

Optimization of Hybrid Wing-Body Aircraft with Stability and Control Considerations

Thomas A. Reist

Research Associate

University of Toronto Institute for Aerospace Studies

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Unconventional Aircraft Concepts

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



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



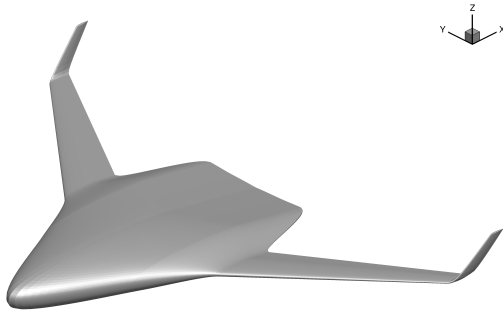
The Hybrid Wing-Body

- One promising unconventional concept is the hybrid wing-body (HWB)
- The HWB has primarily been investigated for large aircraft, where its intrinsic design features are beneficial
- The lack of an empennage makes stability and control (S&C) challenging
 - S&C becomes tightly coupled with configuration design

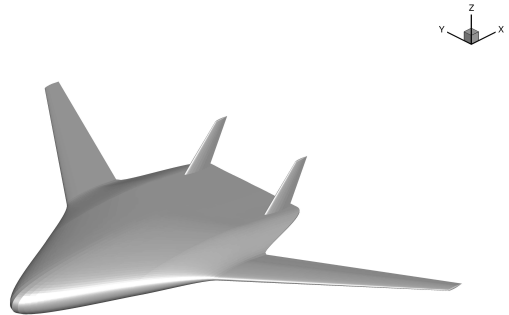


Objectives

- Can an HWB satisfy longitudinal and lateral S&C requirements?
- Are winglet or fin-equipped HWBs more efficient?
- What is the optimal shape for small HWBs?



Winglet-equipped
(BWB100W)

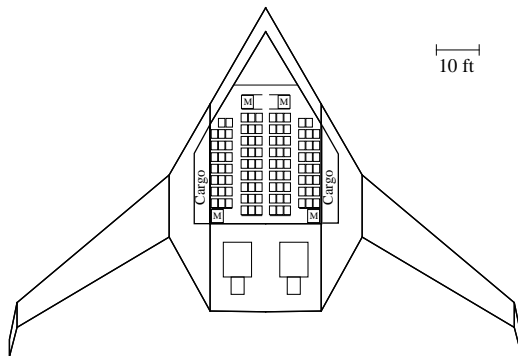


Fin-equipped
(BWB100F)

Design Problem

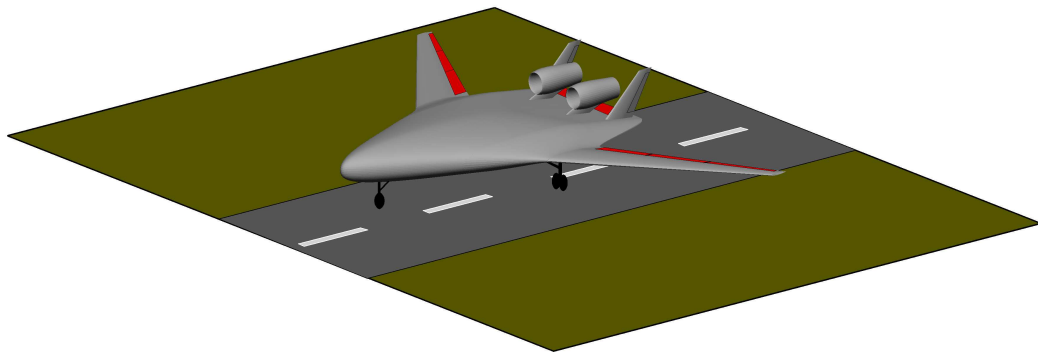
- Regional-class aircraft, similar to the E190
- Seek a design which minimizes a 50/50 combination of MTOW and cruise drag
- Analysis point at the top of climb sizes engines and fuel load
- Trim and longitudinal static (in)stability enforced at this point

Passengers	100
Design mission	
Max range	2,000 nmi
Max payload	22,500 lb
Cruise	
Mach	0.78
Altitude	36,000 ft



