Boundary Layer Ingestion Propulsion – Benefit, Challenges, and Opportunities

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Toronto, Ontario, Canada

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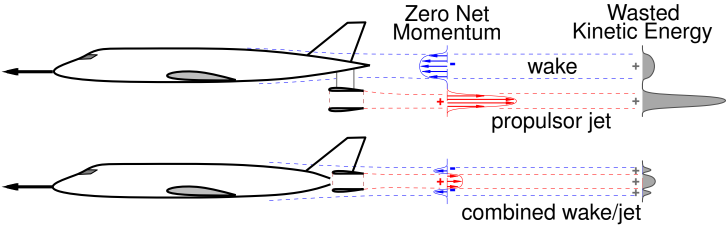
Boundary Layer Ingestion (BLI) Reduces Wasted Energy



- Basic Idea: propulsor ingests and reaccelerates airframe boundary layer
- Less wake and jet kinetic energy for the same net force $\rightarrow$ less power needs to be added to the flow by propulsor $\rightarrow$ less fuel burn

Uranga et al., *Boundary Layer Ingestion Benefit of the D8 Aircraft*

Main Messages: Benefit, Challenges, and Opportunities

- Aerodynamic benefit: reduced *propulsor mechanical flow power* ($\sim$10%)
- Challenges
  - Configuration: "can you explain how BLI reduces drag?"
  - Engine: effect of inlet distortion on efficiency, operability, aeromechanics
- Opportunities
  - New tools: flow power analysis, non-axisymmetric throughflow method
  - Design: non-axisymmetric stator for distortion tolerant turbomachinery

Aggressive NASA Targets for N+3 Performance (2008)

CORNERS OF THE TRADE SPACE	N+1 (2015)*** Generation Conventional Tube and Wing (relative to B737/CFM56)	N+2 (2020)*** Generation Unconventional Hybrid Wing Body (relative to B777/GE90)	N+3 (2025)*** Generation Advanced Aircraft Concepts (relative to user defined reference)
Noise	- 32 dB (cum below Stage 4)	- 42 dB (cum below Stage 4)	-71 dB (cum below Stage 4)
LTO NOx Emissions (below CAEP 6)	-60%	-75%	better than -75%
Performance: Aircraft Fuel Burn	-33%**	-40%**	better than -70%
Performance: Field Length	-33%	-50%	exploit metro-plex* concepts

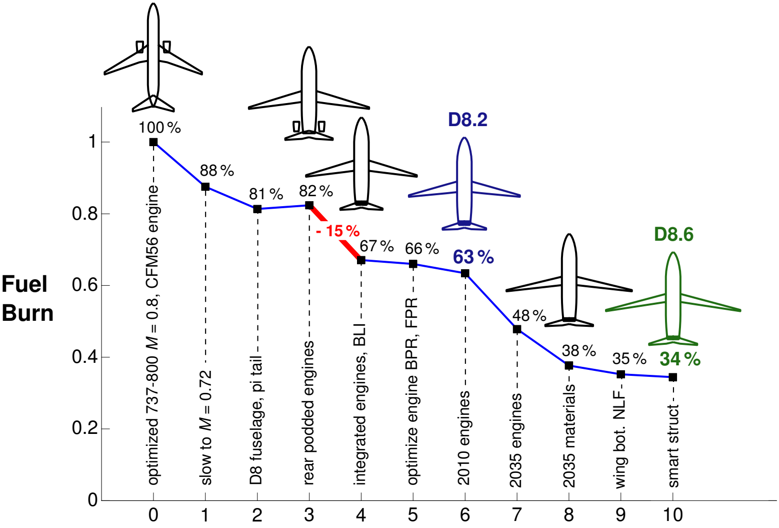
- Phase I (2008-2010): concepts and technologies to reach goals
- Phase II (2010-2015): investigation of key technologies

