Boundary Layer Ingestion

Benefit Quantification and Analysis Framework

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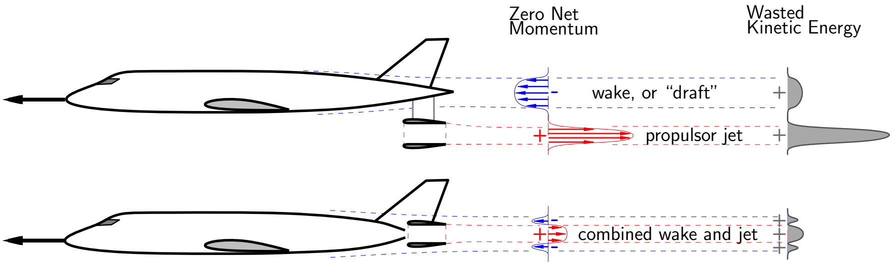
Outline

Boundary Layer Ingestion (BLI)



- BLI reduces wasted KE in combined jet+wake (mixing losses)
- Long known to have large potential, never realized for aircraft
- Ambiguous decomposition into drag (airframe) and thrust (propulsion system)

$\Rightarrow$ use of **power balance** instead of force accounting

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
- D8 wind tunnel tests
  - Quantification of aerodynamic BLI benefit
  - Proof-of-concept for use of BLI in transport aircraft
- Aerodynamic framework developed to analyze aircraft with BLI

Major Collaborators

MIT

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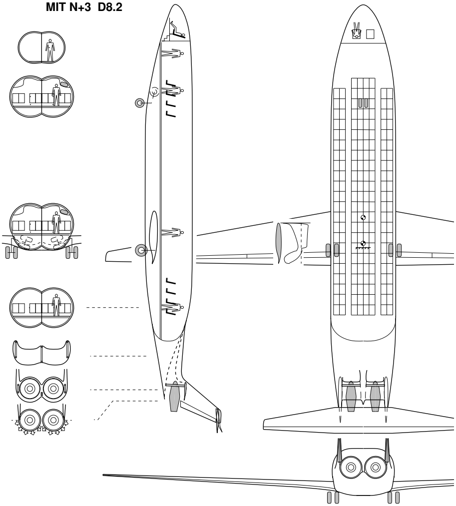
Outline

Phase 1: D8 Aircraft Concept

2008-2010



- 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

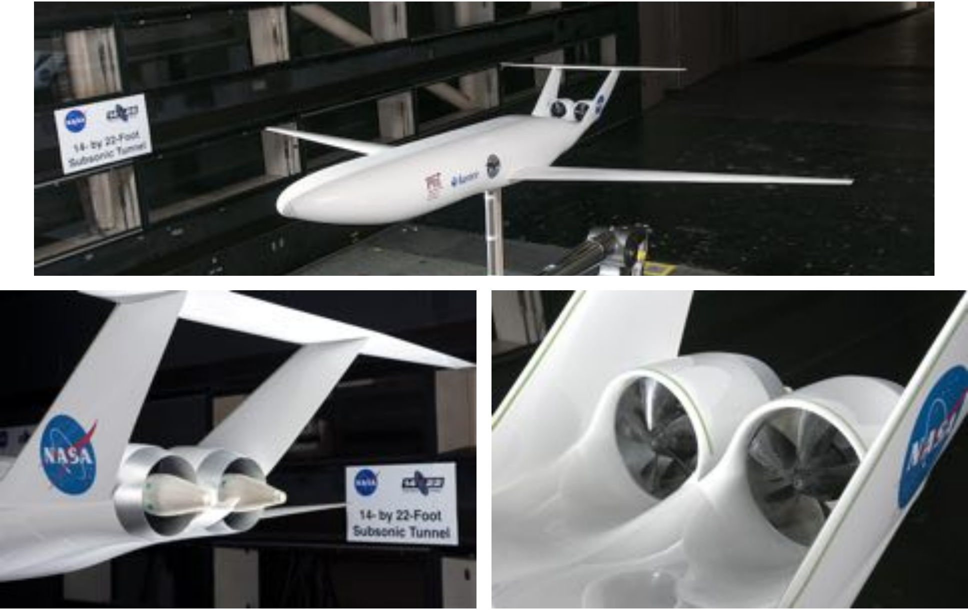
−37% fuel with current tech (configuration)

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

No "magic bullet"

