University of Toronto
Institute for Aerospace Studies

Towards Aerodynamic Shape Optimization of Regional Class Blended-Wing-Body Aircraft for Reduced Environmental Impact

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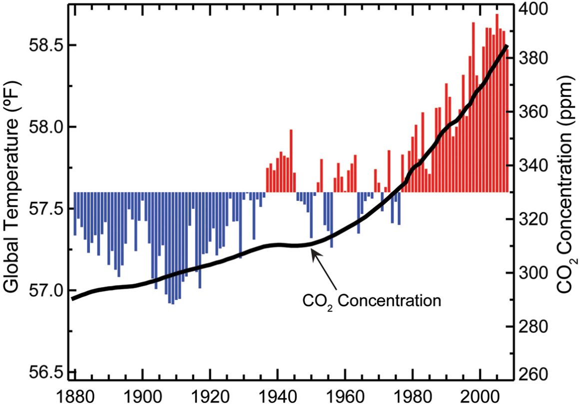
David W. Zingg

May 16$^{\text{th}}$, 2013

Outline

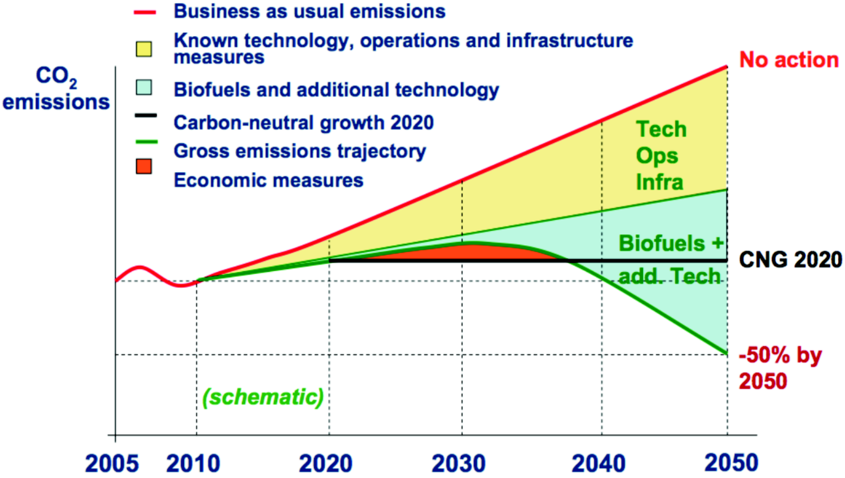
Airline Industry Factors

- Increasing demand for air travel and air freight
- Increasing and volatile fuel prices
- Environmental pressures



Source: US Global Change Research Program

Environmental Goals



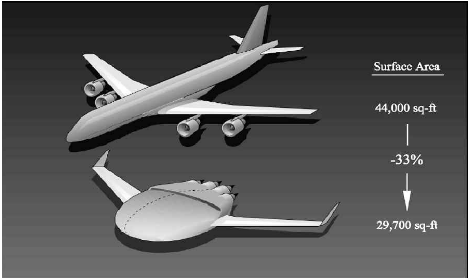
Source: ICAO Environmental Report 2010

The tube-and-wing design has served us well for over 60 years...

... But is a step change in configuration design required?

Design Benefits

- Aerodynamic
  - High wetted aspect ratio gives high lift-to-drag ratio
  - Natural 'area-ruling' improves high-speed performance
- Structural
  - Natural spanloading reduces bending loads
- Propulsive
  - Boundary-layer ingesting engines reduce fuel-burn
- Acoustic
  - Body-mounted engines are acoustically shielded
  - Low landing speed reduces airframe noise



Liebeck, JoA, Vol. 41, No. 1, 2004

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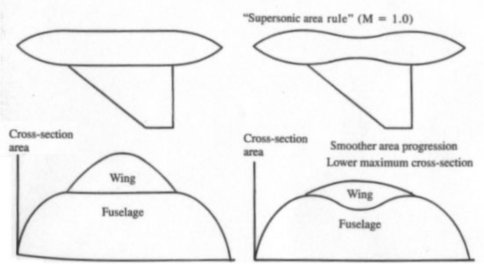

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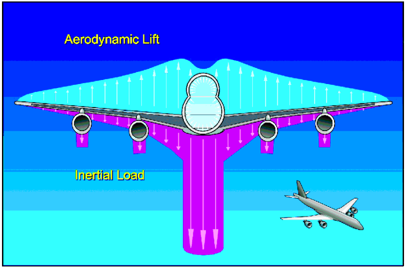

