Power Balance Assessment of BLI Benefits for Civil Aircraft

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AIAA SciTech 2015

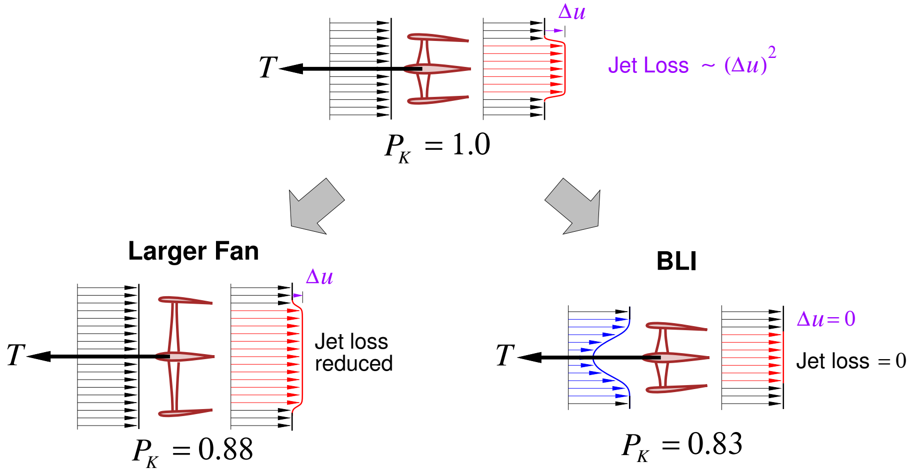
January 5, 2015

Summary

- Fuel burn scales directly with power, not thrust
  - Mechanical flow power (P_K) appropriate metric for BLI assessment
  - Use power balance
- BLI increases propulsive efficiency: less power for given thrust
- No unique comparison between BLI and non-BLI configurations
- BLI benefit from low-speed, sub-scale experiments applicable to full scale

Outline

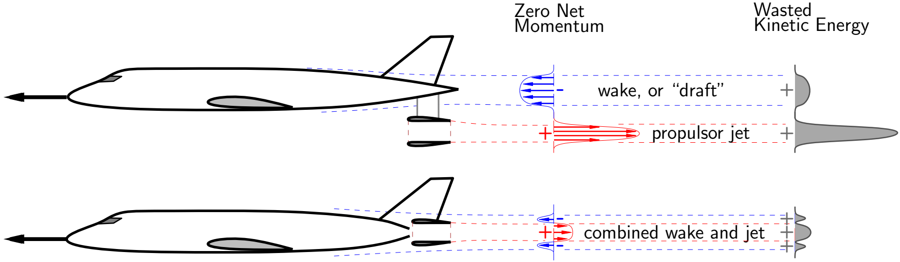
Options for Reducing Power Requirement



Boundary Layer Ingestion

- Part of the body (fuselage) BL is ingested by propulsors
  - Propulsors re-energize the wake
  - BLI reduces wasted energy in combined jet+wake

⇒ Reduced power requirement, fuel burn benefit

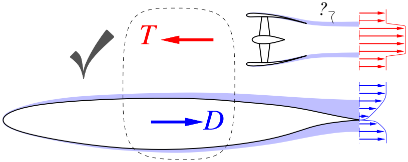


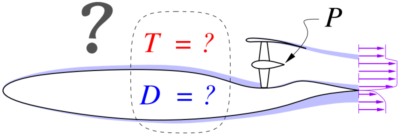
Ambiguous Thrust-Drag Decomposition

For highly integrated configurations, ambiguous decomposition into

thrust	and	drag
(propulsion system)		(airframe)

- Non-uniform flow into propulsor
- Pressure field effects
- Airframe BL (drag) re-energized