E. Greitzer et al. 2010, NASA CR 2010-216794
A. Uranga et al. 2014, AIAA 2014-0906

NASA-MIT Cooperative Agreement NNX08AW63A



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

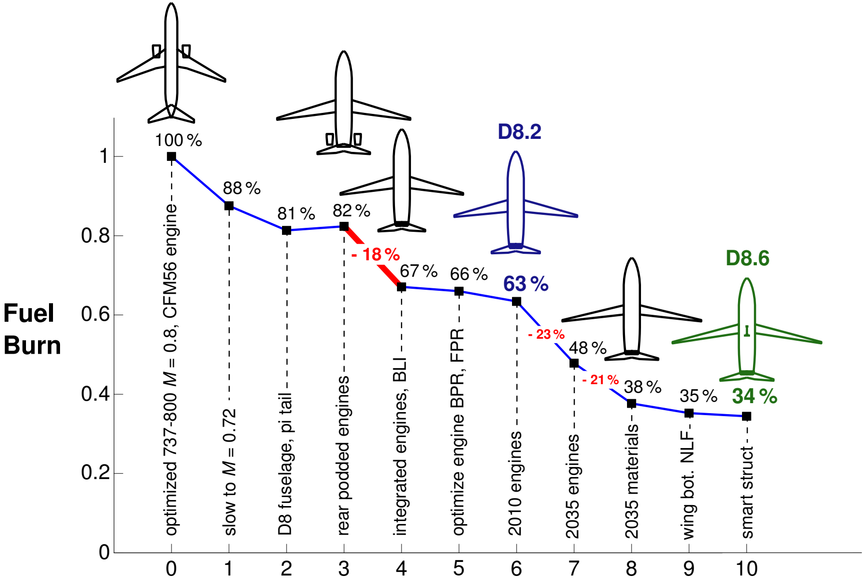
"Morphing" sequence: B737-800 $\mapsto$ D8

- 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 3: Trade-Offs Summary

2015-2017

Metric: Payload-Range Fuel Consumption $= \dfrac{\text{Fuel Energy Consumed}}{\text{Payload Weight} \times \text{Range}}$

- **D8 configuration benefit** $(\mathbf{20} \pm 3)\%$
  relative to tube-and-wing at same cruise speed and technology

- **N+3 technology benefit** $(\mathbf{45} \pm 2)\%$ relative to 1990s tech
  - Tech advances benefit tube-and-wing more:
    D8 has lower structural/total weight and higher payload/total weight

- **Slowing down from Mach 0.78 to 0.72** $(\mathbf{5} \pm 1.5)\%$
  - Tube-and-wing benefits more from lower speed

NASA-MIT Cooperative Agreement NNX15AM91A

Outline

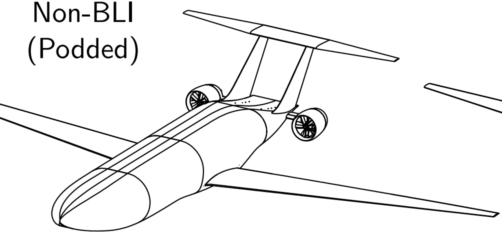
Phase 2: Airframe-Engine Integration

2010-2015

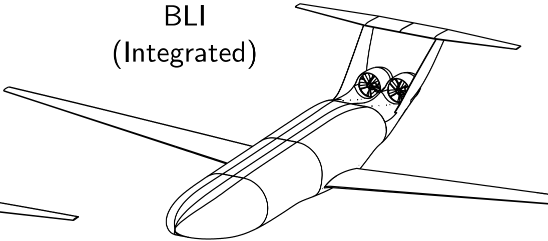
Quantification of D8 BLI benefit (experimental/computational)

- Direct back-to-back comparison of BLI vs non-BLI
- Wind tunnel tests of 1:11 scale (4 m span) powered models

Non-BLI
(Podded)



BLI
(Integrated)



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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

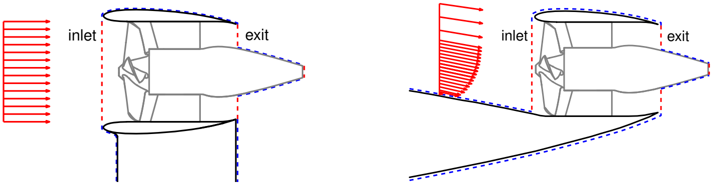
$$P_K = \oint (p_o - p_{o_\infty})\,\mathbf{V}\cdot\hat{n}\,dS \quad \text{(incompressible)}$$