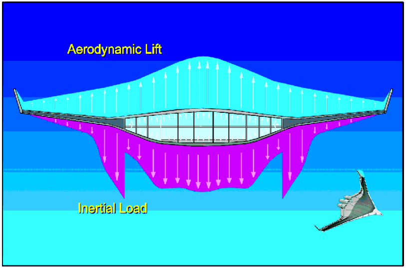

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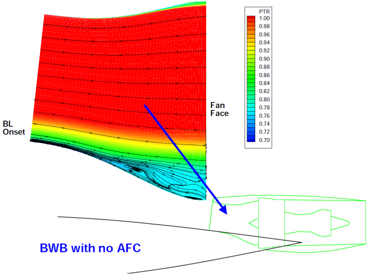

Daggett, NASA/CR-2003-212670, 2003

Design Challenges

- Aerodynamic
  - Shock-free airfoils with sufficient thickness
  - Maintaining stability and control without a tail
- Structural
  - Design of non-cylindrical pressure vessel for the cabin
  - More complicated load-paths
- Propulsive
  - Robust boundary-layer ingesting engine technology
- Passenger comfort
  - Ride quality

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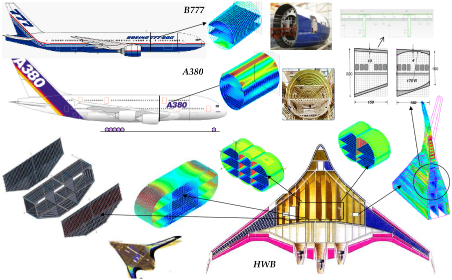

Mukhopadhyay, AIAA 2012-1999, 2012

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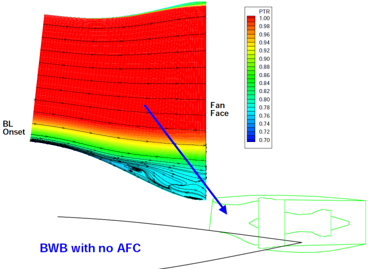

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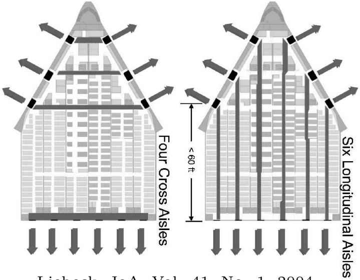


Liebeck, JoA, Vol. 41, No. 1, 2004

The Regional Jet Segment

- Comprises 30% of global aircraft fleet
- Fastest growing segment over the past 30 years

Source: Regional Airline Association 2011 Annual Report

Passengers	100†
Cargo volume	683 ft^3
Payload	23,380 lbs
Max range	2,000 nmi
Cruise speed	0.80 Mach

† Single class at 31" pitch

Similar mission to the CRJ1000ER and E-190

Aerodynamic Shape Optimization

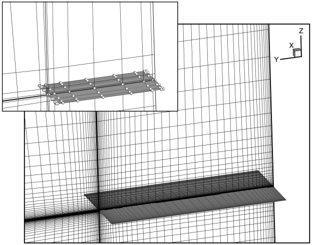
$$\text{Range} = \frac{aM}{c_T}\frac{L}{D}\ln\left(\frac{W_0 + W_{\text{fuel}}}{W_0}\right)$$

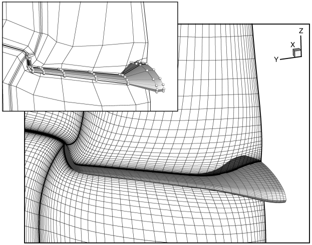
Flight condition effects
Propulsive effects
Aerodynamic effects
Structural effects

- Drag reduction under inviscid flow
  - Flow model: Euler equations
  - Minimize induced drag
  - Eliminate wave drag
- Drag reduction under turbulent flow
  - Flow model: Reynolds-Averaged Navier-Stokes equations
  - Minimize induced drag
  - Eliminate wave drag
  - Minimize profile drag

Geometry parameterization and mesh movement

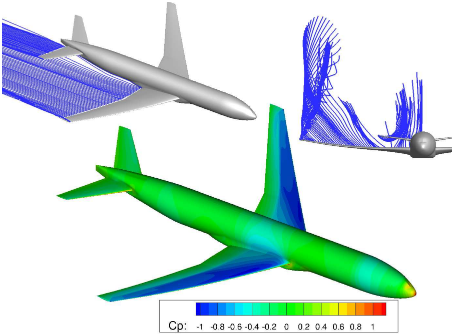
- B-spline geometry parameterization
- Linear elastic mesh movement algorithm applied to the B-spline grid
- Robust for large shape changes