Phase I: Conceptual Design of D8 Advanced Civil Transport

- Cruise Mach number 0.72: reduced drag, unswept wings
- "Double bubble" fuselage: increased carryover lift, pitch-up moment
- BLI: engines ingest 40% fuselage boundary layer (17% total airframe)

www.aurora.aero/d8

Morphing Chart: Path of Configuration Optimization



- BLI provides largest single-step reduction in fuel burn

Greitzer et al., *N+3 Aircraft Concept Designs and Trade Studies, Final Report*

Phase II: Wind Tunnel Assessment of D8 BLI Benefit

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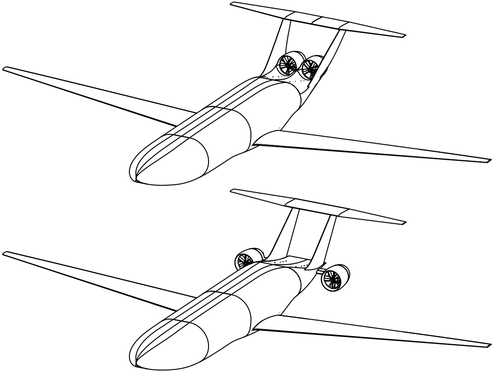
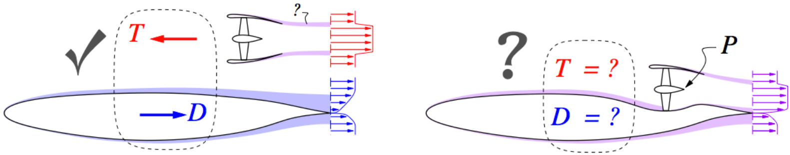


- Comparison of powered models in BLI and non-BLI configurations
- Measurements of net force, power input, stagnation pressures and velocities at propulsor inlet and exit

Contributions in Two Research Areas

1. Configuration aerodynamics (external flow problem)
   - Identification of relevant flow mechanisms associated with BLI
   - Assessment of BLI benefit, inlet distortion challenges
2. Propulsor performance with BLI distortion (internal flow problem)
   - Non-axisymmetric throughflow method for fan distortion response
   - Definition of design attributes for BLI fan stages

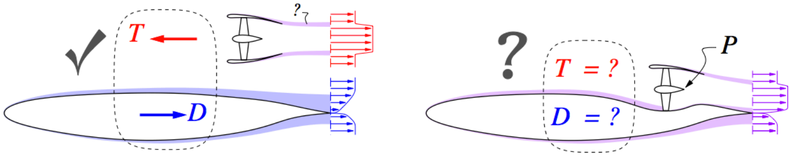
"How does BLI reduce drag?"



Drela, *Power Balance in Aerodynamic Flows*

- Without BLI: engine thrust must balance airframe drag, both well-defined
- With BLI: definitions of thrust and drag ambiguous
  - Propulsor mass flow applies viscous force to airframe
  - Mutual interaction forces due to static pressure perturbations

"~~How~~ *Does* BLI reduce drag?"



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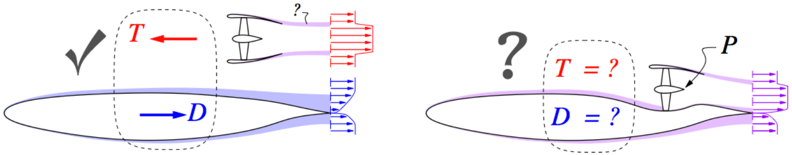
“~~How~~ *Does* BLI reduce drag?” What is “drag”?



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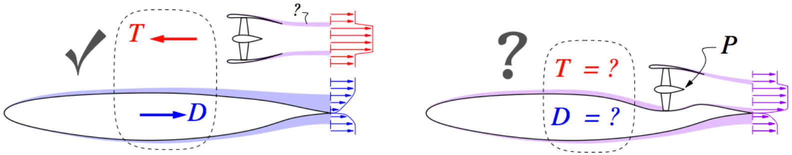
Do We Even Care?