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

Obtaining P_K

Method 1: Integration of the flow on propulsor stream-tube

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

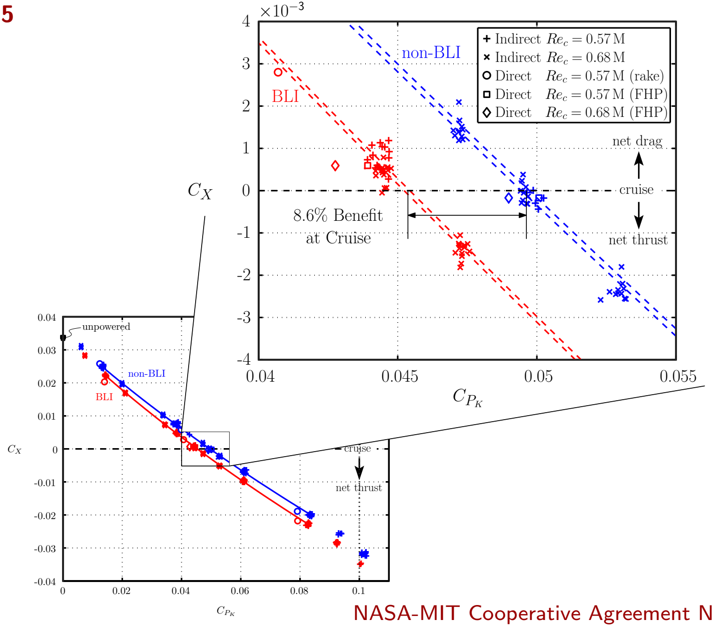


Method 2: Conversion of *electrical power* provided to the propulsor motors

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

Phase 2: Demonstrated Aerodynamic BLI Benefit

2010-2015



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Outline

BLI Benefit Sources

1. Lower propulsor **jet dissipation** and higher **propulsive efficiency**: more useful power put into the flow
2. Lower **surface dissipation** (smaller nacelle size and surface velocities)
3. Lower **wake dissipation** (partial elimination of viscous wake)
4. Lower **weight** due to smaller nacelles and smaller engines, which in turn enables smaller wings, and thus even less weight

1 + **2** + **3** = **aerodynamic benefit**: less flight power required for a given airframe operating at the same lift coefficient

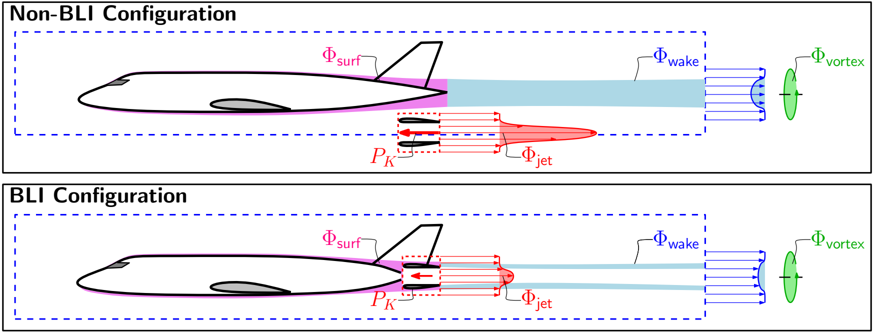
4 = **system-level benefit** after aircraft re-optimizations

Power Balance Method

Consider mechanical energy sources and sinks:

$$[\text{ Net Force }] \quad = \quad [\text{ Dissipation }] \quad - \quad [\text{ Power In }]$$

$$\underbrace{F_X}_{\text{"drag – thrust"}} V_\infty = (\Phi_{surf} + \Phi_{wake} + \Phi_{vortex} + \Phi_{jet}) - (\underbrace{P_K}_{\text{mechanical flow power}} + \underbrace{\cancel{P_V}}_{p\,dV\text{ power}})$$



M. Drela 2009, AIAA Journal 47(7)

Airframe Dissipation (1/2)

- Conventional drag decomposition:

$$D' V_\infty = \underbrace{\Phi'_{\text{surf}} + \Phi'_{\text{wake}}}_{\substack{D'_p V_\infty \\ \text{(profile)}}} + \underbrace{\Phi'_{\text{vortex}}}_{\substack{D'_i V_\infty \\ \text{(induced)}}}$$