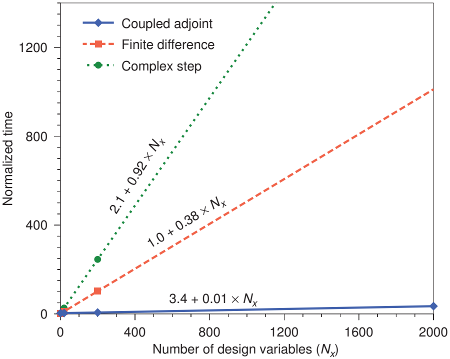
Flow solver

- Newton-Krylov-Schur parallel multiblock implicit flow solver
- Euler and Reynolds-Average Navier-Stokes equations with the one-equation Spalart-Allmaras turbulence model

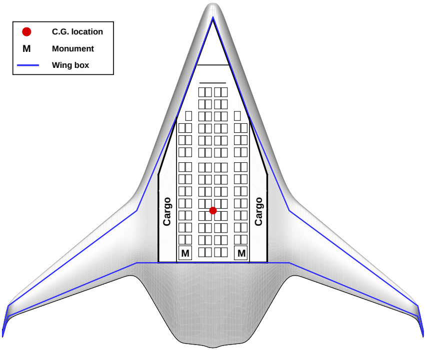


Gradient evaluation

- Via the discrete adjoint method
- Integrated with geometry parameterization, mesh movement, flow solver
- Solution time independent of number of design variables



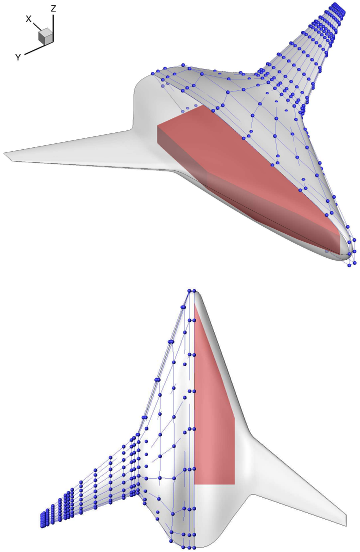
Martins, 2002



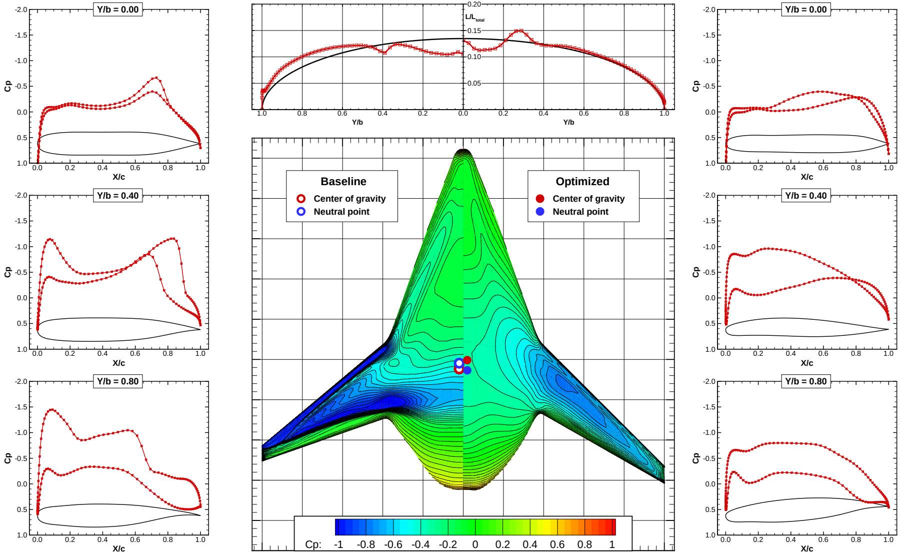
Capacity	
Passengers	98
Crew	4
Cabin floor area	593 ft^2
Cargo volume	683 ft^3
Geometry	
Planform area	2177 ft^2
Total span	90 ft
Length	74 ft
MAC	44 ft
Aspect ratio	3.7
Wetted aspect ratio	1.6
Weight	
MTOW	96,760 lb
OEW	54,710 lb
Payload	23,380 lb
Wing load at MTOW	44 lb/ft^2
Cruise conditions	
Design range	500 nmi
Altitude	40,000 ft
Reynolds number	69 $\times 10^6$
Mach number	0.80
$x_{CG}/c_{\text{center-line}}$	0.65