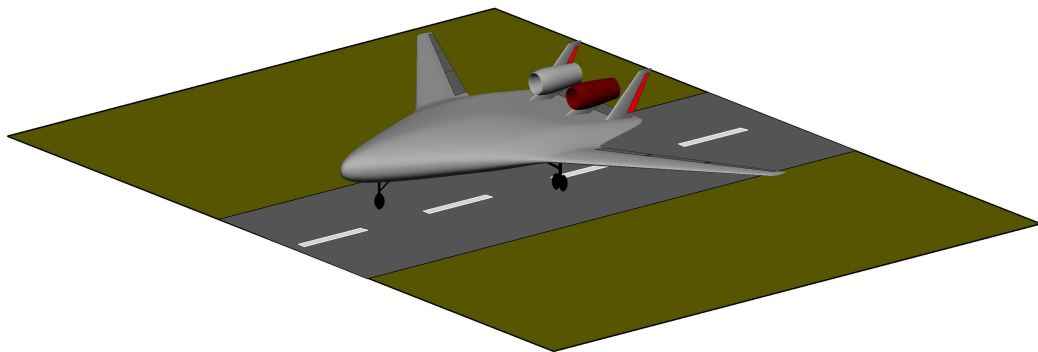
Off-Design S&C Requirements: Longitudinal

- Rotation authority
 - 3 deg/sec attainable at a given rotation speed
- Low-speed trim at extremes of CG envelope
- Control surfaces
 - 1 centerbody elevator, 6 wing-mounted elevons
 - 1/3 of travel allowable to satisfy rotation constraint



Off-Design S&C Requirements: Lateral

- Controllability with one engine inoperative (OEI)
 - Zero bank angle, static proxy for V_{MC_G}
- Cross-wind approach
- Control surfaces
 - 2 winglet/fin-mounted rudders



Multi-Fidelity Multidisciplinary Optimization

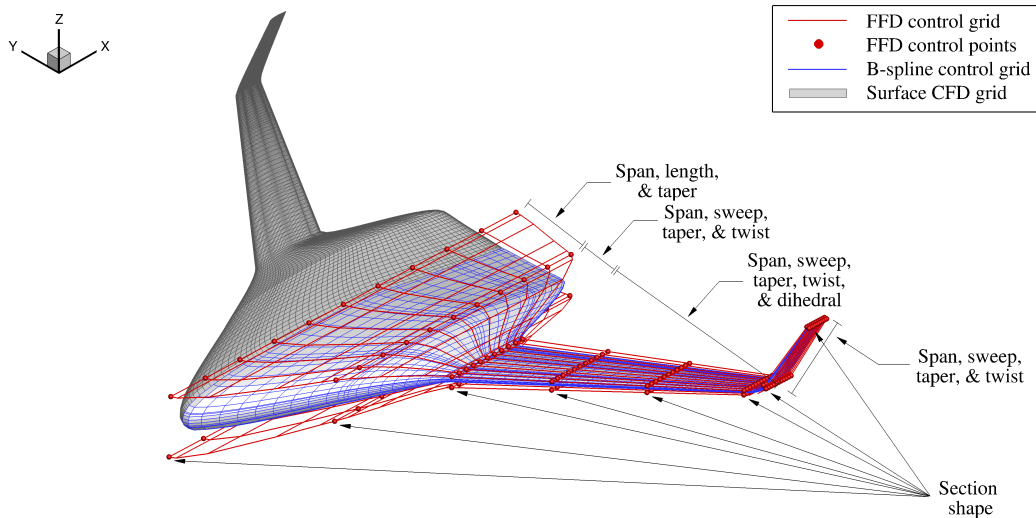
- Fully coupled aerodynamics, structures/weights, and propulsion models for system-level sizing and optimization
- Aerodynamics:
 - RANS solver with SA turbulence model for airframe drag
 - Off-design conditions analyzed in ground effect with moving ground plane
 - Low-fidelity estimates of excrescence, nacelle, and windmilling drag
- Weight and balance:
 - Low-fidelity structural weight models
- Propulsion sizing:
 - Scaling relations for high BPR engines, sized by top of climb requirements
- Fuel loads
 - Breguet range equation and fuel factors
- FFD geometry control
- Gradient-based optimization