- Surface dissipation:

$$\Phi'_{\text{surf}} = (1 - f_{\text{wake}})\, D'_p V_\infty$$

$$\Phi_{\text{surf}} = (1 - f_{\text{wake}})\, D'_p V_\infty - \boxed{\Delta\Phi_{\text{surf}}}$$

where

$$f_{\text{wake}} \equiv \frac{\Phi'_{\text{wake}}}{\Phi'_{\text{surf}} + \Phi'_{\text{wake}}}$$

$$\Delta\Phi_{\text{surf}} \equiv \Phi'_{\text{surf}} - \Phi_{\text{surf}} > 0$$

Airframe Dissipation (2/2)

- Wake dissipation:

$$\Phi'_{\text{wake}} = f_{\text{wake}} \left(\Phi'_{\text{surf}} + \Phi'_{\text{wake}}\right) = f_{\text{wake}}\, D'_p\, V_\infty$$

$$\Phi_{\text{wake}} = \boxed{(1 - f_{\text{BLI}})}\, \Phi'_{\text{wake}} = (1 - f_{\text{BLI}})\, f_{\text{wake}}\, D'_p\, V_\infty$$

where $f_{\text{BLI}} \equiv$ boundary layer **ingestion fraction**

$=$ fraction of total airframe viscous kinetic energy defect ingested by propulsors

- Vortex dissipation: $\Phi_{\text{vortex}} = \Phi'_{\text{vortex}} = D'_i\, V_\infty$

assuming comparison is made with same airframe at fixed C_L

Jet Dissipation

- Jet dissipation (with or without BLI):

$$\Phi_{\mathrm{jet}} = \iint_{\mathrm{exit}} \tfrac{1}{2} (V - V_\infty)^2 \, \mathrm{d}\dot{m}$$

$$= \frac{1}{2} (V_{\mathrm{jet}} - V_\infty)^2 \, \dot{m}$$

for $\dot{m} = N_{\mathrm{prop}} \, \rho_{\mathrm{jet}} \, V_{\mathrm{jet}} \, A_{\mathrm{jet}}$ (total propulsor mass flow)

and assuming uniform velocity V_{jet} across the jet

(jet p_t non-uniformity $\ll$ propulsor p_t rise)

Mechanical Flow Power

$$P_K \equiv \oiint_{\text{prop}} \left[p_\infty - p + \tfrac{1}{2}\rho \left(V_\infty^2 - V^2\right)\right] \mathbf{V}\cdot\hat{\mathbf{n}}\; \mathrm{d}\mathcal{S}$$

$$= \underbrace{\frac{1}{2}\left(V_{\text{jet}}^2 - V_\infty^2\right)\dot{m}}_{\text{(exit)}} - \underbrace{\left(-f_{\text{BLI}}\Phi'_{\text{surf}}\right)}_{\text{(inlet)}}$$

$$= \frac{1}{2}\left(V_{\text{jet}}^2 - V_\infty^2\right)\dot{m} + \boxed{\underbrace{\left(1 - f_{\text{wake}}\right) f_{\text{BLI}}\, D'_p\, V_\infty}_{\text{extra power}}}$$

Parametric Expressions

Parametric expression for **power required** and **stream-wise force** in terms of reference non-BLI configuration and propulsor operation

$$C_{P_K} = N_{\text{prop}} \left[\left(\frac{V_{\text{jet}}}{V_\infty} \right)^2 - 1 \right] \frac{\rho_{\text{jet}}}{\rho_\infty} \frac{V_{\text{jet}}}{V_\infty} \frac{A_{\text{jet}}}{A_{\text{noz}}} \frac{A_{\text{noz}}}{S_{\text{ref}}} + (1 - f_{\text{wake}})\, f_{\text{BLI}}\, C'_{D_p}$$

$$C_X = C'_D - f_{\text{BLI}} C'_{D_p} - \Delta C_{\Phi_{\text{surf}}} - 2 N_{\text{prop}} \left(\frac{V_{\text{jet}}}{V_\infty} - 1 \right) \frac{\rho_{\text{jet}}}{\rho_\infty} \frac{V_{\text{jet}}}{V_\infty} \frac{A_{\text{jet}}}{A_{\text{noz}}} \frac{A_{\text{noz}}}{S_{\text{ref}}}$$

- Valid with and without BLI, depending on value of f_{BLI}
- Jet properties ($\rho_{\text{jet}}, A_{\text{jet}}, V_{\text{jet}}$) with and without BLI may differ
- Quantify BLI benefit relative to known non-BLI configuration

