Aircraft Propulsor Modeling and Design for Boundary Layer Ingestion

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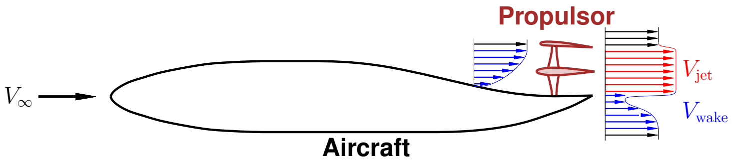
David K. Hall
Postdoctoral Associate
Gas Turbine Laboratory
Department of Aeronautics and Astronautics
Massachusetts Institute of Technology
Email: dkhall@mit.edu

Boundary Layer Ingestion (BLI)



- Propulsion via acceleration of craft's boundary layer flow through engine
- Reduces *flow power* input needed, compared to propulsor in free stream flow, to produce a given aerodynamic force forces on craft

Recent Fuel-Efficient Aircraft Concepts Using BLI

MIT/AFS/P&W/NASA D8

Cambridge/MIT SAX-40

NASA Hybrid-Electric Concept

NASA N3X

www.aurora.aero/d8
http://www.silentaircraft.org
www.nasa.gov/feature/researchers-advance-propulsion-toward-low-carbon-aircraft
www.nasa.gov/content/hybrid-wing-body-goes-hybrid

D8 Advanced Civil Transport Concept

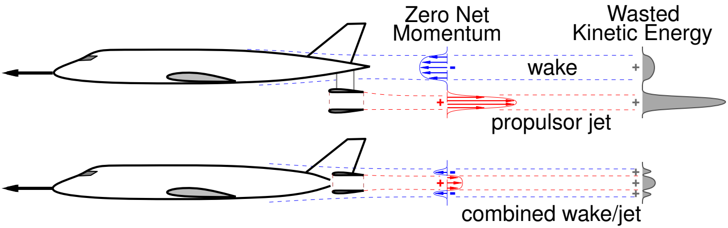
- Cruise Mach number 0.72: reduced drag, unswept wings
- “Double bubble” fuselage: increased carryover lift, pitch-up moment
- BLI: engines ingest 40% fuselage boundary layer (17% total airframe)

www.aurora.aero/d8

Key Messages

- BLI propulsion represents...
  - Benefit: reduction in energy needed to propel aircraft
  - Challenge: impact of non-uniform flow on engine performance
- Turbomachinery description using momentum and energy source distributions captures 3D BLI distortion flow mechanisms
- Definition of conceptual aero design attributes for BLI fan stages
  - Circumferential variation of downstream fan exit guide vanes
  - Let distortion pass through propulsor *unattenuated*

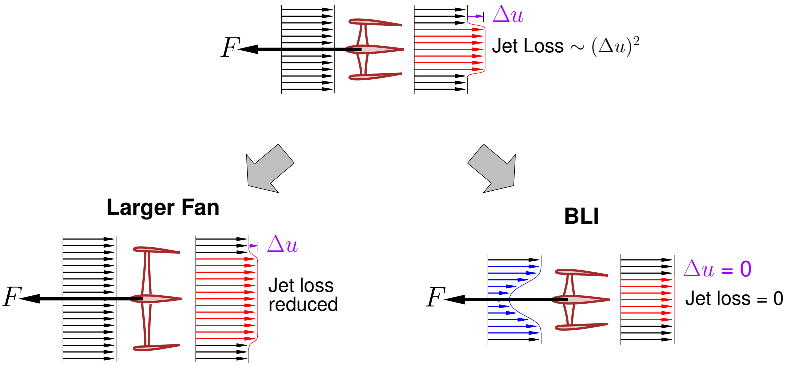
External Aerodynamics View: BLI Reduces Wasted Energy



- Steady level, flight: zero net streamwise force
  $\rightarrow$ zero downstream momentum flux
- BLI: propulsor accelerates low momentum boundary layer fluid
  - Smaller momentum defect/excess in combined wake/jet
  - Less wasted energy $\rightarrow$ reduced flow power input, fuel burn

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

Propulsor View: BLI Reduces Jet Loss



- Options for increasing propulsive efficiency $V \times F/(\dot{m}\Delta\text{KE})$
  - Larger fan $\rightarrow$ increased weight and drag, installation challenges
  - BLI $\rightarrow$ step change at fixed size, other installation challenges