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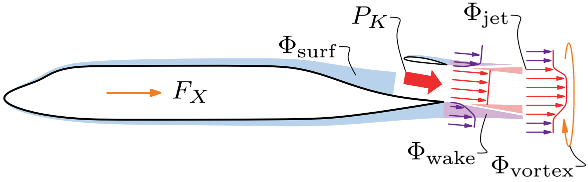
- Fuel burn related to *power added to flow by the propulsor*

Aerodynamic Analysis Based on Power Balance



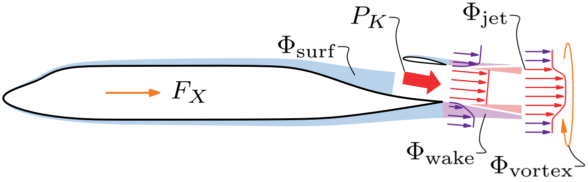
- Power added to flow by propulsor (P_K) balances lost power due to dissipation (Φ) in shear layers, jets, vortex system

$$\underbrace{P_K - \Phi_{\text{jet}}}_{\text{net propulsive power}} = \underbrace{\Phi_{\text{surf}} + \Phi_{\text{wake}} + \Phi_{\text{vortex}}}_{\text{total airframe dissipation}} - F_X V_\infty$$

- Can estimate power requirements from *isolated airframe* performance

Drela, *Power Balance in Aerodynamic Flows*

Physical Mechanisms of BLI Aerodynamic Benefit



1. **Jet dissipation reduction:**
   Power added to boundary layer flow with lower average velocity
   $\rightarrow$ reduced jet velocity, wasted kinetic energy

2. **Wake dissipation reduction:**
   No wake mixing in ingested flow
   (book-keeping: downstream losses clearly defined as jet dissipation)

Propulsive Efficiency as a Measure of Jet Dissipation

- Rational definition in terms of power and dissipation (lost power)

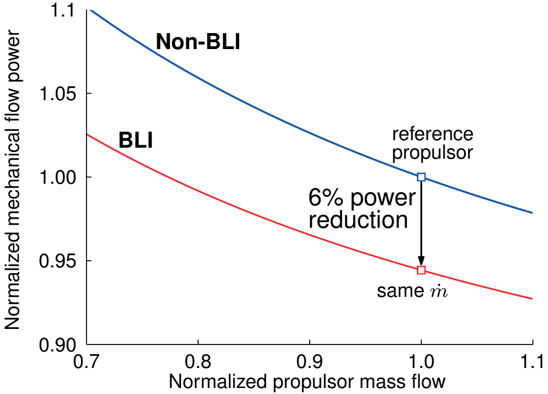
$$\eta_p \equiv \frac{\text{useful power delivered to airframe}}{\text{power added to the flow}} = \frac{P_K - \Phi_{\text{jet}}}{P_K}$$

- BLI increases propulsive efficiency
  - Power $\sim \dot{m}\Delta$KE added to fluid with $V < V_\infty$
  - Reduced jet velocity and jet dissipation $\sim \dot{m}(V_{\text{jet}} - V_\infty)^2$

- BLI Power reduction: airframe dissipation reduction and propulsive efficiency increase

$$P_K = \frac{\Phi_{\text{surf}} + \Phi_{\text{wake}} + \Phi_{\text{vortex}}}{\eta_p} \quad \frac{\text{airframe dissipation (wake)} \downarrow}{\text{propulsive efficiency} \Uparrow\Uparrow}$$

BLI Benefit Depends on Propulsor Sizing



- BLI yields decreased flow power. . .