Major Design Parameters for BLI Aircraft

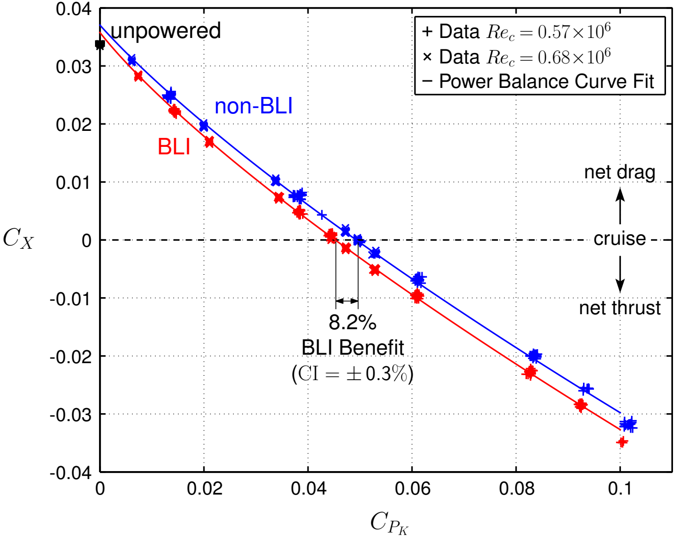
(i) **Ingested dissipation** $f_{\text{BLI}} C'_{D_p}$

(ii) How "well-designed" the BLI engine **installation** is $\Rightarrow$ $\Delta\Phi_{\text{surf}}$

(iii) **Propulsor operating points** for each of the configurations
$\Rightarrow$ respective propulsor jet velocities or mass flows

Data Mining: Application to D8 Wind Tunnel Tests

Use expressions for C_{P_K} and C_X to fit experimental data ($C_L = C_L' = 0.64$)

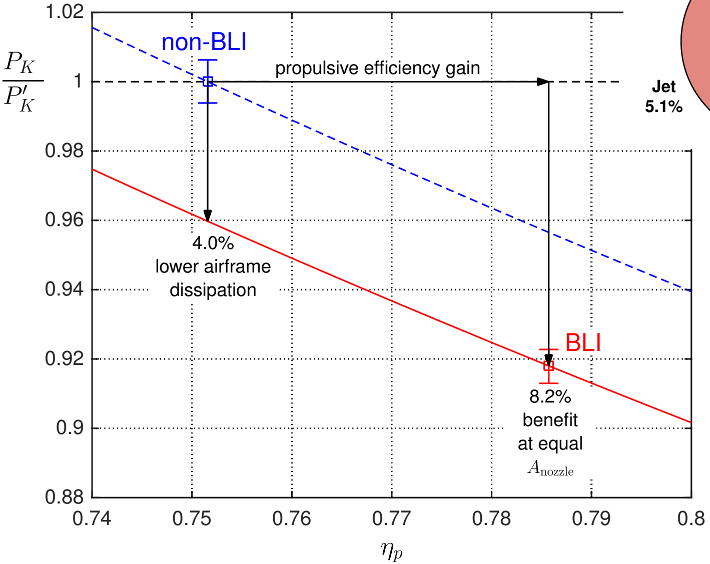


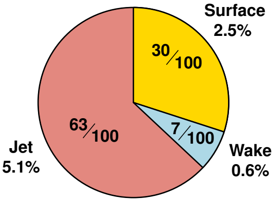
$$C_D' = 0.0370$$
$$\Delta C_{\Phi_{surf}} = 0.0012$$
$$f_{wake} = 0.080$$
$$\frac{A_{jet}}{A_{noz}} = 0.955$$

