = 500 nmi
- Mach 0.78
- W/S = 110.2 lb/ft^2, T/W = 0.336
- Pratt & Whitney PW1919G engines

Assume current technology levels for strut-braced wing

- Composite wing structures
- No natural laminar flow wings
- No advanced flow control
- No new engine technology

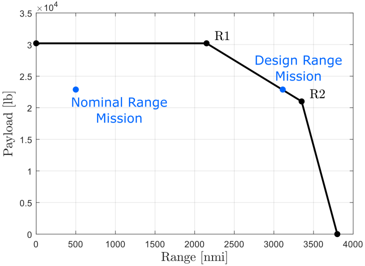


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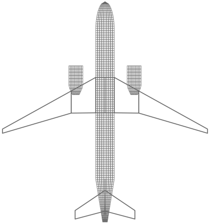
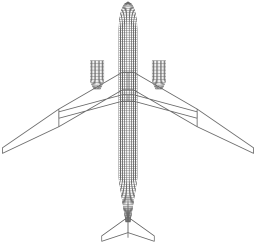
Photo credits: *Embraer*

Results: Conceptual-Level MDO



CTW100



SBW100

Parameter	CTW100	SBW100	Δ
Geometry			
Span [ft]	110.6	136.0	–
Aspect ratio [–]	10.84	16.87	+55.6%
Wing wetted area [ft^2]	1,915	2,638	+37.8%
Reference area [ft^2]	1,129	1,096	–
Weights			
MTOW [lb]	124,370	120,370	-3.2%
MZFW [lb]	102,230	100,050	–
OEW [lb]	72,030	69,850	-3.0%
Airframe [lb]	36,480	35,060	–
Propulsion [lb]	12,470	12,140	–
Systems [lb]	17,340	17,100	–
Operational [lb]	5,730	5,570	–
MFW [lb]	30,450	27,350	-10.2%
Propulsion			
Maximum TO thrust (per engine) [lb]	20,860	20,290	–
Cruise thrust (per engine) [lb]	4,160	2,780	–
Cruise TSFC [lb/lb/hr]	0.5872	0.5900	+0.5%
Aerodynamics			
Mach number [–]	0.78	0.78	–
Initial cruise altitude [ft]	37,000	45,860	–
Reynolds number [million]	22.04	9.65	–
Cruise L/D [–]	18.2	21.3	+17.0%
Cruise C_L [–]	0.46	0.71	–
Cruise lift [lb]	100,828	97,980	–
Cruise drag [lb]	5,540	4,600	–
Fuel			
Block fuel [lb]	5,100	4,720	-7.5%

[1] All operating conditions and cruise parameters are in reference to the start of cruise for the 500 nmi mission

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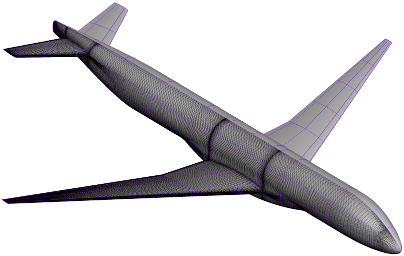
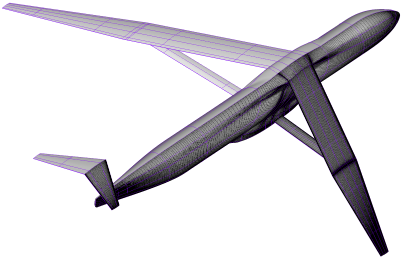
High-Fidelity Aerodynamic Shape Optimization

Geometry and Mesh



CTW100

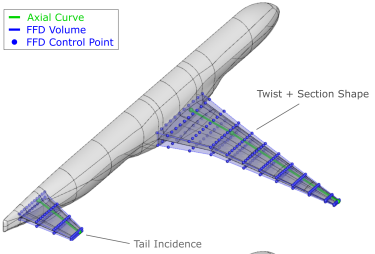


SBW100

- Optimization requires sufficient grid resolution to resolve relevant aerodynamic features while keeping computational cost reasonable
- Optimize on *medium* mesh resolution of the Drag Prediction Workshop (DPW) guidelines, which is ”representative of current engineering drag predictions”
- Grid refinement is performed post-optimization to obtain grid-converged C_L, C_D, and L/D