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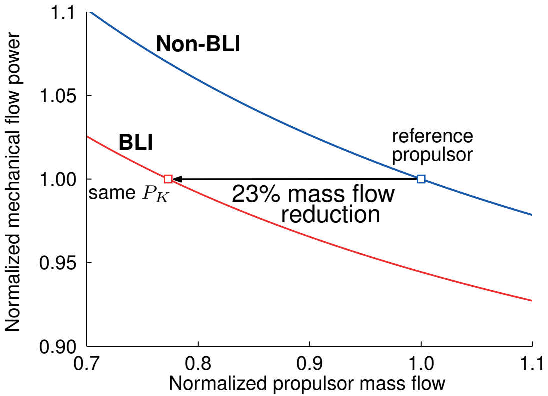
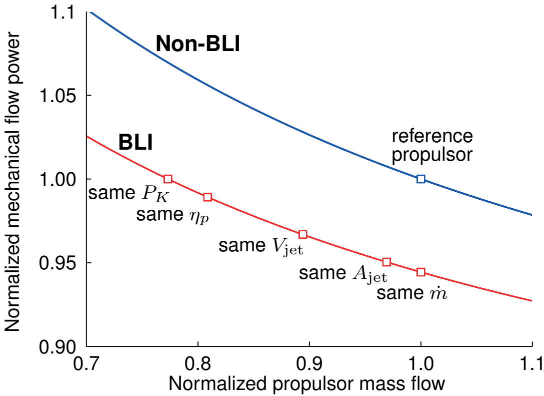


- BLI yields decreased flow power, decreased mass flow (engine size and weight)...

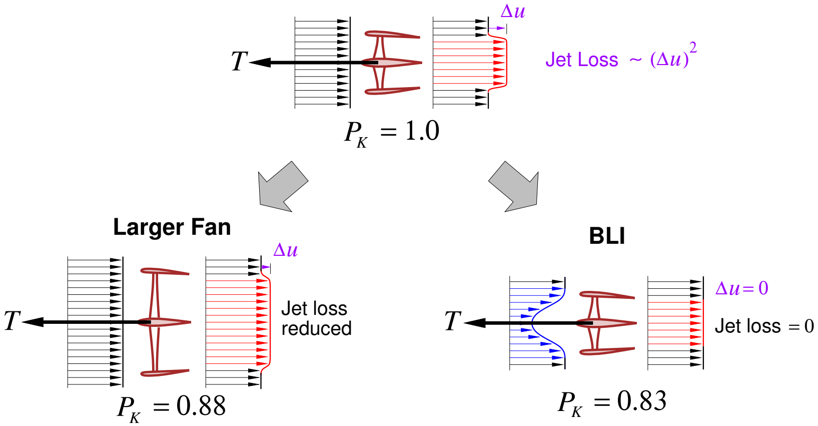
BLI Benefit Depends on Propulsor Sizing



- BLI yields decreased flow power, decreased mass flow (engine size and weight), or combination of both
  $\Rightarrow$ *No unique comparison of BLI and non-BLI propulsion systems*

Hall et al., *Boundary Layer Ingestion Propulsion Benefit for Transport Aircraft*

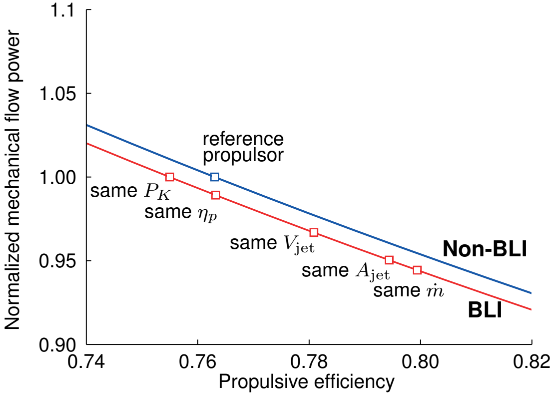
Options for Increasing Propulsive Efficiency



- Decrease FPR $\rightarrow$ increased weight and drag, installation challenges
- BLI $\rightarrow$ step change at fixed size, other installation challenges