$$C_{X_0} = 0.0357$$
$$C_{D_{airframe}} = 0.0338$$

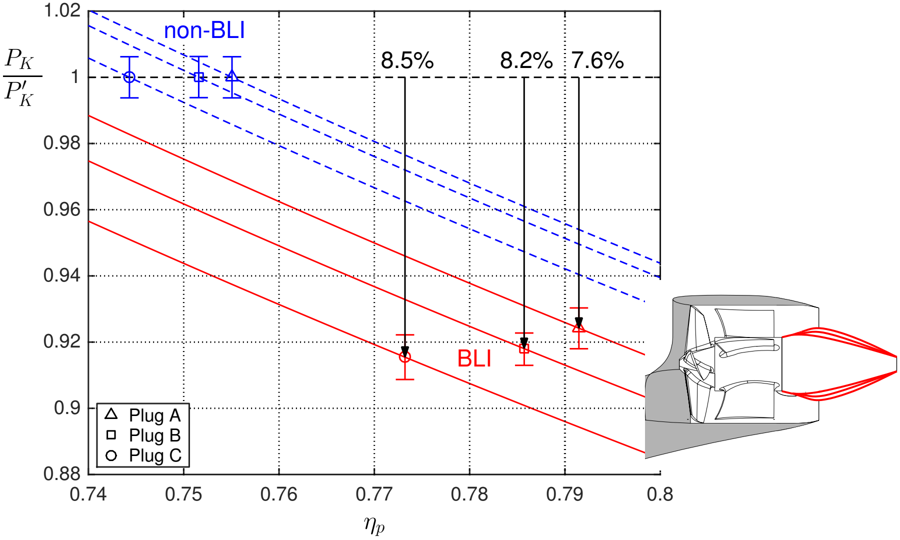
Propulsive Efficiency

$$\eta_p \equiv \frac{P_K - \Phi_{\text{jet}}}{P_K}$$

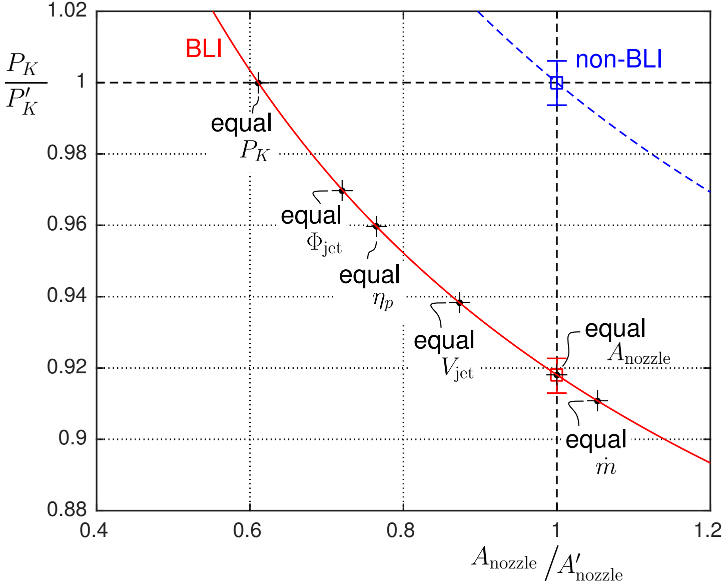




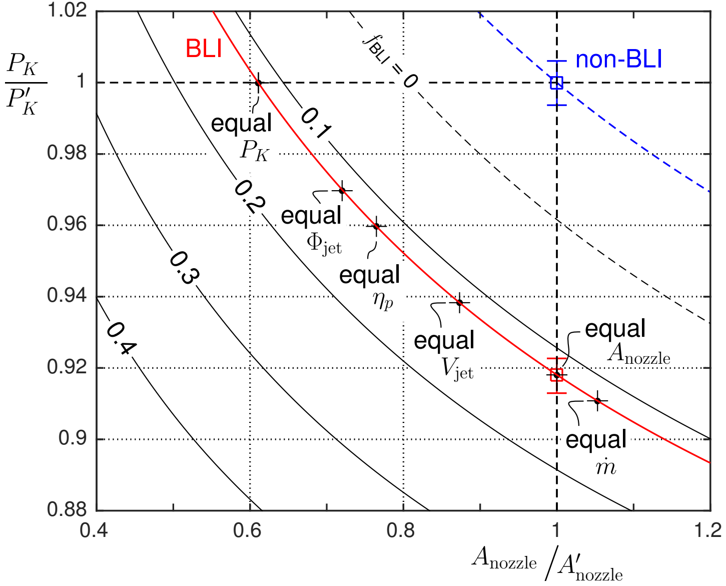
Variable Nozzle Area: Different Propulsor Designs