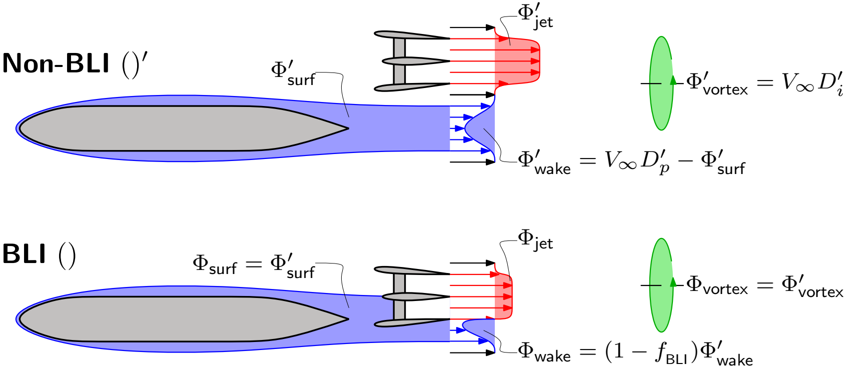




Power Balance Method

Consider mechanical energy sources and sinks: [Power In] = [Dissipation]

$$\underbrace{P_K}_{\text{mechanical flow power}} = \Phi_{\text{jet}} + \Phi_{\text{wake}} + \Phi_{\text{surf}} + \Phi_{\text{vortex}}$$



Mechanical Flow Power

$$P_K \equiv \oiint \left[(p - p_\infty) + \frac{1}{2}\rho \left(V^2 - V_\infty^2 \right) \right] \mathbf{V} \cdot \hat{n}\, dS$$

For given configuration, P_K is:

- Measure of mechanical energy added to flow by propulsor

$$P_K \quad \sim \quad \text{mass flow} \times \Delta\,(\text{mechanical energy})$$

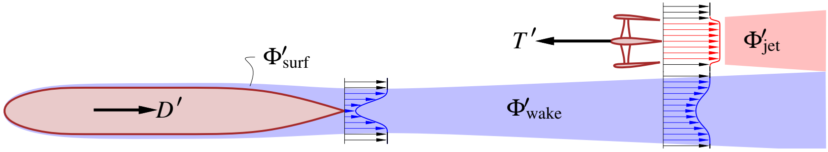
- Well defined even for highly integrated configurations
- Independent of fan characteristics
  (operating point, efficiency, distortion response)
- Surrogate for fuel burn: $\dot{m}_{\text{fuel}} = \dfrac{P_K}{h_{\text{fuel}}\, \eta_{th}\, \eta_f}$
- Surrogate for shaft power: $P_S = \dfrac{P_K}{\eta_f}$

Outline

Non-BLI Propulsor ($f_{\mathrm{BLI}} = 0$)

$$T' = D'$$
$$P'_K = \Phi'_{\mathrm{jet}} + \Phi'_{\mathrm{surf}} + \Phi'_{\mathrm{wake}} = \frac{T' V_\infty}{\eta'_p}$$

- Wasted KE in wake and jet

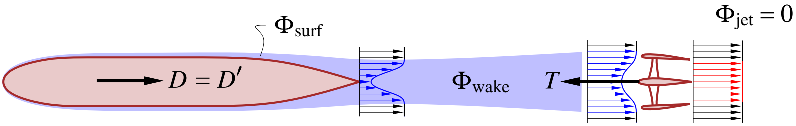


Propulsor Far Downstream with $f_{\mathrm{BLI}} = 1$, $V_{\mathrm{jet}} = V_\infty$

$$T' = D'$$

$$P_K = \cancel{\Phi_{\mathrm{jet}}} + \underbrace{\Phi'_{\mathrm{surf}} + \Phi_{\mathrm{wake}}}_{\substack{\text{ingested KE defect} \\ \text{(upstream dissipation)}}} = D' V_\infty$$

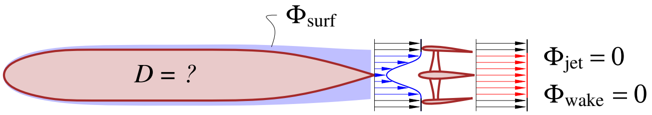
- Eliminated jet dissipation



Propulsor at Body's TE with $f_{\mathrm{BLI}} = 1$, $V_{\mathrm{jet}} = V_\infty$

$$P_K \;=\; \cancel{\Phi_{\mathrm{jet}}} \;+\; \underbrace{\Phi'_{\mathrm{surf}}}_{\text{ingested KE defect}} \;+\; \cancel{\Phi_{\mathrm{wake}}} \;<\; D' \, V_\infty$$