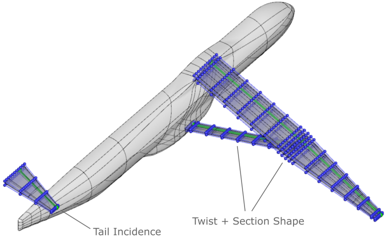
CTW100: Conventional Tube-and-Wing RJ

Objective	Minimize cruise drag
Design Variables (281)	Angle of attack (1)
	Twist (16)
	Section shape (264)
Nonlin. Constraints (13)	Constant lift (1)
	Zero pitching moment (1)
	Minimum wing volume (1)
	Minimum $(t/c)_{\mathrm{max}}$ (10)

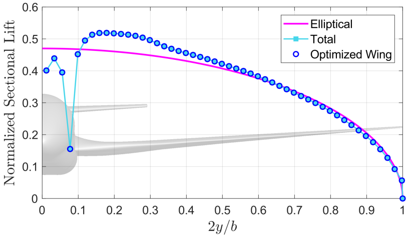


SBW100: Strut-Braced-Wing RJ

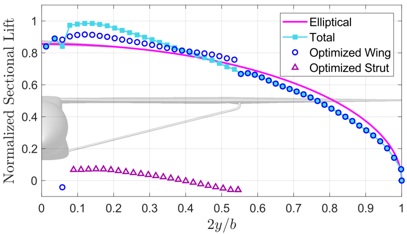
Objective	Minimize cruise drag
Design Variables (946)	Angle of attack (1)
	Twist (43)
	Section shape (902)
Nonlin. Constraints (33)	Constant lift (1)
	Zero pitching moment (1)
	Minimum wing/strut volume (1)
	Minimum $(t/c)_{\mathrm{max}}$ (30)



Results: Optimized Spanwise Lift Distributions



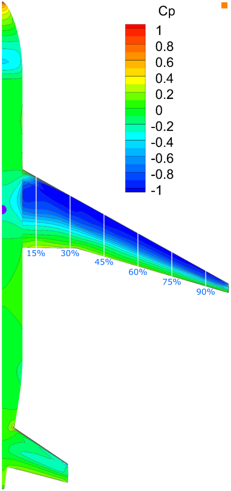
CTW100: $\alpha = 3^{\circ}$, $C_L = 0.46$, $C_D = 0.0207$, $L/D = 22.4$



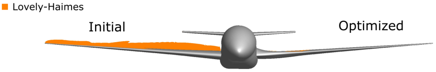
SBW100: $\alpha = 3^{\circ}$, $C_L = 0.71$, $C_D = 0.0286$, $L/D = 24.8$

- Elliptical in form but shifted inboard due to trim constraint, and to avoid high sectional C_L over outboard portion of wing
- Negative lift over strut is introduced to alleviate adverse flow effects within wing-strut junction; compensated by more lift over inboard portion of wing
- Strut produces some lift near root