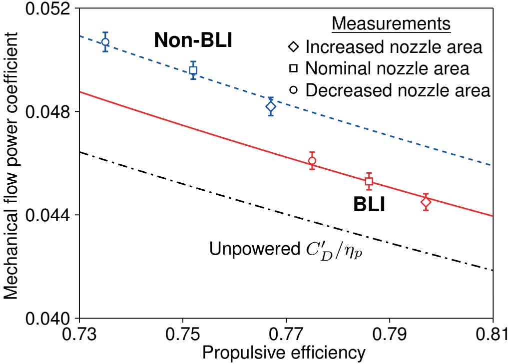
Uranga et al., *Power Balance Assessment of BLI Benefits for Civil Aircraft*

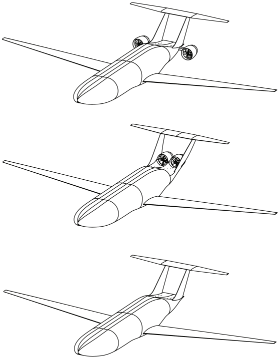
Experimental Assessment of D8 Aerodynamic BLI Benefit

- Experiments in NASA Langley Research Center Subsonic Wind Tunnel
- D8 model in BLI, non-BLI, and unpowered configurations
- Metric: flow power required for zero net streamwise force at design AoA

Aviation Week & Space Technology, September 30, 2013
www.nasa.gov/content/down-to-earth-future-aircraft-0

BLI Benefit: Reduction in Required Flow Power





- BLI reduces flow power 8–10% depending on nozzle area $\rightarrow$ mass flow
- Mechanism of benefit: reduced flow dissipation (reduced lost power)
  - Reduced wake and nacelle losses (vertical distance between curves)
  - Reduced jet mixing loss, increased propulsive efficiency

Uranga et al., *Aircraft and Technology Concepts for an N+3 Subsonic Transport, Phase 2 Final Report*
Hall et al., *Boundary Layer Ingestion Propulsion Benefit for Transport Aircraft*

BLI Challenge: Engine Operation with Inlet Distortion

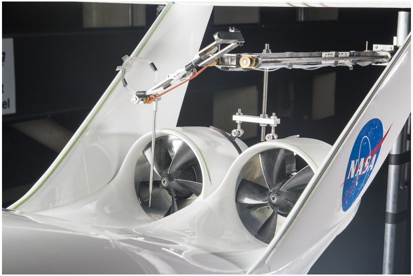
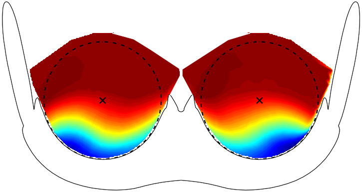


Photo credit: NASA/George Homich

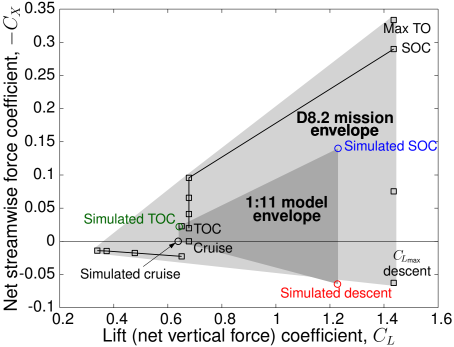


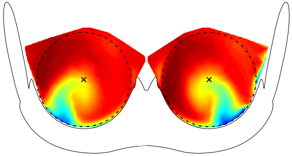
Inlet total pressure distortion

- Efficiency: continuous operation at "off-design" conditions
- 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 propagation mechanisms

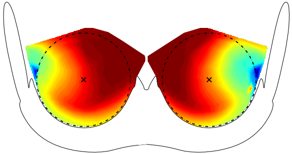
Gunn and Hall, *Aerodynamics of Boundary Layer Ingesting Fans*
Perovic et al., *Stall Inception in a Boundary Layer Ingesting Fan*
Florea et al., *Aerodynamic Analysis of a Boundary Layer Ingesting Distortion-Tolerant Fan*
Defoe and Spakovszky, *Effects of Boundary-Layer Ingestion on the Aero-Acoustics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