- Eliminated jet + wake dissipation

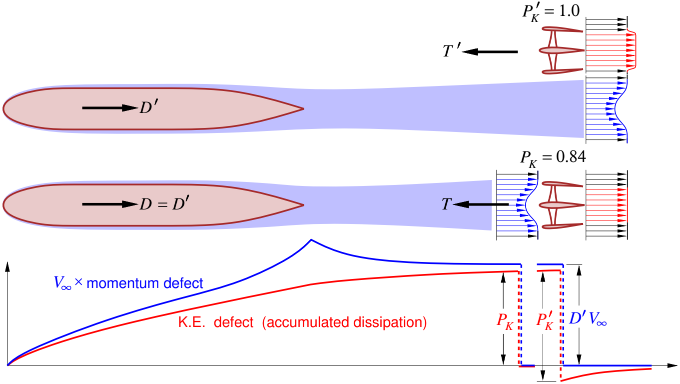


BLI with Force Accounting

$$P_K = \cancel{\Phi_{\text{jet}}} + \Phi'_{\text{surf}} + \Phi_{\text{wake}}$$

$$T' = \rho V_\infty^2 \Theta_\infty = \dot{m} V_{\text{jet}} - \dot{m} V_\infty$$

$$T = \underbrace{\rho V_\infty^2 \Theta_\infty}_{\text{momentum defect}} = \underbrace{\dot{m} V_\infty}_{\text{"gross thrust"}} - \underbrace{\left(\dot{m} V_\infty - \rho V_\infty^2 \Theta_\infty\right)}_{\text{"ram drag"}}$$



BLI with Force Accounting

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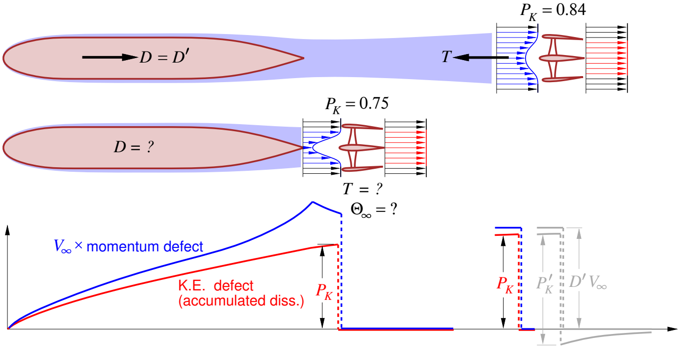


Message: Use Energy, Not Momentum

- *Momentum defect* (or "ram drag") is not the appropriate measure

  What matters is the ingested *kinetic energy defect*

- Kinetic energy defect unaffected by static pressure fields
  - All quantities well-defined
  - No fictitious expansion to free-stream pressure required

- BLI reduces jet and wake dissipation
  $\Rightarrow$ *power* needed to obtain a given net force (useful work) is reduced

  $\Rightarrow$ *propulsive efficiency*

Outline

Propulsive Efficiency

Traditional definition

$$\eta_p' = \frac{\text{thrust power to vehicle}}{\text{net mechanical power to flow}} = \frac{T' V_\infty}{\frac{1}{2}\dot{m}\left(V_{\text{jet}}^2 - V_\infty^2\right)}$$

But what is thrust with BLI?