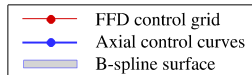
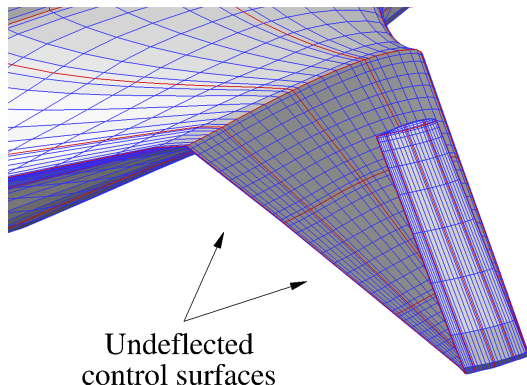
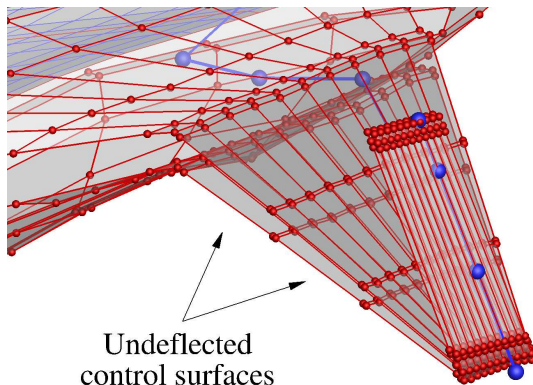
Optimization Problem

Objective		minimize $\frac{1}{2} \frac{MTOW}{MTOW_{ref}} + \frac{1}{2} \frac{D}{D_{ref}}$
Design variables	Geometric:	(See next slide)
	Cruise:	$-2.5^\circ \leq AoA \leq +2.5^\circ$
	OEI:	$0.0^\circ \leq AoA \leq +2.0^\circ$
		$-30^\circ \leq \delta_r \leq +30^\circ (\times 2)$
	Rotation:	$0.0^\circ \leq AoA \leq +2.0^\circ$ $-25^\circ/3 \leq \delta_e \leq +25^\circ/3 (\times 7)$
Constraints	Geometric:	Cabin shape constraint Wing fuel volume Tip strike clearance Ground clearance
	Cruise:	Longitudinal trim $K_{n_{CG \text{ aft}}} \geq -4\%$
	OEI:	Yaw moment = 0
	Rotation:	Rate-of-rotation $\geq 3 \text{ deg/sec}$

Geometric Design Variables

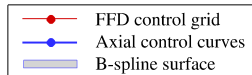
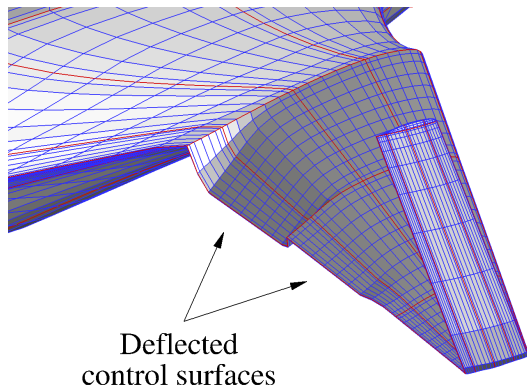
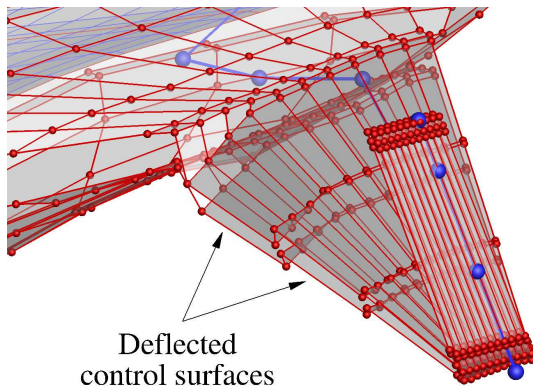


Control Surface Modelling



- Results in continuous mold-line control surface
- Validation with plain flap data shows good agreement for AoA and deflections considered here

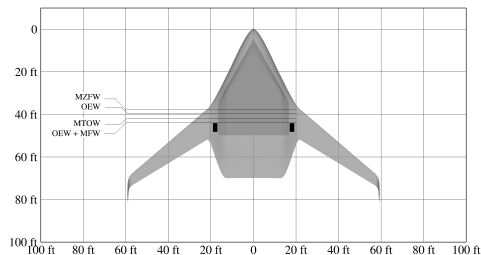
Control Surface Modelling



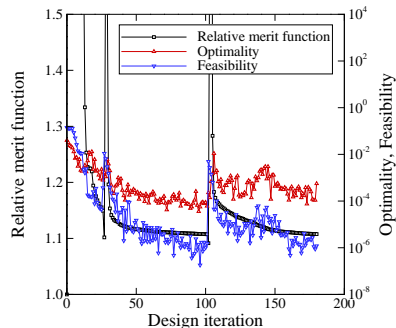
- Results in continuous mold-line control surface
- Validation with plain flap data shows good agreement for AoA and deflections considered here

