MIT's N+3 Project: The D8 Aircraft Concept and Its Boundary Layer Ingestion Benefit

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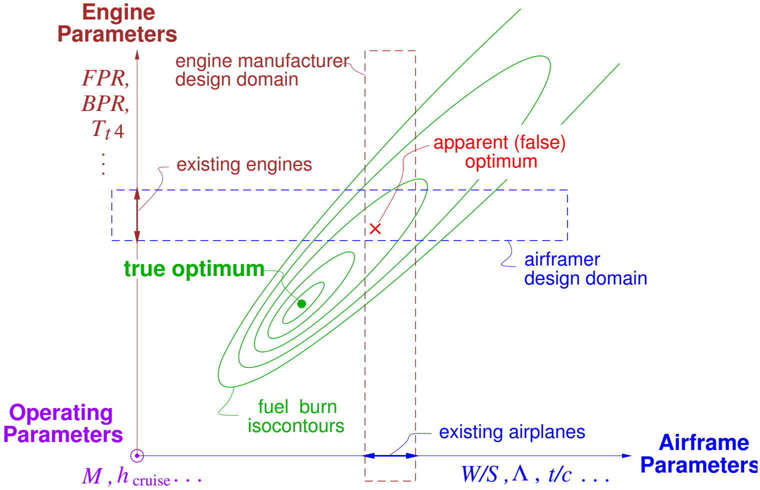
Summary

- Closer integration of propulsion system and airframe provides new opportunities to reduce fuel burn and emissions of commercial aircraft
  - Boundary layer ingestion (BLI)
  - Novel configurations
  - System optimization (airframe, engine, operations)
- Flow power and dissipation in power balance framework provide useful metrics for integrated configurations

True Optimum

Optimization of the aircraft as an integrated system can reach higher levels of fuel efficiency than separate optimization of airframe and propulsion system



M. Drela

MIT N+3 Project

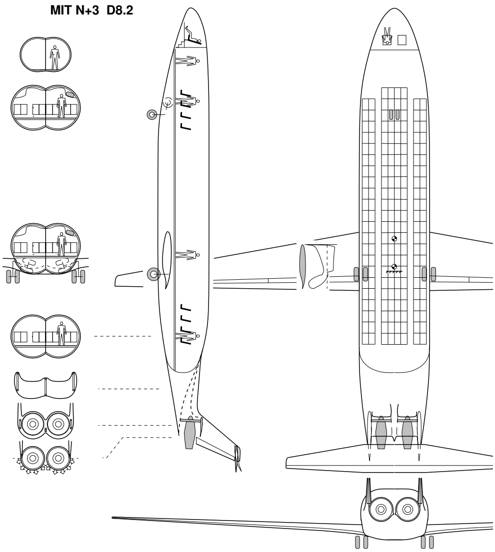
NASA N+3 Program, Fixed Wing Project

- Develop advanced aircraft concepts and enabling technologies for step improvements in fuel efficiency and emissions of commercial aircraft entering service in 2025 – 2035

Phase 1 (2008 – 2010)

- MIT-led team developed the *double-bubble* D8 aircraft concept
- Opportunity to impact the way the industry thinks about aircraft and propulsion

The D8 Aircraft Concept



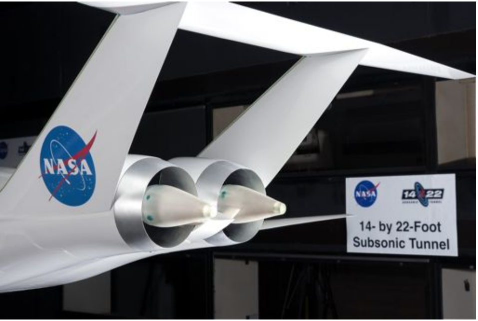
- B737-800/A320 class
- 180 PAX, 3,000 nm range
- Double-bubble lifting fuselage with pi-tail
- Two aft, flush-mounted engines ingest $\sim$40% of fuselage BL
- Cruise Mach 0.72

–37% fuel with current tech (configuration)

–66% fuel with advanced tech (2025-2035)

No "magic bullet"