Instead, define in terms of propulsive power

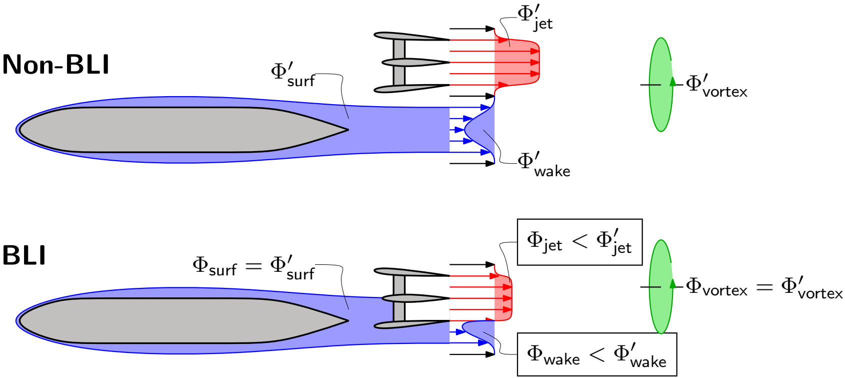
$$\boxed{\eta_p = \frac{\text{net propulsive power to vehicle}}{\text{power added to flow}} = \frac{P_K - \Phi_{\text{jet}}}{P_K}}$$

- Measures losses in propulsor jet (Φ_{jet} is wasted KE)
- Consistent with thrust-based definition with no BLI: $P_K' - \Phi_{\text{jet}}' = T' V_\infty$

Physical Bases of BLI Benefit

- Reduced jet dissipation (higher propulsive efficiency)
- Reduced wake dissipation (lower “effective” drag)

$$\underbrace{P_K \; - \; \Phi_{\rm jet}}_{\text{Net propulsive power}} \;=\; P_K\,\eta_p \;=\; (1 - f_{\rm BLI})\,\Phi'_{\rm wake} \;+\; \Phi'_{\rm surf} \;+\; \Phi'_{\rm vortex}$$



Outline

BLI Benefit Metric

BLI benefit (aerodynamic)

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

Power metric

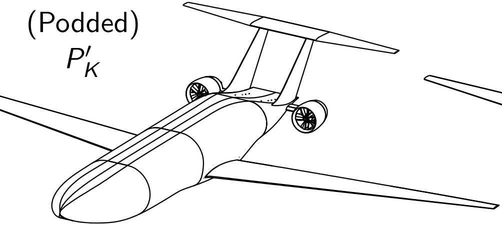
Mechanical flow power transmitted to the flow by the propulsors

Power saving quantified by ratio of flow power with BLI relative to non-BLI

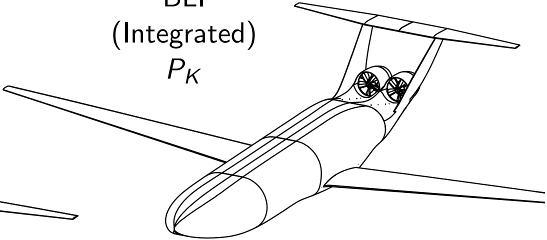
$$\text{Power Ratio} \equiv \frac{\text{power required with BLI}}{\text{power required without BLI}} = \frac{P_K}{P'_K}$$

BLI Benefit Metric

non-BLI
(Podded)
P'_K



BLI
(Integrated)
P_K



$$\text{Power Ratio} = \frac{P_K}{P'_K} = 1 - \text{PSC}$$

Power Saving Coefficient (PSC) introduced by L.H. Smith 1993, *J. Prop. Power* 9(1)

Power Savings

$$\boxed{\frac{P_K}{P'_K} = \frac{\eta'_p}{\eta_p}\left(1 - \frac{f_{\text{BLI}}\Phi'_{\text{wake}}}{\Phi'_{\text{airframe}}}\right)}$$