Uranga et al., *Power Balance Assessment of BLI Benefits for Civil Aircraft*

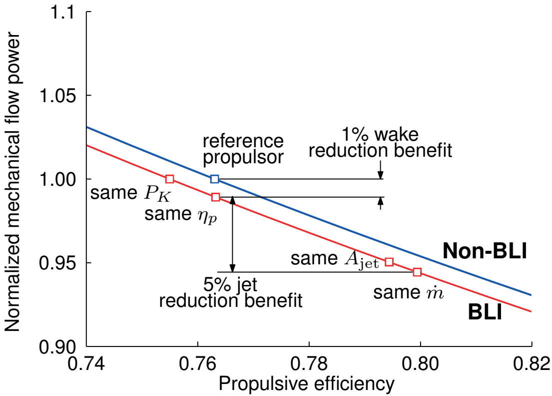
Primary BLI Benefit: Increased Propulsive Efficiency



- BLI yields higher propulsive efficiency for given propulsor mass flow
- Small wake dissipation reduction ($\sim$1% of total airframe dissipation)

Hall et al., *Boundary Layer Ingestion Propulsion Benefit for Transport Aircraft*

Primary BLI Benefit: Increased Propulsive Efficiency



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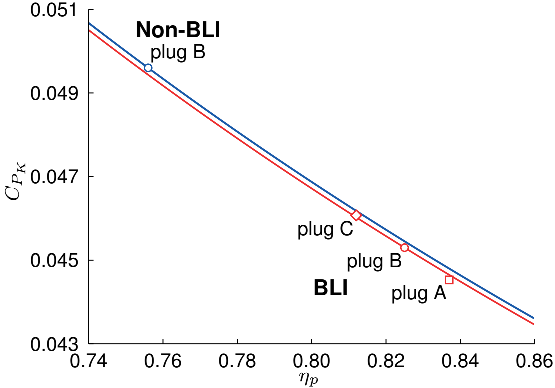
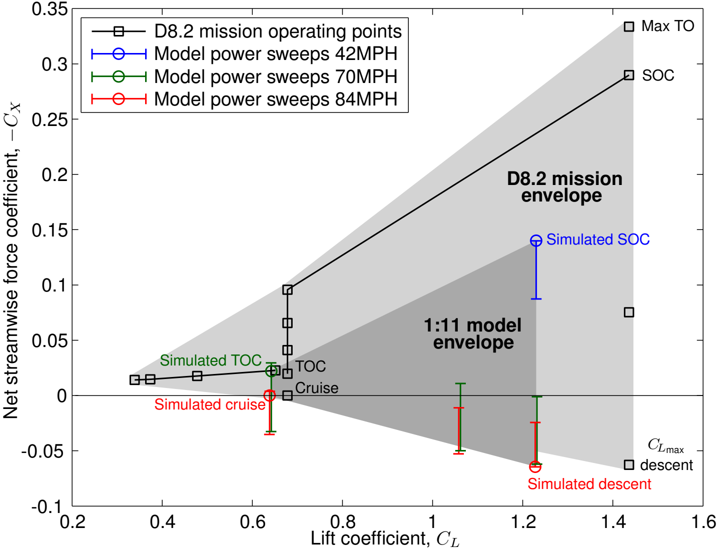
Experimental Assessment of Aerodynamic BLI Benefit



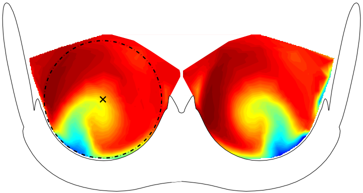
- Measured power vs net force in BLI and non-BLI configurations
- Propulsive efficiency benefit; negligible change in airframe dissipation
- BLI benefit: **8.6%** at equal nozzle area, **10.3%** at equal mass flow

Uranga et al., *Aircraft and Technology Concepts for an N+3 Subsonic Transport, Phase 2 Final Report*

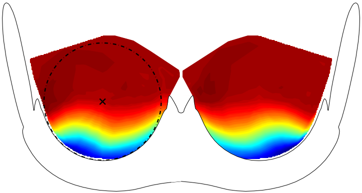
Measurements Taken Over Range of Operating Conditions



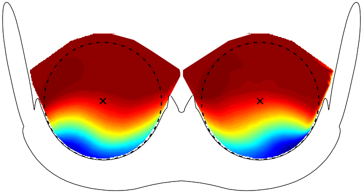
Variations in Inlet Stagnation Pressure Distortions