Typical Mission Inlet Total Pressure Distortion Variations

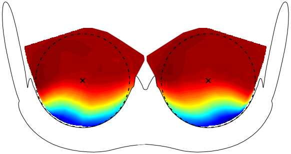




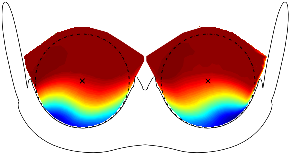
Simulated Start of Climb



Simulated Descent



Simulated Top of Climb

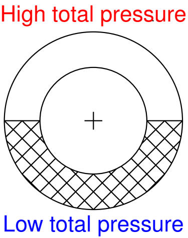


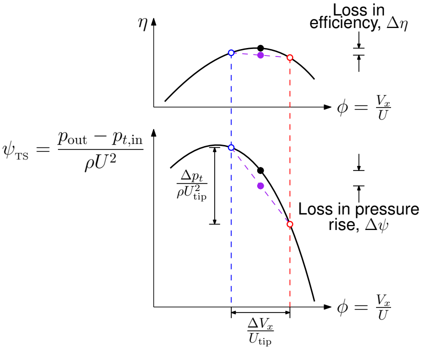
Simulated Cruise

Inlet Distortion: Current State-of-the-Art

- Compressor distortion response
  - Analytical methods based on *parallel compressor* model (quasi-1D)
  - Correlations between inlet distortion and performance descriptors
- Full-wheel unsteady RANS CFD for BLI fan assessment
  - Requires detailed turbomachinery geometry
  - Not suited for *conceptual* design (before blade shapes known)
- Civil aero-engine fans designed for uniform inlet conditions
  - BLI fan distortion response studies (so far) based on *existing designs*

Parallel Compressor Theory (Quasi-1D)

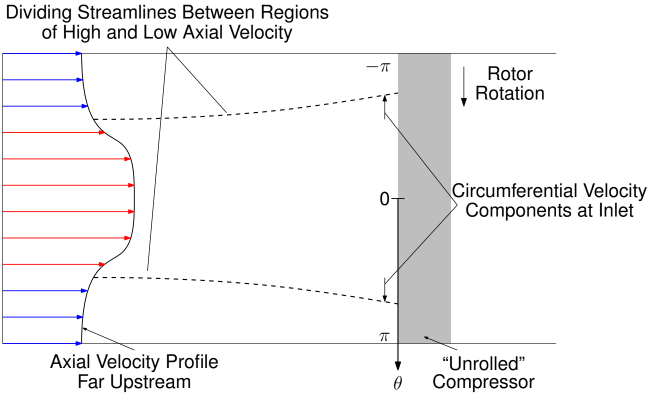




- Streams of different total pressure operate at points on uniform flow pressure rise versus flow characteristic
- Compressor *attenuates* total pressure distortion
- Steeper (more negative slope) characteristic reduces velocity distortion

Longley and Greitzer, *Inlet Distortion Effects in Aircraft Propulsion System Integration*

Upstream Circumferential Flow Redistribution (2D)



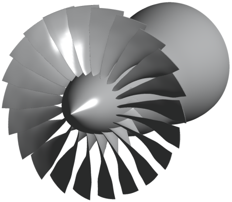
- Axial velocity distortion attenuation yields upstream swirl distortion
- Performance responds to *incidence* at blade row

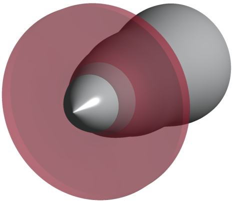
Longley and Greitzer, *Inlet Distortion Effects in Aircraft Propulsion System Integration*

Contributions of the Current Research

- Computational model for non-uniform, 3D flow through turbomachinery
  - Distortion response behavior *without detailed blade design*
  - Low computational cost appropriate for early design, sensitivity studies
- Description of mechanisms that affect performance of fan stages with BLI inlet distortion
- Assessment of effect of stage design on distortion response
- Definition of *conceptual design attributes* for BLI propulsors

New Approach for 3D BLI Fan Flow Analysis





$$\nabla(\rho \mathbf{V}) = 0$$

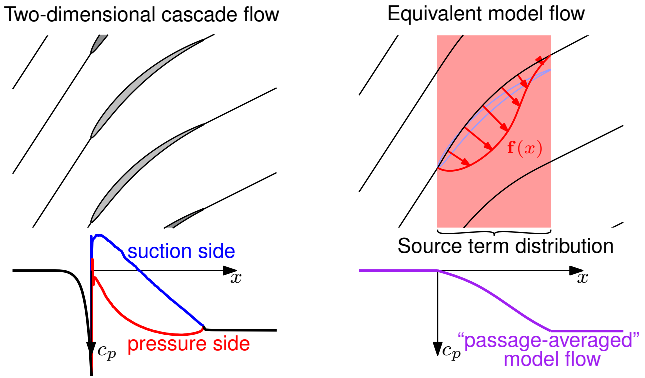
$$\mathbf{V} \cdot \nabla \mathbf{V} + \frac{1}{\rho} \nabla p = \boxed{\mathbf{f}}$$

$$\mathbf{V} \cdot \nabla h_t = \boxed{\mathbf{V} \cdot \mathbf{f} + \dot{e}}$$

- Replace rotor and stator blade rows with containing distributed momentum and energy sources
  - Represent effect of blades on *pitchwise-averaged* basis
- Sources ($\mathbf{f}$ and $\dot{e}$) modeled as function of conceptual design variables
- Capability to assess design sensitivities *without detailed blade design*