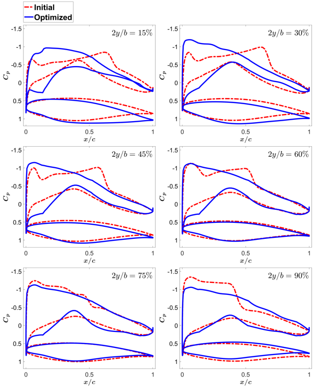
Results: Optimized CTW100



Surface pressure contours

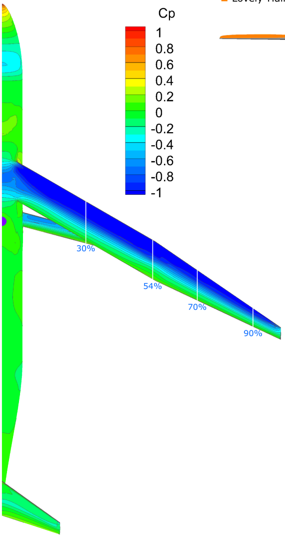


Shock surfaces

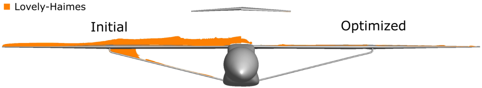


Pressure distributions

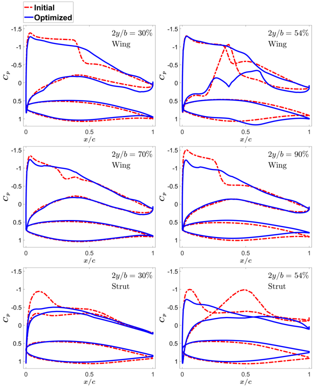
Results: Optimized SBW100



Surface pressure contours



Shock surfaces



Pressure distributions

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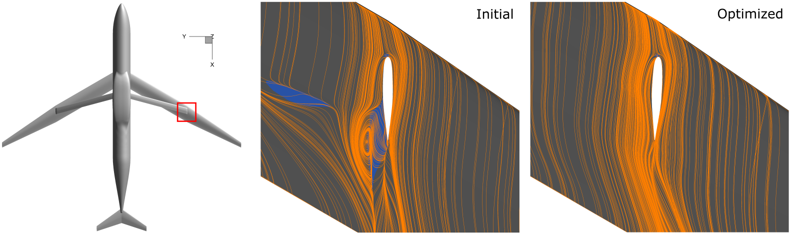
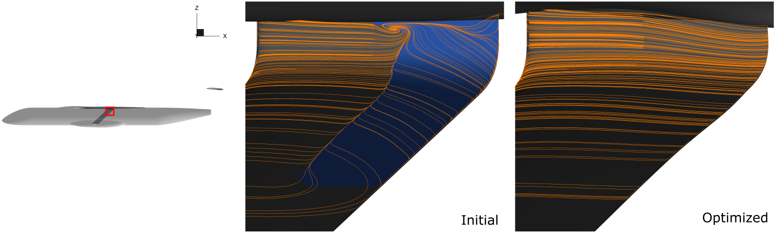
Results: Junction Streamlines and Separation Surfaces



Bottom view of lower wing



Side view of inner strut

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Results: Optimized Aircraft Performance

For block fuel, we reintroduce from the low-order models:

- Weight and propulsion
- Excrescence drag
- Drag for vertical tail, nacelles, and pylons
- Fuel from takeoff, climb, descent, and landing

Parameter	CTW100	SBW100	Δ
High Fidelity: Wing, Fuselage, Horizontal Tail			
Cruise L/D [–]	22.4	24.8	$+10.9\%$
Cruise C_L [–]	0.46	0.71	$+53.4\%$
Cruise C_D [–]	0.0207	0.0286	$+38.3\%$
Cruise lift [lb]	100,950	98,030	-2.8%
Cruise drag [lb]	4,506	3,951	-12.3%
Low + High Fidelity: Full Aircraft			
Cruise L/D [–]	18.9	21.9	$+15.6\%$
Cruise C_L [–]	0.46	0.71	$+53.4\%$
Cruise C_D [–]	0.0245	0.0326	$+32.8\%$
Cruise lift [lb]	100,950	98,030	-2.8%
Cruise drag [lb]	5,331	4,484	-15.9%
Block fuel [lb]	4,995	4,666	-6.6%

[1] Performance parameters are for the 500 nmi nominal mission.

Conclusions and Future Work

Conclusions and Future Work

Conclusions

- Demonstrated the feasibility of designing a low-drag transonic strut-braced wing through single-point aerodynamic shape optimization based on the RANS equations
- Mitigated shock formation and boundary-layer separation from the wing-strut junction at Mach 0.78
- With current technology levels, the optimized strut-braced-wing regional jet offers a 6.6% reduction in block fuel over a 500 nmi mission compared to a similarly-optimized conventional tube-and-wing regional jet

Future Work

- Perform multipoint optimization to determine if low wave drag of the strut-braced-wing regional jet can be maintained over a range of cruise conditions
- Investigate the relative fuel burn savings of a strut-braced-wing single-aisle transport aircraft

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