E. Greitzer et al. 2010, NASA CR 2010-216794



Photos NASA/George Homich

System Impact of BLI

BLI benefits

- *Aerodynamic* (direct) benefits
  - Reduced jet and wake dissipation
  - Reduced nacelle wetted area
- *System-level* (secondary) benefits
  - Reduced engine weight
  - Reduced nacelle weight
  - Reduced vertical tail size
  - Compounding from reduced overall weight

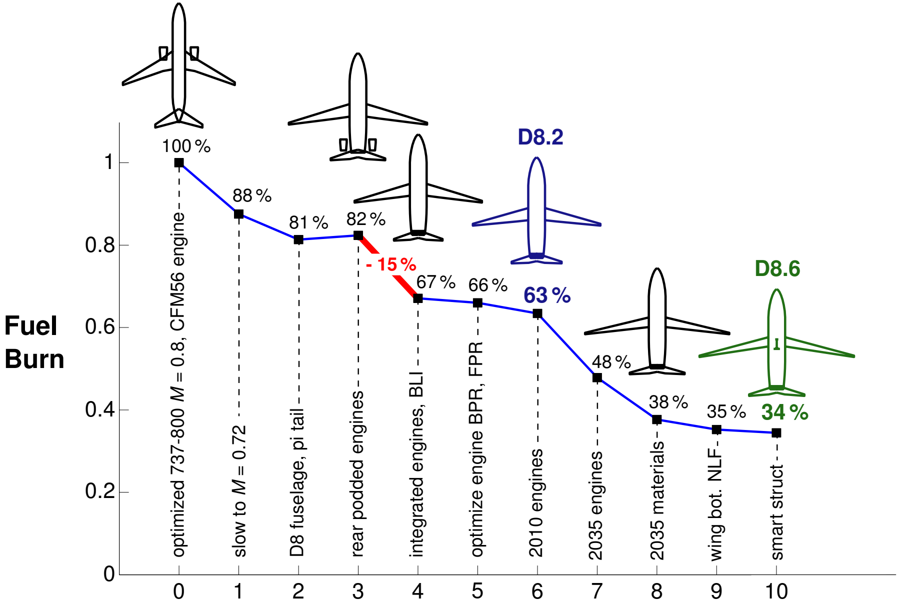
"Morphing" sequence: B737-800 $\mapsto$ D8

- Features of D8 introduced one at a time
- Sequence of conceptual designs, optimized at each step (TASOPT)

E. Greitzer et al. 2010, NASA CR 2010-216794

M. Drela 2011, AIAA 2011-3970

Morphing Sequence: B737-800 $\mapsto$ D8.2 $\mapsto$ D8.6



Phase 2: Nov. 2010 – Nov. 2014

Research thrusts

- Airframe-propulsion system integration (Task 1)
  - Define/design aft section of D8 (integration of engines into fuselage)
  - Quantify aerodynamic benefit of BLI
  - Propulsor performance with distortion from BLI
  - Phenomena, expected (and unexpected) behavior

- High efficiency, high pressure ratio small core engines (Task 2)
  - Limits to performance
  - Technology opportunities for performance enhancement
  - Innovative propulsion system architectures

NASA N+3 Phase 2

How

- Direct, back-to-back comparison of non-BLI and BLI configurations
  (podded) (integrated)
- Turbomachinery characterization

Tools

- Experiments at NASA Langley 14×22 wind tunnel and MIT tunnels
- Computational studies
- Close collaboration with NASA