Optimization of Winglet and Fin-Equipped Designs

- Begins from a section-optimized BWB at cruise (no S&C constraints)
- Active constraints at convergence:
 - All trim and S&C constraints
 - Fuel volume and tip strike (with max dihedral)
 - Winglet root chord and sweep go to their lower bounds (5 ft, 30°)
 - AoA on ground goes to its upper bound (2°)
 - Wing at forward position
 - Minimum thickness on portions of the chord at the wing tip



Cruise-optimized starting geometry

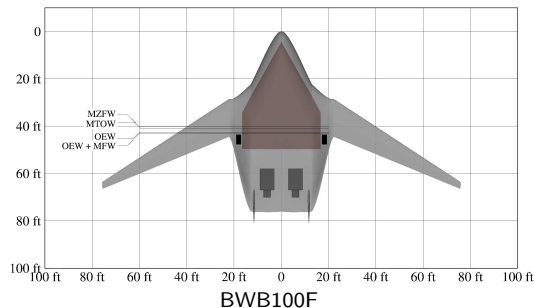
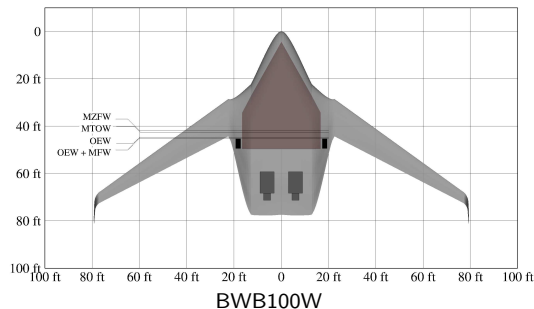


Optimization convergence history

Optimized Designs

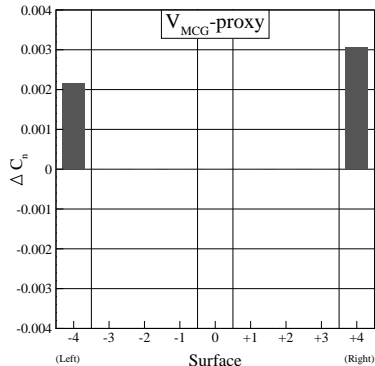
	HWB100W	HWB100F
MTOW [lb]	121,100	119,000
MZFW [lb]	94,900	93,300
OEW [lb]	72,400	70,800
Max fuel weight [lb]	26,200	25,700
Max payload [lb]	22,500	22,500
Cruise thrust [lb]	3,400	3,400
SLS thrust [lb]	15,400	15,000
Span [ft]	158.2	151.2
Cruise drag [lb/cnts]	6,110/84.5	5,960/86.8
Cruise C_L [-]	0.163	0.168
Cruise L/D [-]	19.3	19.4
Cruise K_n [% MAC]	+1.6	+0.8

- Fin-equipped HWB has small weight and aerodynamic advantage

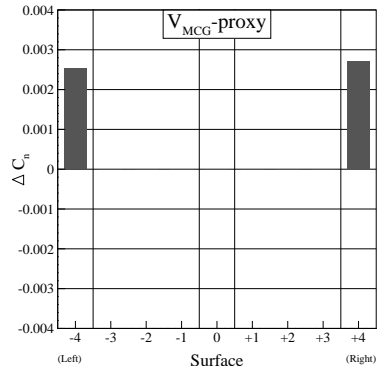


Lateral Control

- Controls saturate
- Wing design for the fin-equipped HWB is decoupled from the OEI constraint, and is driven by performance
- OEI constraint drives winglet/fin size and wing sweep/span for winglet-equipped configuration