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

Model Flow Represents Pitchwise-Averaged Flow



- Model flow "smears out" blade-to-blade features
  - Circumferentially uniform inlet flow $\rightarrow$ axisymmetric response
  - Circumferentially non-uniform inlet flow $\rightarrow$ distortion transfer

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

Body Forces Generate Flow Turning, Work, Entropy

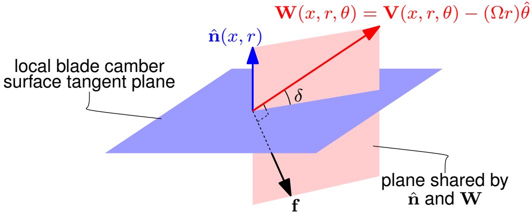
- Streamwise-normal force produces streamline curvature
- Can relate source terms to relative velocity $\mathbf{W}$, work $\mathrm{d}h_t$, loss $T\mathrm{d}s$

$$\mathbf{V} \cdot \nabla h_t = (\Omega r) f_\theta$$

$$T\mathbf{V} \cdot \nabla s = \dot{e} = -\mathbf{W} \cdot \mathbf{f}, \quad \text{where } \mathbf{V} = \mathbf{W} + (\Omega r)\hat{\theta}$$

- Total enthalpy rise proportional to circumferential force in rotating frames (Euler Turbine Equation)
- Entropy rise proportional to relative streamwise-parallel force, corresponding energy source
  - Decompose $\mathbf{f}$ into relative streamwise-normal and -parallel components

Blade Loading Model



$$\nabla(\rho \mathbf{V}) = 0$$

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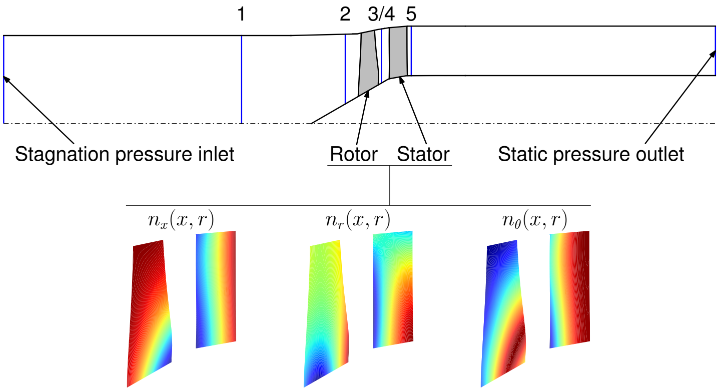
$$\mathbf{V} \cdot \nabla h_t = \boxed{\mathbf{V} \cdot \mathbf{f}}$$

- Force scaling: 2D airfoil analogy $$|\mathbf{f}| = \frac{(2\pi\delta)(\frac{1}{2}W^2/|n_\theta|)}{2\pi r/B}$$
- Force normal to streamline in relative-frame (isentropic) $$\mathbf{W} \cdot \mathbf{f} = 0$$
- Force acts in plane shared by $\hat{\mathbf{n}}$ and $\mathbf{W}$ $$(\mathbf{W} \times \hat{\mathbf{n}}) \cdot \mathbf{f} = 0$$
- Force acts to reduce local deviation, δ $$\text{sign}(\mathbf{f} \cdot \hat{\mathbf{n}}) = -\text{sign}(\mathbf{W} \cdot \hat{\mathbf{n}})$$

$\Rightarrow$ *Body force as closed-form function of local velocity vector, camber surface*

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

Assessment of New Method: Whittle Lab Fan Rig



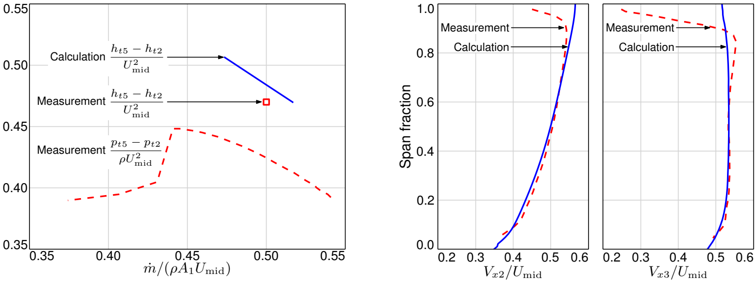
- Model assessed against experimental and computational results
- Camber geometry $\hat{\mathbf{n}}(x,r)$ based on LE, TE metal angle distributions