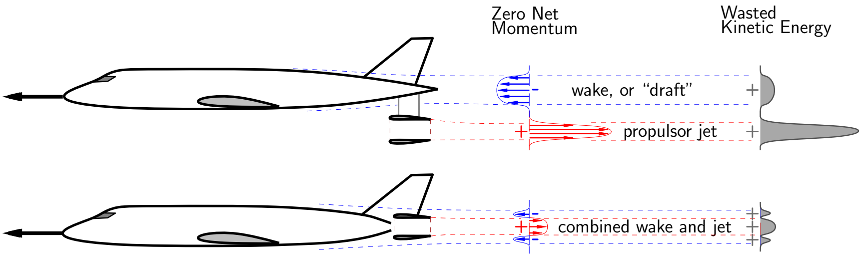
Outline

Nomenclature

$F_X \ , \ C_X = \dfrac{F_X}{q_\infty S}$	Net stream-wise force ("drag minus thrust")
$P_E \ , \ C_{P_E} = \dfrac{P_E}{q_\infty S V_\infty}$	Electrical power supplied to propulsors
$P_K \ , \ C_{P_K} = \dfrac{P_K}{q_\infty S V_\infty}$	Mechanical flow power through propulsors
$V_\infty \ , \ q_\infty = \dfrac{1}{2}\rho_\infty V_\infty^2$	Free-stream (tunnel) speed, dynamic pressure
S	Reference area (1686 in^2, 1.088 m^2 at 1:11 scale)
D	Propulsor fan diameter (5.67 in, 0.072 m at 1:11 scale)

BLI Analysis

- Ambiguous decomposition into drag (airframe) and thrust (propulsion system)
- Use power balance method instead of force accounting
- BLI reduces wasted KE in combined jet+wake (mixing losses)

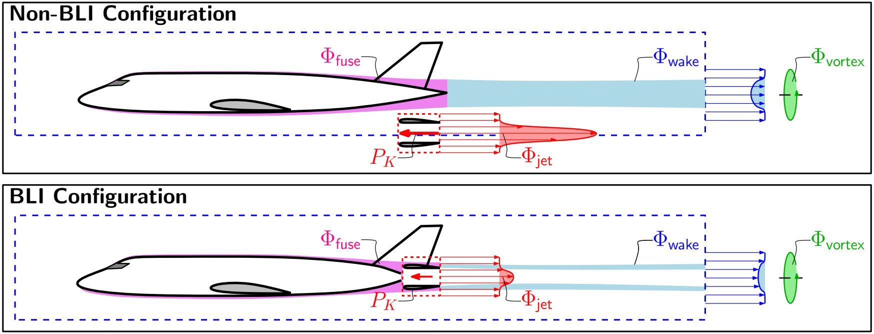


M. Drela 2009, AIAA Journal 47(7)

Power Balance method

Consider mechanical energy sources and sinks: $[\,\text{Power In}\,] \;=\; [\,\text{Dissipation}\,]$

$$\underbrace{\cancel{P_S}}_{\text{shaft power}} + \underbrace{\cancel{P_V}}_{p\,dV\text{ power}} + \underbrace{P_K}_{\text{mechanical flow power}} = \Phi_{\text{jet}} + \Phi_{\text{wake}} + \Phi_{\text{fuse}} + \Phi_{\text{vortex}} + \underbrace{\dot{E}}_{\text{power out of CV}}$$



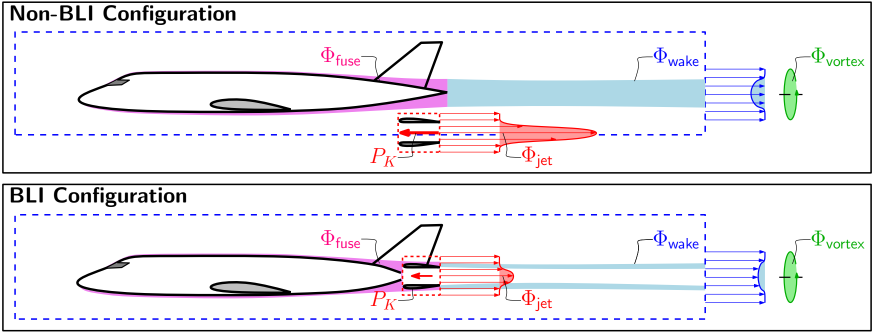
M. Drela 2009, AIAA Journal 47(7)

Power Balance method

Aerodynamic (direct) benefit of BLI configuration

Reduced jet + wake dissipation, reduced nacelle wetted area

$$\underbrace{P_K^{\rm BLI} - \Phi_{\rm jet}^{\rm BLI}}_{\text{Net propulsive power}} = P_K^{\rm BLI}\,\underbrace{\eta_p^{\rm BLI}}_{>\eta_p} = \underbrace{\Phi_{\rm wake}^{\rm BLI}}_{(1-f_{\rm BLI})\Phi_{\rm wake}} + \Phi_{\rm fuse}^{\rm BLI} + \Phi_{\rm vortex}$$