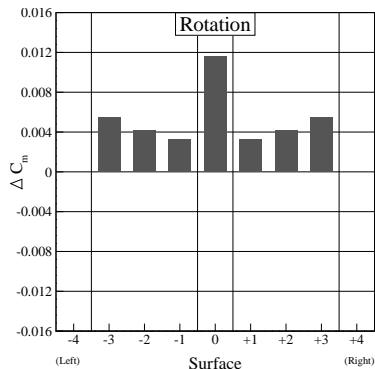
BWB100W



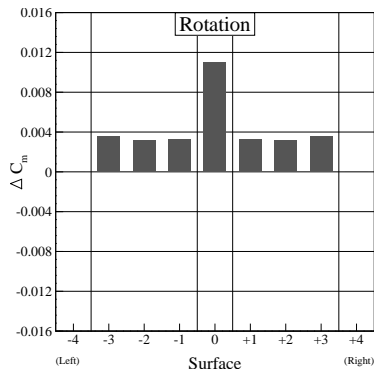
BWB100F

Longitudinal Control: Rotation

- Controls saturate
- Centerbody elevator most effective
- Strong driver of planform. Drives:
 - Centerbody length
 - Wing sweep/span



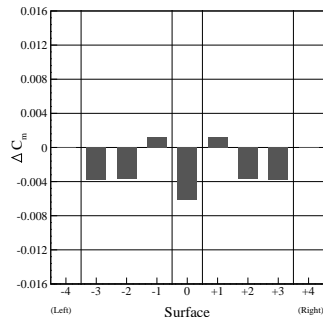
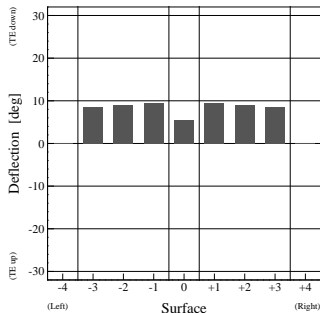
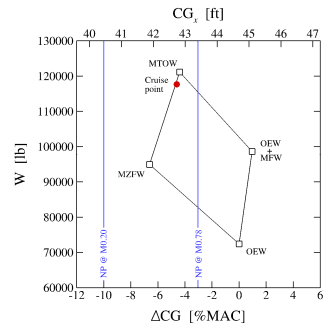
BWB100W



BWB100F

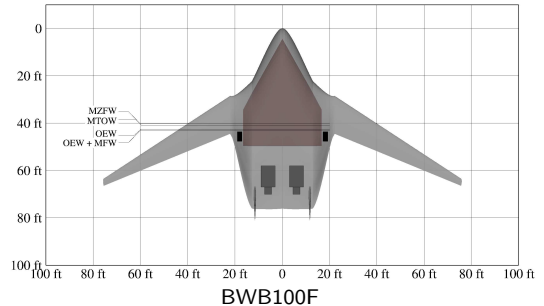
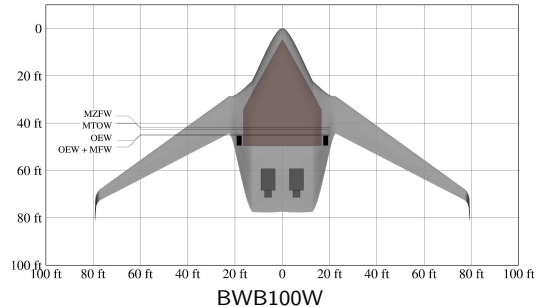
Longitudinal Control: Low Speed Trim

- Low speed (Mach 0.20) trimability checked post-optimization at fore and aft CG conditions
- Redundant control problem, so minimum drag solution sought
- Centerbody elevator provides sufficient pitch authority to trim
- BWB100W control solution shown



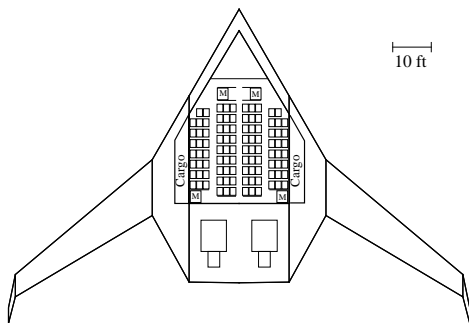
Centerbody Inefficiencies

- Centerbody weight fraction is high
 - 40% OEW
- Large weight/drag penalty from aft centerbody