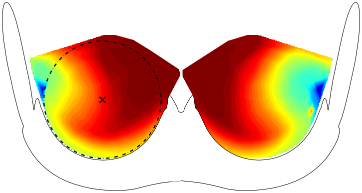
Simulated Start of Climb (high power)



Simulated Top of Climb

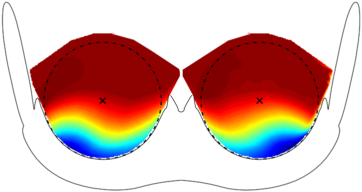


Simulated Cruise



Simulated Max C_L Descent (low power)

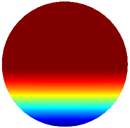
Challenge: Engine Operation with Inlet Distortion

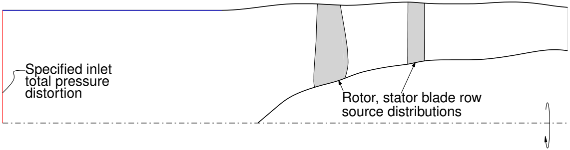


- Fan efficiency (primary focus)
  - Part of the fan always operating at “off-design” conditions
  - *Do fan losses outweight external aerodynamic benefit?*
    - Current fans estimated to lose 1-2% efficiency with BLI type inlet distortion
  - *Can we design the fan to operate better with distortion?*
- Engine stability: decreased fan stall margin, distortion fed into LPC
- Aeromechanics: unsteady once-per-revolution force on BLI fan blade
- Noise: BLI changes generation and propogation mechanisms

Gunn and Hall, *Aerodynamics of Boundary Layer Ingesting Fans*
Florea et al., *Aerodynamic Analysis of a Boundary Layer Ingesting Distortion-Tolerant Fan*
Perovic et al., *Stall Inception in a Boundary Layer Ingesting Fan*
Defoe and Spakovszky, *Effects of Boundary-Layer Ingestion on the Aero-Acoustics of Transonic Fan Rotors*

New Capability Developed for Fan Distortion Analysis



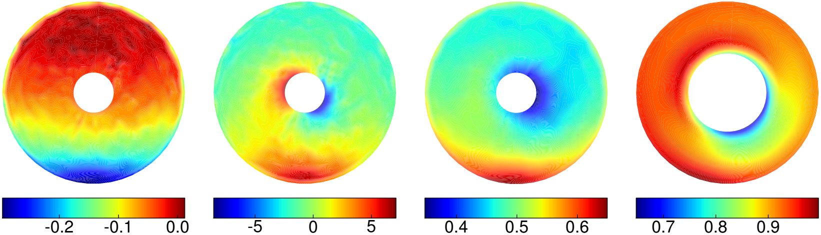


- Non-axisymmetric throughflow method
  - Design characterized by velocity triangles, detailed geometry not needed
  - Steady calculation on annular domain (grid size $\approx$ single passage RANS)

- Parametric study on effect of design on distortion response
  - Rotor: Design point flow and loading coefficient, radial loading distributions
  - Stator: axial location, circumferential variations in exit flow angle

Hall, et al., *Analysis of Fan Stage Design Attributes for Boundary Layer Ingestion*

Analysis Captures Relevant Behavior with Distortion



Fan inlet total pressure coefficient $\frac{p_{t,\mathrm{inl}} - p_{\mathrm{ref}}}{\rho U_{\mathrm{mid}}^2}$

Rotor incidence angle (degrees) $\beta_{\mathrm{inl}} - (\beta_{\mathrm{inl}})_{\theta-\mathrm{avg}}$

Fan pressure rise coefficient $\frac{p_{t,\mathrm{out}} - p_{t,\mathrm{inl}}}{\rho U_{\mathrm{mid}}^2}$

Fan exit total pressure coefficient $\frac{p_{t,\mathrm{out}} - p_{\mathrm{ref}}}{\rho U_{\mathrm{mid}}^2}$