M. Drela 2009, AIAA Journal 47(7)

BLI Benefit

BLI benefit (aerodynamic)

Savings in power required for given net stream-wise force with BLI engines relative to non-BLI engines

Power metric

Mechanical flow power transmitted to the flow by the propulsors

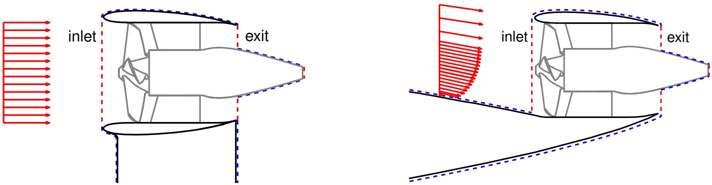
$$P_K = \oint (p_o - p_{o_\infty}) \mathbf{V} \cdot \hat{n} \, dS$$

$$\text{BLI benefit} \equiv \left. \frac{P_{K_{\text{non-BLI}}} - P_{K_{\text{BLI}}}}{P_{K_{\text{non-BLI}}}} \right|_{\text{at given } F_X}$$

Obtaining P_K

Method 1: Integration of the flow over cross-section of the stream-tube upstream and downstream of the propulsor: flow survey data

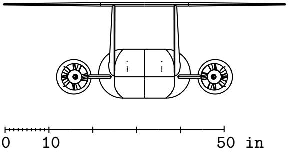
$$P_K = \int_{\text{exit}} (p_o - p_{o_\infty}) \mathbf{V} \cdot \hat{n} \, dS - \int_{\text{inlet}} (p_o - p_{o_\infty}) \mathbf{V} \cdot \hat{n} \, dS$$



Method 2: From *electrical power* provided to the propulsor motor, which is related to mechanical flow power through fan and motor efficiencies

$$\underbrace{P_K}_{\substack{\text{mechanical}\\ \text{flow power}}} = \underbrace{\eta_f}_{\substack{\text{fan}\\ \text{efficiency}\\ P_K/P_S}} \times \underbrace{\eta_m}_{\substack{\text{motor}\\ \text{efficiency}\\ P_S/P_E}} \times \underbrace{P_E}_{\substack{\text{electrical}\\ \text{power}}}$$

Podded (non-BLI) Configuration



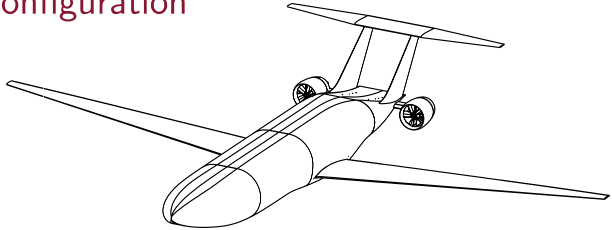
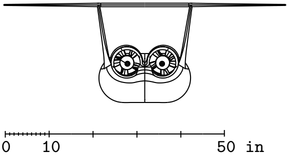


Photo NASA/George Homich

Integrated (BLI) Configuration



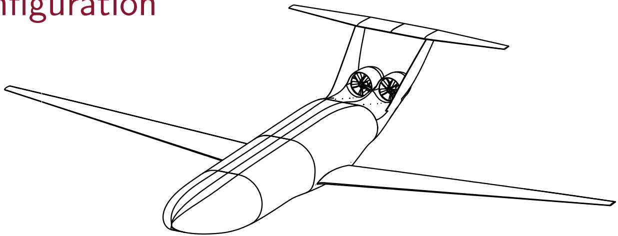
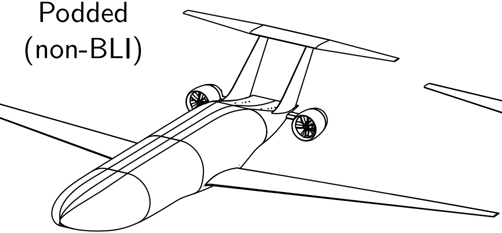