Bases for Comparison



Bases for Comparison



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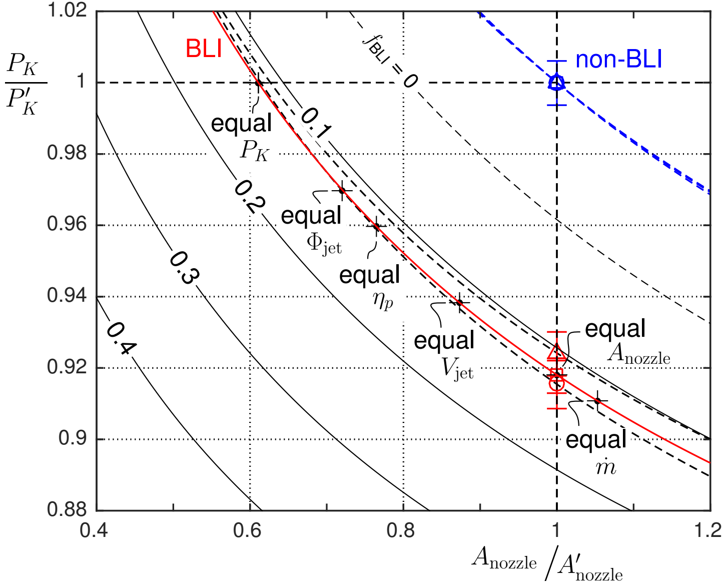
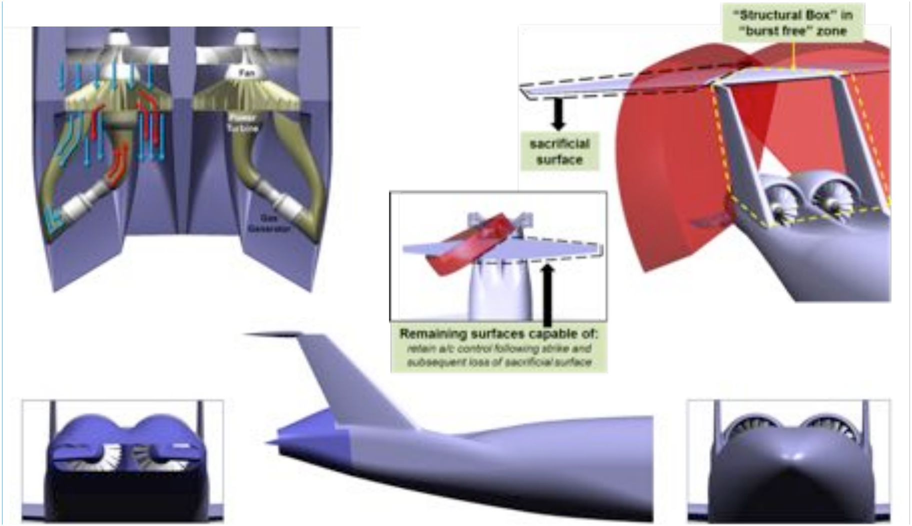


Outline

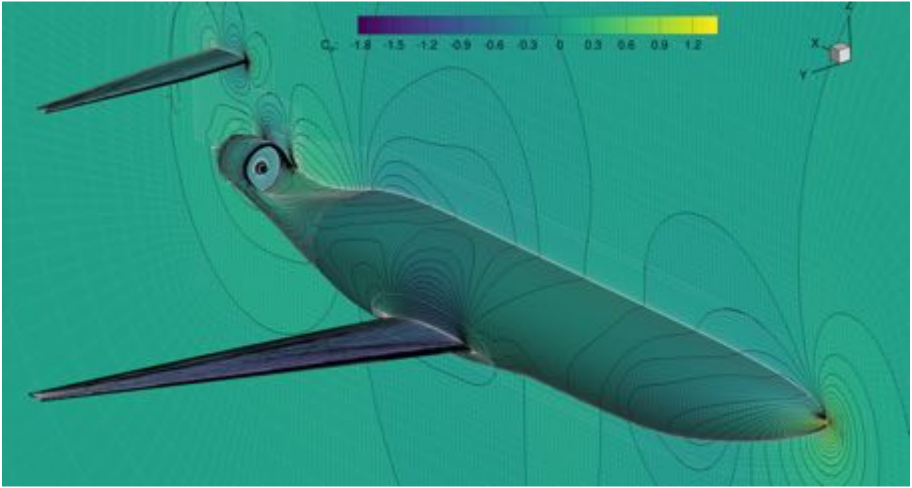
High-Efficiency, High-OPR, Small Cores (N+3 Phase 2, P&W)

Pratt & Whitney – Lord et al., AIAA 2015-0071 : reverse core engine arch.