Gunn and Hall, *Aerodynamics of Boundary Layer Ingesting Fans*
Hall et al., *Analysis of Fan Stage Conceptual Design Attributes for Boundary Layer Ingestion*

Computational Methodology

- Grid
  - Generated using Pointwise
  - Wedge domain 22.5°, butterfly mesh upstream of spinner
    - Axisymmetric flow: single wedge domain
    - Full-wheel with distortion: 16 copies of wedge domain
  - Grid-converged ψ vs ϕ characteristic for 1.8M cell full-wheel domain
- Solver
  - ANSYS CFX
  - Inviscid flow: laminar flow, zero viscosity, slip walls
- Boundary conditions and turbomachinery specification
  - Inlet stagnation pressure $p_t(r, \theta)$ specified
  - Oulet static pressure specified, radial equilibrium
  - Rotor, stator camber surfaces $\hat{\mathbf{n}}(x, r)$, rotor angular velocity Ω specified
- Reduced timestep size ($\sim$5% default) to ensure convergence

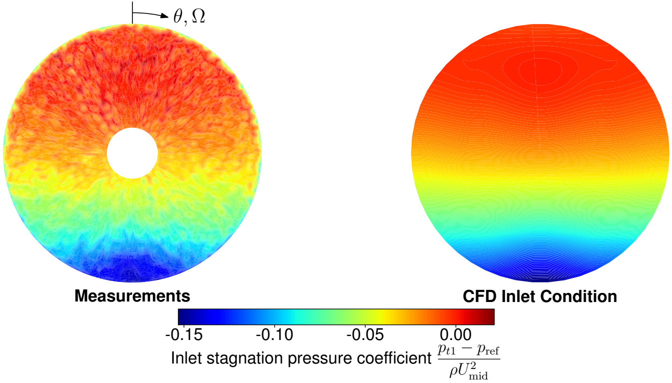
Source Term Method Captures Axisymmetric Throughflow



- Stagnation enthalpy rise coefficient within 3% at design point
- Agreement with axial velocity away from endwalls
  - Will be seen that endwall circumferential variations with distortion captured

Gunn and Hall, *Aerodynamics of Boundary Layer Ingesting Fans*
Hall et al., *Analysis of Fan Stage Conceptual Design Attributes for Boundary Layer Ingestion*

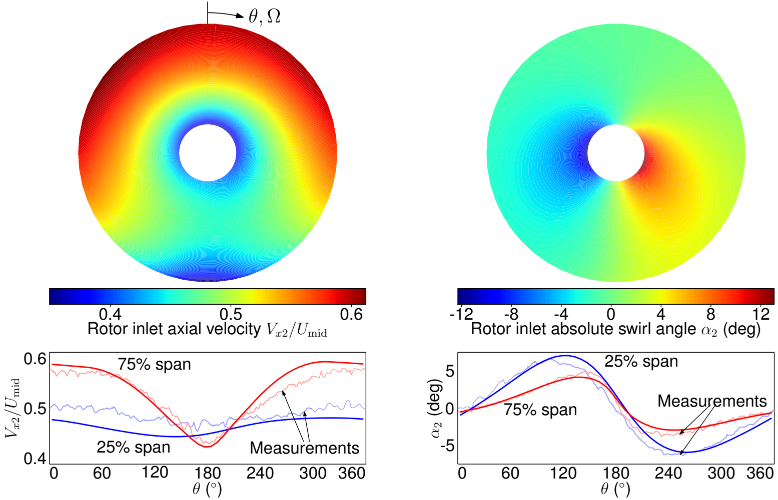
Inlet Condition for BLI Distortion Calculations



- Screen-generated inlet distortion
- Body force analysis of (smoothed) distortion case; serves two purposes:
  1. Assess model against experimental and computational results
  2. Identify and describe relevant BLI fan flow features

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

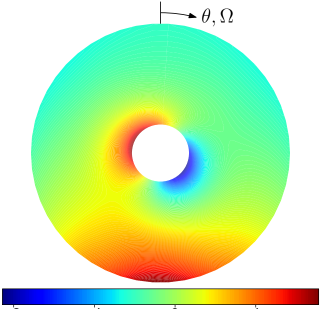
Velocity and Swirl Distortion Due to Upstream Redistribution