- Upstream flow redistribution $\rightarrow$ significant incidence ranges ($>10^\circ$)
  - Fan “pulls harder” on low velocity fluid $\rightarrow$ top-to-bottom redistribution
  - Incidence increase near tip due to reduced axial velocity, decrease/increase near hub due to co-/counter-swirl

- Non-uniform fan work input (pressure rise)
  - Increased incidence $\rightarrow$ increased pressure rise
  - Distortion attenuation near tip, amplification near hub

Summary of Parametric Study Findings

- Goal: reduce non-uniformity in *velocity changes* across blade row
  $\rightarrow$ reduce blade operating point excursions and unsteady forcing

- 1D: May be better to *limit* amount of fan rotor distortion attenuation
  - Reduce co- and counter-swirl induced by upstream redistribution
  - Distortion in jet has negligible effect on propulsive efficiency benefit

- 2D: Radial loading distribution had smallest effect on distortion response

- Non-axisymmetric stator geometry to improve fan efficiency
  - Trailing edge: use circumferential variations in exit swirl to set up favorable rotor back-pressure ("destructive intereference" with inlet distortion)
  - Leading edge: set metal angle to accept rotor exit distortion

Concluding Remarks

- ***Benefit***: BLI enables step change reduction in aircraft fuel burn
- ***Challenges***: unexplored design space
  - No clear definition of propulsion system requirements
  - Engine inlet distortions for all flight conditions, including cruise
- ***Opportunities***: new technologies lead to new ways of thinking
  - Tools: power balance (external), source distribution model (internal)
  - Design: non-axisymmetric turbomachinery to mitigate distortion effects

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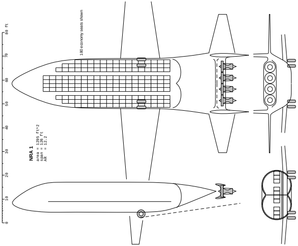
Progress in BLI Propulsion for Civil Aviation

2008



2010

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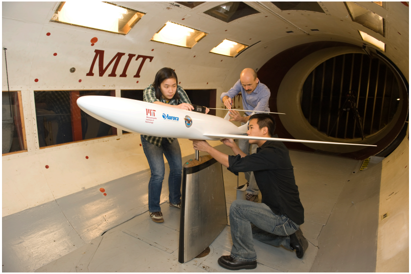
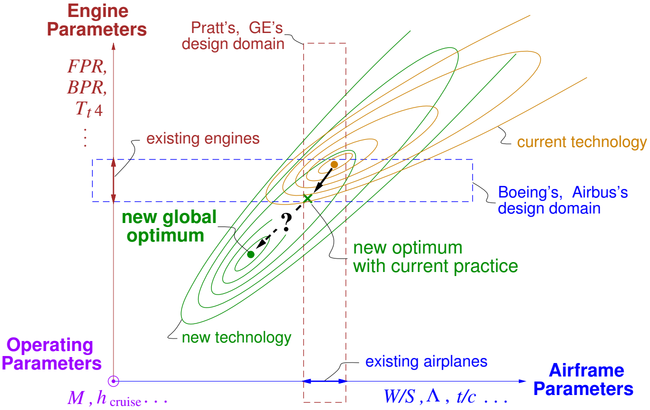


2013

2016

Strong Interactions to Advance Technology



- Role of fundamental research: thinking outside the box
  - Identification and early development of breakthrough technologies
  - Teaming with experts and stakeholders increases credibility and impact

Drela, *Simultaneous Optimization of the Airframe, Powerplant, and Operation of Transport Aircraft*

Concluding Remarks

- ***Collaboration****: key requirement for addressing the difficult challenge of reducing the impact of aviation on climate change*
- ***Benefit***: BLI enables step change reduction in aircraft fuel burn
- ***Challenges***: moving outside the box
  - No clear definition of propulsion system requirements
  - Engine inlet distortions for all flight conditions, including cruise
- ***Opportunities***: new technologies lead to new ways of thinking
  - Tools: power balance (external), source distribution model (internal)
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