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.
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 ~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
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 ↔ 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 ↔ D8.2 ↔ D8.6

- Optimized 737-800 M = 0.8, CFM56 engine
- Slow to M = 0.72
- D8 fuselage, pi tail
- Rear podded engines
- Integrated engines, BLI
- Optimize engine BPR, FPR
- 2010 engines
- 2035 engines
- 2035 materials
- Wing bot. NLF
- Smart struct

Fuel Burn

- 100%
- 88%
- 81%
- 82%
- 67%
- 66%
- 63%
- 48%
- 38%
- 35%
- 34%
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

1 Introduction

2 Methodology
   - Performance Metric for BLI
   - Configurations
   - Approach

3 Results

4 Summary
Nomenclature

\[ F_X, \quad C_X = \frac{F_X}{q_\infty S} \]
Net stream-wise force ("drag minus thrust")

\[ P_E, \quad C_{P_E} = \frac{P_E}{q_\infty S V_\infty} \]
Electrical power supplied to propulsors

\[ P_K, \quad C_{P_K} = \frac{P_K}{q_\infty S V_\infty} \]
Mechanical flow power through propulsors

\[ V_\infty, \quad q_\infty = \frac{1}{2} \rho_\infty V_\infty^2 \]
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 and thrust (airframe) (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: \[
\text{Power In} = \text{Dissipation}
\]

\[
P_s + p \, dV + P_K = \Phi_{\text{jet}} + \Phi_{\text{wake}} + \Phi_{\text{fuse}} + \Phi_{\text{vortex}} + \dot{E}
\]

- \(P_s\): Shaft power
- \(p \, dV\): Power due to pressure
- \(P_K\): Mechanical flow power
- \(\Phi_{\text{jet}}\): Jet power
- \(\Phi_{\text{wake}}\): Wake power
- \(\Phi_{\text{fuse}}\): Fuse power
- \(\Phi_{\text{vortex}}\): Vortex power
- \(\dot{E}\): Power out of CV

Non-BLI Configuration

BLI Configuration

M. Drela 2009, AIAA Journal 47(7)
Power Balance method

Aerodynamic (direct) benefit of BLI configuration

*Reduced jet + wake dissipation, reduced nacelle wetted area*

\[ P_{\text{BLI}} - \phi_{\text{BLI jet}} = P_{\text{K}} \eta_{\text{BLI}} > \eta_p \]

\[ = \phi_{\text{BLI wake}} + (1 - f_{\text{BLI}}) \phi_{\text{wake}} + \phi_{\text{fuse}} + \phi_{\text{vortex}} \]

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Non-BLI Configuration

BLI Configuration

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*

\[
P_K = \int (p_o - p_{o\infty}) \mathbf{V} \cdot \hat{n} \, dS
\]

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

\[
P_K = \frac{P_K}{P_S} \times \frac{\eta_f}{\eta_m} \times \frac{P_E}{P_S}
\]
Podded (non-BLI) Configuration

Photo NASA/George Homich
Integrated (BLI) Configuration

Photo NASA/George Homich
Back-to-Back Comparison

BLI benefit = \frac{C_{P_K}^{\text{podded}} - C_{P_K}^{\text{integrated}}}{C_{P_K}^{\text{podded}}} \quad \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 similarity 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
  \[ V_\infty = 70 \text{ mph}, \quad M_\infty = 0.09, \quad Re_c = 570,000 \]

- 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

1 Introduction

2 Methodology

3 Results
   - BLI Benefit
   - Flow Surveys
   - Dissipation

4 Summary
BLI Benefit

\[ C_{PK\text{ BLI}} < C_{PK\text{ non-BLI}} \text{ for any given } C_X \]

or

\[ C_{X\text{ BLI}} > C_{X\text{ non-BLI}} \text{ for any given } C_{PK} \]

Streamwise force coeff. \( C_X \) ("drag – thrust")

6% BLI benefit at simulated cruise

Mechanical flow power coeff. \( C_{PK} \)
Survey Propulsor Inlet and Outlet

Rotating rake system in wind tunnel experiments
Integrated Propulsor Ingested Flow

“Benign” stratified flow

Total pressure coefficient \( C_{p_t} = \frac{p_t - p_{t\infty}}{q_{\infty}} \)

Experiments

\[ \alpha = 2^\circ \]
11 kRPM (cruise)

\[ \alpha = 6^\circ \]
13 kRPM (climb)

\( \frac{z}{D_{fan}} \)

\( \frac{y}{D_{fan}} \)

\( \frac{y}{D_{fan}} \)

BL profile
Integrated Propulsor Exit Flow

Experiments

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

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

Clean exit flow

Total pressure coefficient

\[ C_p = \frac{p_t - p_{t\infty}}{q_{\infty}} \]
Dissipation as a Measure of Configuration Performance

Cut X=130

Unpowered
Podded
Integrated

\( \zeta \)
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.

Dissipation computed on wake plane downstream of separation.
Outline

1. Introduction
2. Methodology
3. Results
4. Summary
Conclusion

- Aero BLI benefit: 6% ± ? 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
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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