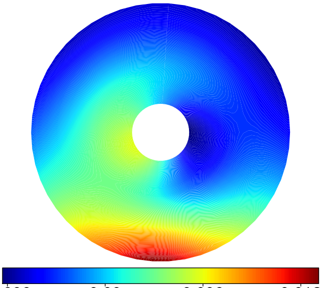


- Top-to-bottom redistribution, strong swirl non-uniformity near hub

Gunn and Hall, *Aerodynamics of Boundary Layer Ingesting Fans*
Hall et al., *Analysis of Fan Stage Conceptual Design Attributes for Boundary Layer Ingestion*

Rotor Incidence and Work Input Distortions are Similar

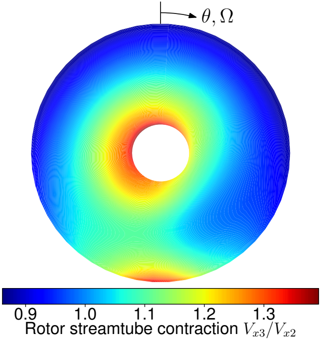


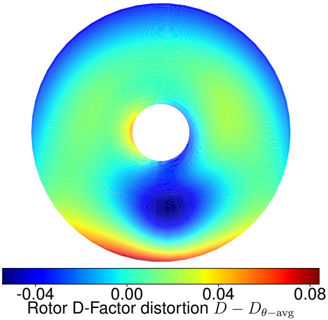


- Combined axial velocity, swirl distortions $\rightarrow$ incidence
  - Hub: co- and counter-swirl, uniform axial velocity
  - Tip: no swirl, low axial velocity in low stagnation pressure region
- Work input non-uniformity dominated by flow turning (not velocity)

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

Rotor Streamtube Contraction and Diffusion Factor

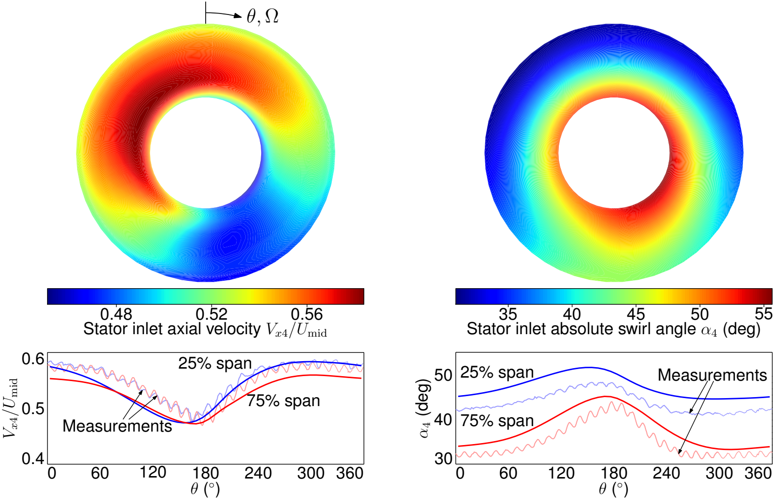




- Increased work input $\rightarrow$ low stagnation pressure streamtube contraction
- Diffusion factor: $D = 1 - \dfrac{W_{\text{out}}}{W_{\text{in}}} + \dfrac{|r_{\text{out}} W_{\theta\text{out}} - r_{\text{in}} W_{\theta\text{in}}|}{W_{\text{in}}} \dfrac{2\pi/B}{c_{\text{ref}}}$
  - Hub and tip: large diffusion due to large turning (incidence)
  - Midspan: Reduced diffusion due to streamtube contraction (acceleration)

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

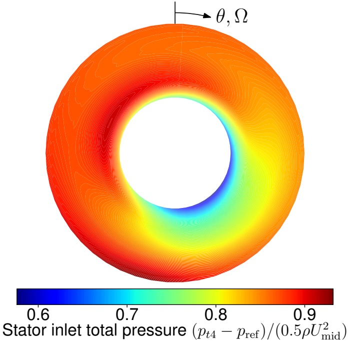
Stator Inlet Velocity and Swirl Angle Distortions

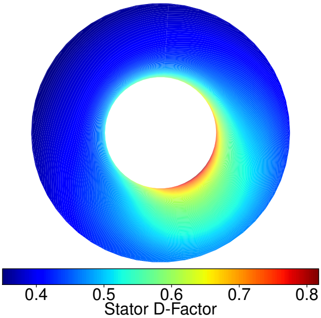


- Decreased axial velocity, increased swirl downstream of low inlet stagnation pressure region

Gunn and Hall, *Aerodynamics of Boundary Layer Ingesting Fans*
Hall et al., *Analysis of Fan Stage Conceptual Design Attributes for Boundary Layer Ingestion*