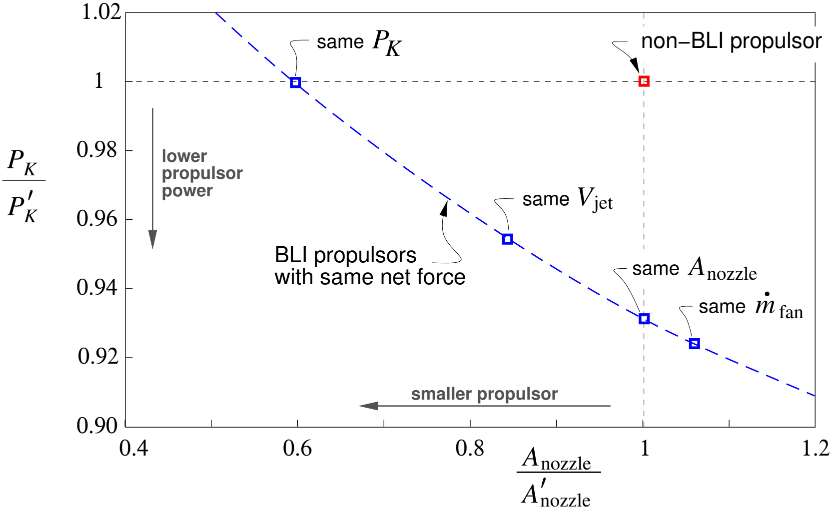
Benefit comes from reductions in

- Wake dissipation
- Jet dissipationand hence increase in η_p

Dominant effect in BLI benefit is increase in η_p for representative aircraft

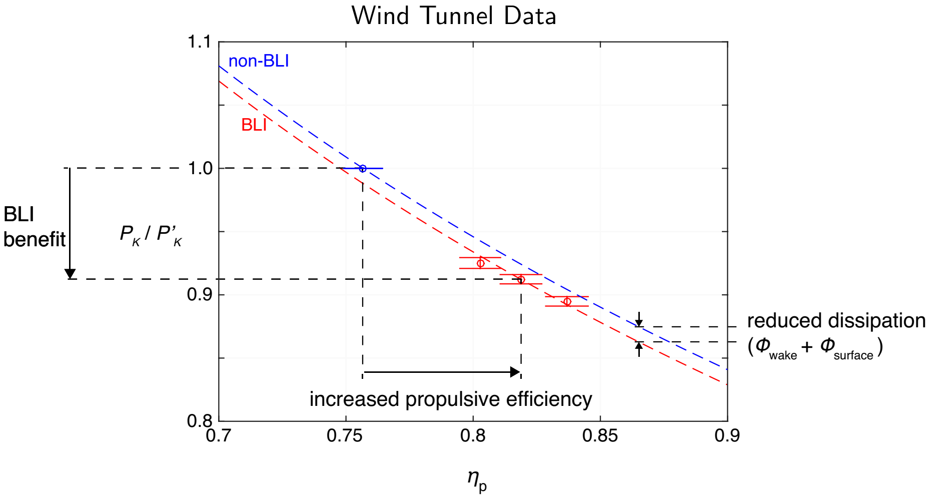
Power vs Nozzle Area (Propulsor Size)

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



Power vs Propulsive Efficiency

We have more than a configuration-specific benefit number
⇒ BLI benefit curve for range of propulsors (nozzle areas, propulsive efficiencies)



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Importance of Low-Speed, Sub-Scale Experiments

BLI benefit results from low-speed, sub-scale experiments are applicable to full-scale aircraft

- BLI benefit is not explicitly dependent on Mach or Re (only affect the specifics of turbomachinery, e.g. η_f, P_S)
- Key BLI performance parameters are matched with full-scale D8
  - Similar overall $L/D \simeq 21$
  - Similar fraction of ingested kinetic energy defect, f_{BLI}
  - Similar jet velocity ratios $V_{\mathrm{jet}}/V_{\infty}$, propulsive efficiencies η_p

Low-speed, sub-scaled wind tunnel experiments = proof-of-concept

First back-to-back assessment of BLI vs non-BLI

Acknowledgments

Funding

NASA Fundamental Aeronautics Program, Fixed Wing Project
under Cooperative Agreement NNX11AB35A

Thanks to

Staff at NASA Langley 14×22 Foot Subsonic Wind Tunnel

NASA Fixed Wing Project management

N. Cumpsty, Y. Dong, A. Epstein, E. Gallagher, A. Murphy, J. Sabnis, G. Tillman, H. Youngren