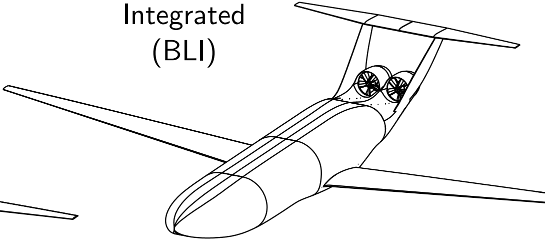
Photo NASA/George Homich

Back-to-Back Comparison

Podded
(non-BLI)



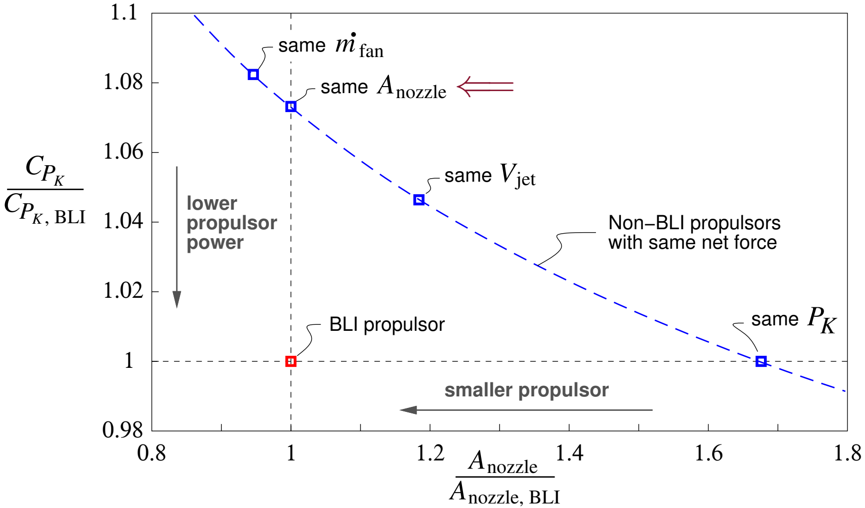
Integrated
(BLI)



$$\text{BLI benefit} = \left. \frac{C_{P_K \, \text{podded}} - C_{P_K \, \text{integrated}}}{C_{P_K \, \text{podded}}} \right|_{\text{at given } C_X}$$

Bases for Comparison

Given a BLI propulsor with some jet velocity, mass flow, nozzle area, how do you choose an "equivalent" non-BLI propulsor as basis for comparison?



Scaling Considerations for Low Speed Study

No dynamic symilarity between full-size D8 and experiments:
Reynolds number and Mach number are not matched

⇒ How do we ensure BLI benefit results are representative of full-size conditions?

- Airframe scaled geometrically by 1:11 from full-size, current-technology D8 (fuselage, wing and tail planforms, fan diameter)
- Wing profiles and sweep designed for low speed (low Mach, low Re)
- Propulsion system scaling
  - Use same propulsion system for both BLI and non-BLI
  - Data taken with varying nozzle area to bracket design power and propulsive efficiency at cruise condition
- Investigate off-design points