Stator Inlet Total Pressure and Diffusion Factor





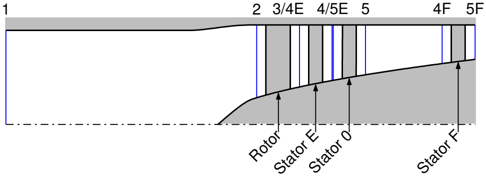
- Non-uniform rotor pressure rise attenuates total pressure distortion near tip, amplifies total pressure distortion near hub
- Uniform stator exit flow angle $\rightarrow$ diffusion (loading) driven by incidence

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

Summary: Features of 3D Fan Flow with BLI Inlet Distortion

- Top-to-bottom upstream flow redistribution $\rightarrow$ rotor incidence distortion
- Non-uniform work input similar to incidence distortion
- Axial velocity distortion *attenuation* via non-uniform streamtube contraction through rotor
- Diffusion factor as performance metric: includes effects of flow turning, streamtube contraction (more important in rotor) on performance

Parametric Study of Distortion Response vs Stage Design



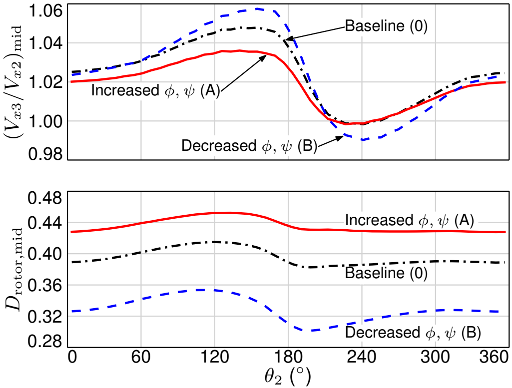
- Design variables
  - Stage design point flow and loading coefficients, ϕ and ψ
  - Radial distribution of rotor stagnation enthalpy rise, Δh_t vs r
  - Axial rotor-stator spacing
  - Circumferential variation in stator geometry $\rightarrow$ outlet flow angle

- Performance metric: diffusion factor
  - Local circumferential variation represents range of off-design excursions

- Summary of findings
  - Increasing ϕ, ψ (i.e., *shallower* characteristic) beneficial near midspan
  - Non-axisymmetric stator can reduce or eliminate rotor flow distortions

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

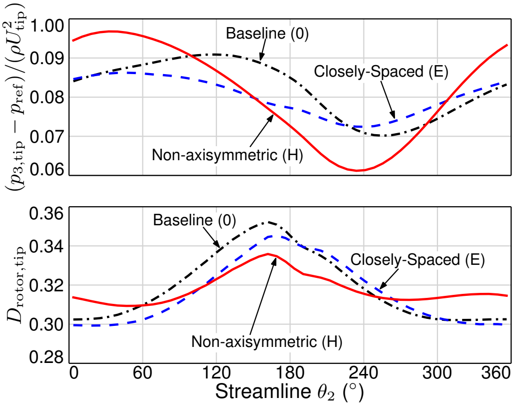
Increasing Stage ϕ, ψ Beneficial Near Midspan



- Reduced inlet swirl distortion $\rightarrow$ more uniform streamtube contraction
- Circumferential variation reduced at cost of increased average loading

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

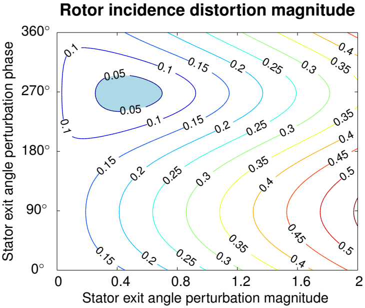
Stator Can Produce Favorable Rotor Back-Pressure

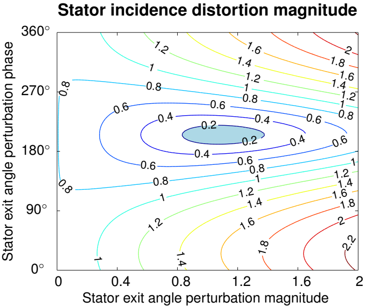


- Closely-spaced, non-axisymmetric stators reduce rotor back pressure where diffusion factor is highest
  - Larger stator inlet swirl $\rightarrow$ stator static pressure rise $\rightarrow$ reduced stator inlet (rotor exit) static pressure
  - Non-axisymmetric stator exit swirl used to control exit static pressure