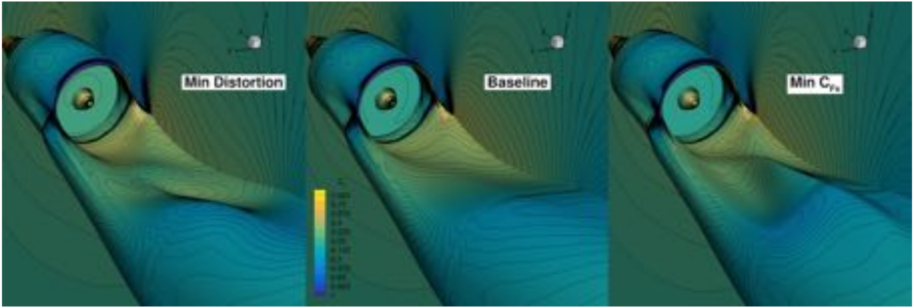
D8 Transonic Design (N+3 Phase 3, U.Michigan)

Transonic wing and engine integration MDO for Mach = 0.72, 0.78 : aero-structural optimization with loosely coupled engine model



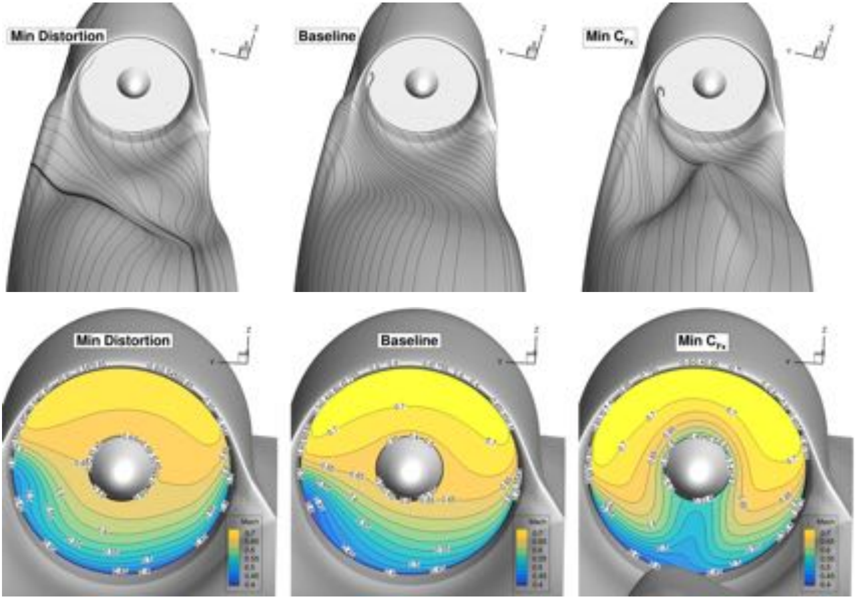
Airframe-Propulsion Integration Challenges

Integration lines strongly dependent on optimization's objective function



- Hard to identify MDO objective: need fully coupled engine model
- High sensitivity of fan face condition to diffuser shape

Airframe-Propulsion Integration Challenges



References

Drela, M., “Power Balance in Aerodynamic Flows”, *AIAA Journal*, Vol. 47, No. 7, 2009, pp. 1761–1771. doi:10.2514/1.42409 **[power balance method]**

Uranga, A., Drela, M., Greitzer, E., Titchener, N., Lieu, M., Siu, N., Huang, A., Gatlin, G., and Hannon, J., “Preliminary Experimental Assessment of the Boundary Layer Ingestion Benefit for the D8 Aircraft”, AIAA-2014-0906, *52nd AIAA Aerospace Sciences Meeting, SciTech 2014*, National Harbor, Maryland, 13–17 Jan. 2014. doi:10.2514/6.2014-0906 **[preliminary wind tunnel test results, morphing chart]**

Uranga, A., Drela, M., Greitzer, E. M., Hall, D. K., Titchener, N. A., Lieu, M. K., Siu, N. M., Casses, C., Huang, A. C., Gatlin, G. M., and Hannon, J. A., “Boundary Layer Ingestion Benefit of the D8 Transport Aircraft”, *AIAA Journal*, Vol. 55, No. 11, pp. 3693–3708, 2017. doi:10.2514/1.J055755 **[wind tunnel tests]**

Uranga, A., Drela, M., Hall, D. K., and Greitzer, E. M., “Analysis of the Aerodynamic Benefit from Boundary Layer Ingestion for Transport Aircraft”, *AIAA Journal*, in press **[analysis, “data mining”]**

Hall, D. K., Huang, A. C., Uranga, A., Greitzer, E. M., Drela, M., and Sato, S., “Boundary Layer Ingestion Propulsion Benefit for Transport Aircraft”, *Journal of Propulsion and Power*, Vol. 33, No. 5, pp. 1118–1129, 2017. doi:10.2514/1.B36321 **[analysis]**

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