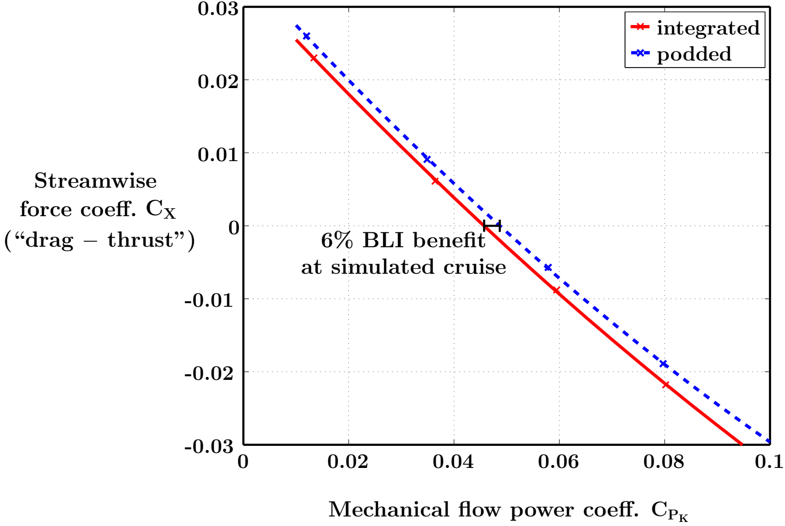
Experimental Approach

- NASA Langley 14×22 Foot Subsonic Wind Tunnel
  $V_\infty = 70$ mph, $M_\infty = 0.09$, $Re_c = 570{,}000$
- 1:11 scale, 13.4 ft span, powered D8 model
- Podded and integrated configurations share a large part of hardware
  - Common wings and front 80% of fuselage
  - Common propulsor units plug into interchangeable tails
    (fan stage, motor, center-body, housing, nozzle, electronics)
  - All model surfaces tripped
- Data collection
  - Forces and moments (internal NASA balance)
  - Electrical power
  - Fan wheel speed
  - Rake system for total and static pressure surveys

Outline

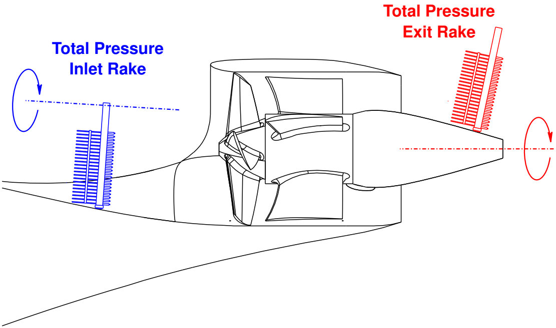
BLI Benefit

$C_{P_K \text{ BLI}} < C_{P_K \text{ non-BLI}}$ for any given C_X
or $C_{X \text{ BLI}} > C_{X \text{ non-BLI}}$ for any given C_{P_K}



Survey Propulsor Inlet and Outlet

Rotating rake system
in wind tunnel experiments



Integrated Propulsor Ingested Flow

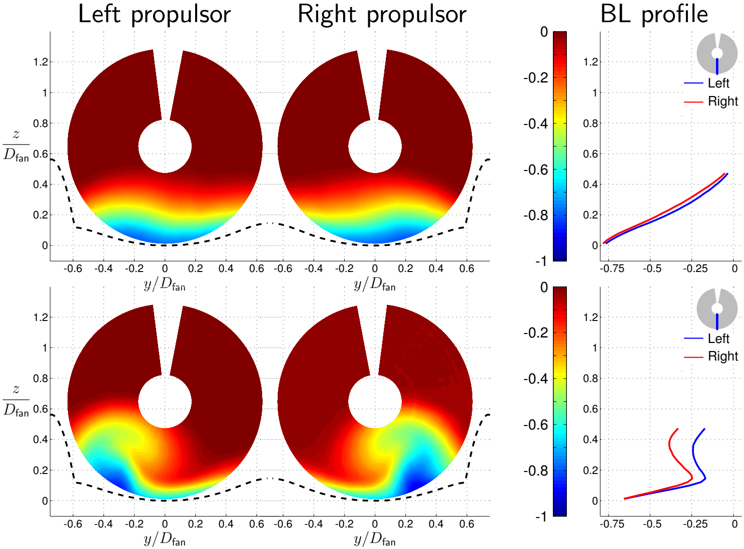
"Benign" stratified flow

Total pressure coefficient $C_{p_t} = \dfrac{p_t - p_{t_\infty}}{q_\infty}$

Experiments

$\alpha = 2^\circ$
11 kRPM
(cruise)

$\alpha = 6^\circ$
13 kRPM
(climb)