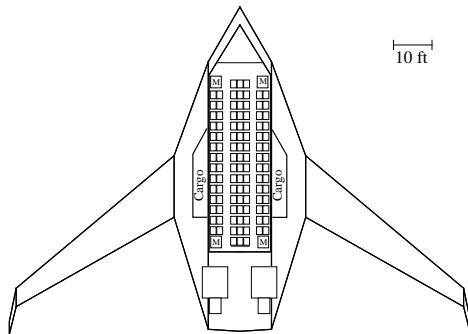


Narrow Centerbody Derivatives

- Wasted space aft of the cabin leads to large weight penalty
- Investigate alternative cabin layouts which permit a narrower, more elongated, centerbody
- Past work at UTIAS has suggested there is also an L/D benefit due to reduced wetted area
- Optimize as before, but with new cabin shape constraints which reflect the layouts shown below



12 abreast
(BWB100W)

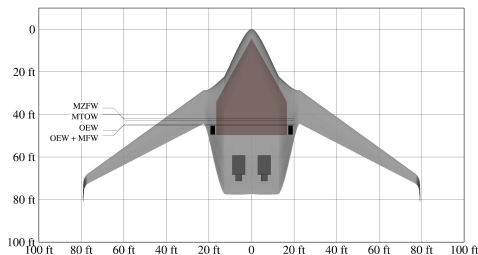


7 abreast
(BWB100W-N7)

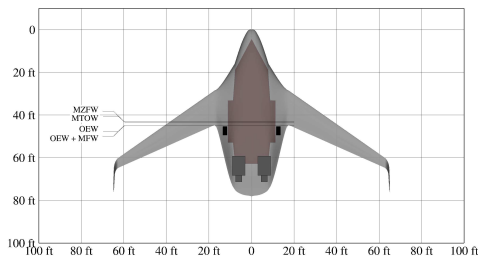
Comparison of Wide and Narrow Centerbody Designs

	HWB100W	HWB100W-N7
MTOW [lb]	121,100	108,600
MZFW [lb]	94,900	85,800
OEW [lb]	72,400	63,300
Max fuel weight [lb]	26,200	22,900
Max payload [lb]	22,500	22,500
Cruise thrust [lb]	3,400	2,960
SLS thrust [lb]	15,400	13,200
Span [ft]	158.2	129.6
Cruise drag [lb/cnts]	6,110/84.5	5,190/91.5
Cruise C_L [-]	0.163	0.186
Cruise L/D [-]	19.3	20.3
Cruise K_n [% MAC]	+1.6	+0.4

- Up to a 10% reduction in MTOW
 - More efficient centerbody reduces OEW by up to 9,100 lb
- Up to 5% higher L/D due to reduced wetted area and increased wing loading



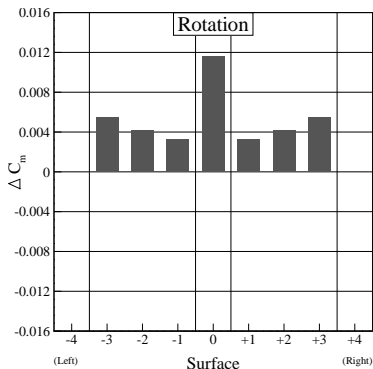
HWB100W



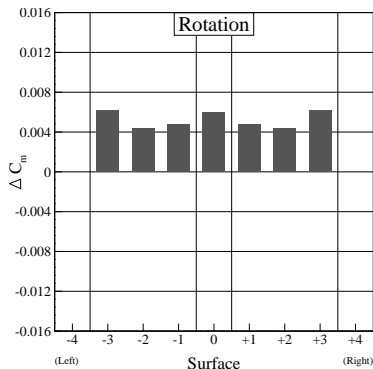
HWB100W-N7

Comparison of Rotation Authority

- Centerbody elevator effectiveness reduced by 50% relative to the BWB100W
- Optimizer does not significantly increase the centerbody length, instead opting to improve cabin packing efficiency
- Trimmable at low speed, but requires all control surfaces



BWB100W



BWB100W-N7

Conclusions

- Both winglet and fin-based control methods are capable of satisfying the S&C requirements studied here
- Fin-equipped design is superior
 - Lower MTOW and higher cruise L/D
 - Fin-equipped configuration would also benefit from acoustic shielding
- More elongated cabin layout offers weight and aerodynamic benefits
 - Longitudinal control is more challenging
 - Engine installation challenges for this configuration
 - Attains maximum aerodynamic efficiency at lower altitude
 - Lower span → gate constraint would be less detrimental





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