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

Exit Flow Angle Variations Eliminate Incidence Variations





- Linearized circumferential distortion response analysis
- Perturbation in stator exit flow angle results in changes in incidence
  - Two design variables: exit flow angle perturbation magnitude and phase
  - Destructive interference effect: exit conditions “cancel out” inlet distortion

Hall, *Analysis of Civil Aircraft Propulsors with Boundary Layer Ingestion*

Fan Stage Conceptual Design Attributes for BLI

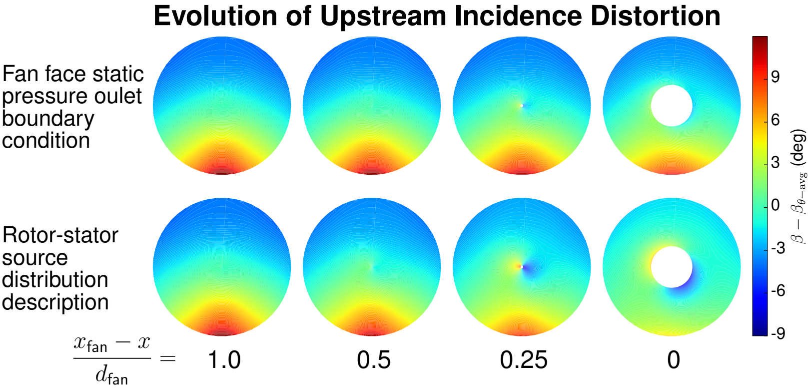
- Rotor passes distortion with *minimal* attenuation
  - Reduced “off-design” excursions $\rightarrow$ decreased losses, unsteady forcing
  - Shallow characteristic slope reduces upstream redistribution
- Stator provides favorable rotor back-pressure
  - Non-axisymmetric vane exit angle to manipulate static pressure distortion
  - Reduced rotor-stator spacing to increase interactions
- Stator accepts rotor exit distortion
  - Reducing rotor distortion attenuation increases stator inlet distortion
  - Non-axisymmetric stator LE metal angle to match flow, minimize loss

Ongoing/Future Work: Turbomachinery Modeling & Design

- Continuing development of source distribution modeling methodology
  - Transonic flows
  - Loss model (parallel force) and endwall effects
  - Inverse design
- Beyond conceptual design attributes: more detailed design
  - Re-design fan exit guide vanes for existing fan
  - Clean sheet BLI fan design incorporating findings

Future Work: Modeling for Propulsor-Airframe Integration

- Current state-of-the-art: oulet/inlet BCs at nacelle inlet, nozzle exit
  - Does not capture fan-distortion interaction $\rightarrow$ fan rotor incidence



Future Work: Modeling for Propulsor-Airframe Integration

- Current state-of-the-art: oulet/inlet BCs at nacelle inlet, nozzle exit
  - Does not capture fan-distortion interaction $\rightarrow$ fan rotor incidence
- Benefits of turbomachinery source distribution description
  - Captures fan-distortion interaction $\rightarrow$ correct inlet conditions
  - Models internal flow with negligible additional computational cost
  - Means of passing engine performance data between organizations
- What fidelity of propulsor model is required for integrated aircraft CFD?
  - Models: inl/out BCs, actuator disks, source term methods, FW URANS
  - Metrics: fan power, efficiency, inlet conditions; nacelle LE stagnation point
  - Outcome: criteria for model applicability
    - Hypothetical example: inl/out BC can be used if inlet $\ell/d >$1.5

Future Work: BLI Fan Aeromechanics

- Aeromechanics likely greater challenge than aero efficiency
  - Existing fans experience $\sim$1-3% efficiency drop (vs 10% BLI benefit)
  - BLI yields 1-per-rev unsteady force *at design point*
- Circumferential variations in $\mathbf{f}$ represents local unsteady blade force
  - Utility of source term method for low reduced frequency forced response?
  - Can carry out analogous parametric study with unsteady forcing metric
  - Outcome: design attributes for reduced unsteady force
- Hypothesis: existence of design attributes that yield low loss *and* low unsteady force

Conclusion

- BLI represents aerodynamic benefit and challenge for turbomachinery
- Turbomachinery source term description captures BLI fan flow features
  - Upstream top-to-bottom redistribution $\rightarrow$ non-uniform rotor incidence, work input, streamtube contraction, diffusion
  - Rotor exit axial velocity $\rightarrow$ stator inlet swirl angle, static pressure rise
- Definition of conceptual aero design attributes for BLI fan stages
  - Circumferential variation in design of downstream fan exit guide vanes
  - Let distortion pass through propulsor *unattenuated*
- Model shows promise for addressing aerodynamics, aeromechanics, and integration challenges of BLI

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