Integrated Propulsor Exit Flow

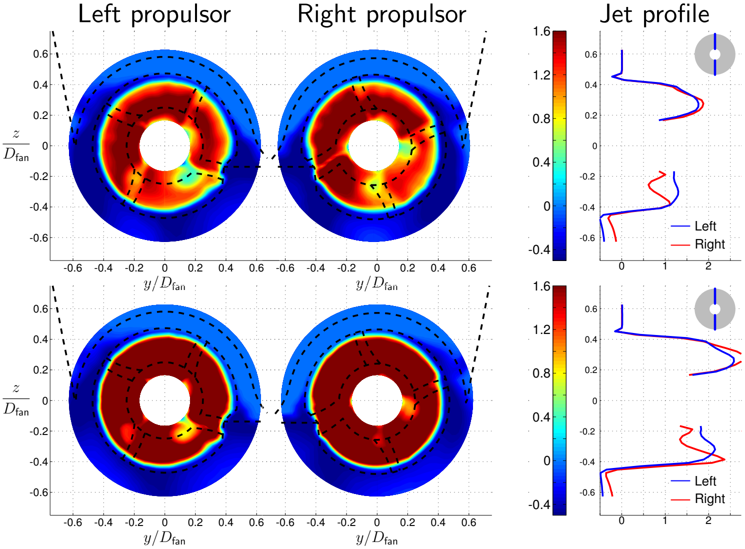
Clean exit flow

Total pressure coefficient $C_{p_t} = \dfrac{p_t - p_{t_\infty}}{q_\infty}$

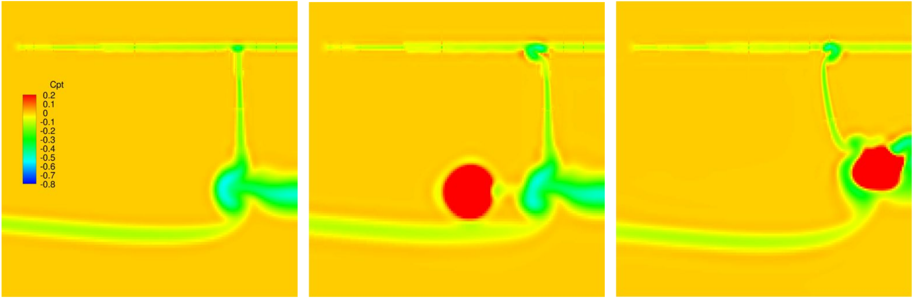
Experiments

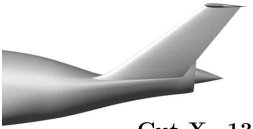
$\alpha = 2^\circ$
11 kRPM
(cruise)

$\alpha = 6^\circ$
13.5 kRPM
(climb)

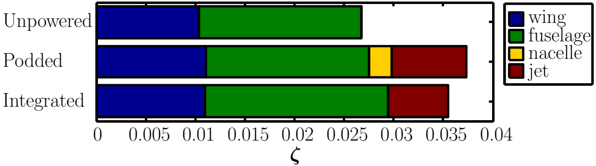


Dissipation as a Measure of Configuration Performance



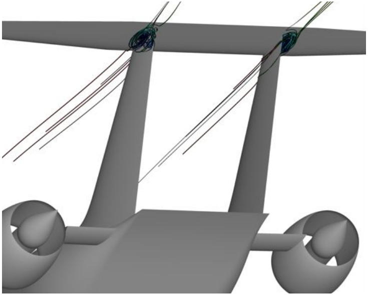


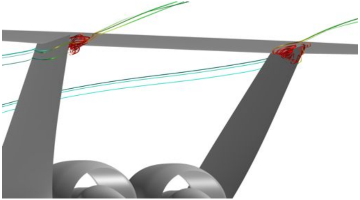
Cut X=130

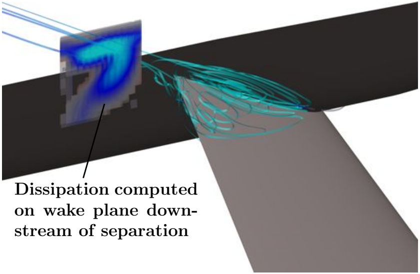


Dissipation as a Measure of Configuration Performance

Both podded and integrated configurations show separation at the junctures of vertical tails and horizontal tail: $\sim 1.2\%$ of total dissipation







Outline

Conclusion

- Aero BLI benefit: $6\% \pm ?$ saving in power (fuel) with BLI at cruise
- Estimated total, system-level fuel burn savings of 15% enabled by BLI
- D8 with estimated 37% fuel saving over conventional tube-and-wing can be built "today"

Data supports feasibility of using BLI to improve fuel efficiency
and viability of D8 concept

An exciting project aimed at
changing the way industry thinks about aircraft and propulsion,
and the look of civil transport aircraft

Acknowledgments

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MIT N+3 team

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Staff at NASA Langley 14×22 Foot Subsonic Wind Tunnel

NASA Fixed Wing Project management