Optimization Problem

- Objective:
  - Minimize drag
- Design variables:
  - B-spline control points
  - Angle-of-attack
- Geometric constraints:
  - Cabin shape
  - Span and area
  - Geometric limits
- Optimization under inviscid flow:
  - Stability-constrained
- Optimization under turbulent flow:
  - Trim-constrained



Optimization Under Inviscid Flow



Baseline pressure profiles

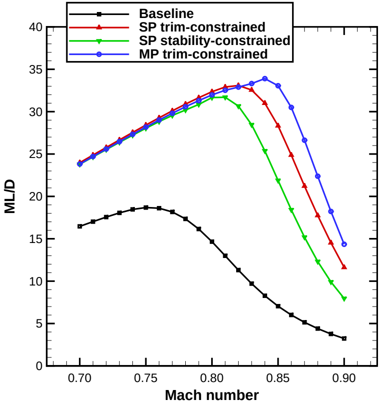
Baseline and optimized surface pressure and spanwise lift distributions

Optimized pressure profiles

Inviscid Performance

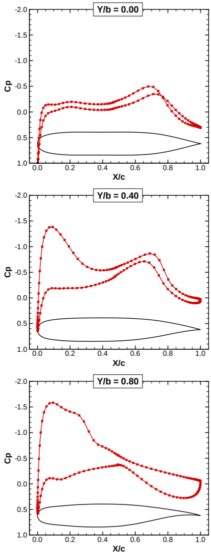
	AoA	C_M	K_n	L/D
Baseline	1.85	-0.021	-2.8	18.3
Optimized	3.01	0.000	+4.9	39.6

- Drag reduction of 55% while creating a trimmed and stable design
  - Wave drag eliminated
  - Induced drag reduced
- Stability constraint incurs a 2% drag penalty

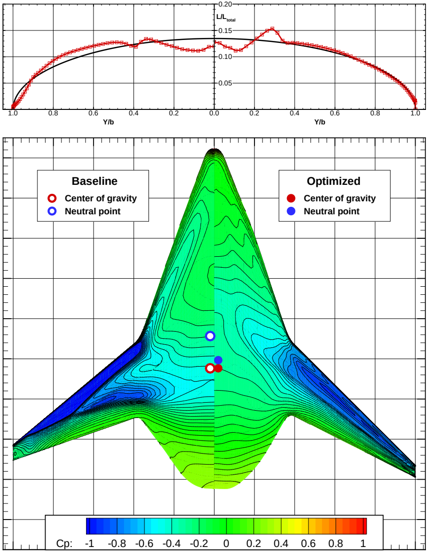


$$R = \frac{aM}{c_T}\frac{L}{D}\ln\left(\frac{W_0 + W_{\text{fuel}}}{W_0}\right)$$

Optimization Under Turbulent Flow



Baseline
pressure profiles



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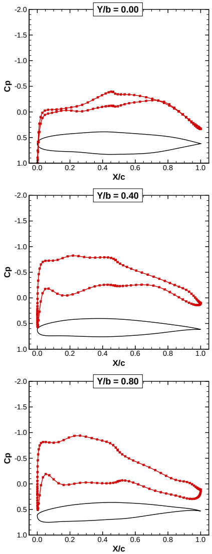
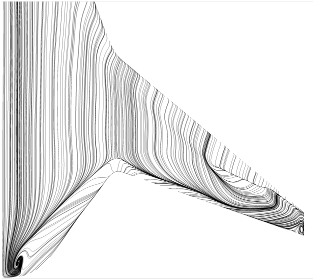


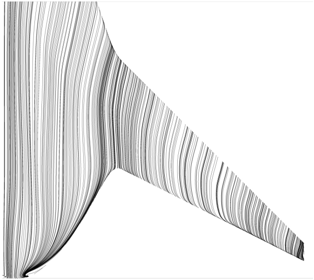
Optimized
pressure profiles

Turbulent Performance

	AoA	C_M	K_n	L/D
Baseline	3.96	0.007	-15.6	10.3
Optimized	2.98	0.000	-4.0	16.7

- Drag reduction of 40% while creating trimmed design
    - Wave drag eliminated
    - Induced drag reduced
    - Profile drag reduced


Baseline


Optimized

Conclusions

Conclusions & Future Work

Conclusions

- Aerodynamic shape optimization is a powerful tool for drag reduction
- High-fidelity aerodynamic shape optimization applicable to full configuration optimization

Future Work

- Aerodynamic shape optimization of an equivalent tube-and-wing design
- Aerostructural optimization is required to demonstrate feasibility of regional jet BWB concept

Thank You

Questions?

Financial support provided by:

BOMBARDIER the evolution of mobility

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