Development of a Robust Distortion Tolerant Low-Pressure-Ratio Fan for Boundary-Layer-Ingesting Engines

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The work presented here will be published in a NASA Contractor Report (NASA CR) entitled “Robust Design for Embedded Engine Systems”
BLI Propulsor Technology Genesis and Applications

Common Aircraft w/NASA’s ERA Project

N2A-EXTE Hybrid Wing Body Aircraft
Credit: United Technologies Research Center / NASA

Technology Potentially Applicable To

ND8 / D8
Credit: NASA / MIT / Aurora Flight Sciences

Ascent 10
Credit: DZYNE Technologies / Brendan Kennelly

STARC-ABL
Credit: NASA

Future BLI Aircraft

Credit: NASA / MIT / Aurora Flight Sciences

Credit: United Technologies Research Center / NASA

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Propulsion Benefits of Boundary Layer Ingestion

Conventional Propulsion

Boundary Layer Ingesting Propulsion

Thrust: \( T = \dot{m}(U_j - U_{in}) \)

Power: \( P = \frac{\dot{m}}{2}(U_j^2 - U_{in}^2) \)

Propulsive Efficiency:

\[
\eta_{p,conv} = \frac{2U_0}{U_0 + U_{j,conv}} \\
\eta_{p,BLI} = \frac{2U_0}{U_{in,BLI} + U_{j,BLI}}
\]


For Constant Thrust and Air Flow and Reduced Inlet Velocity, Jet Velocity Must Decrease

Thrust is Maintained With Reduced Power Input Due to Higher Propulsive Efficiency
Fuel Burn Benefits Obtained from Boundary Layer Ingestion

N+2 benefit space addressed in present program

Propulsive efficiency relation (Smith) converted to fuel burn for UHB cycle & BWB aircraft boundary layer parameters (%FB per %TSFC = 1.28, R = 1, K = 0.65)

BWB, Upper Center Fuselage Viscous Drag (N+2)

Full Vehicle Viscous Drag (N+3)

N+3 target benefit space ~10%

N+2 benefit space defined in existing study
System Studies Defined Technology Needs

- High Level System Study\(^1,2\): Significant System-Level benefits can be achieved (~3-5% fuel burn for HWB Aircraft)

Benefits on the order of ~10% possible for configurations with larger ingested drag fractions

Benefits within the range of those reported by previous investigators; limiting theoretical maximum benefit described by 1-D theory of Smith\(^3\)

Fuel burn reduction benefits compared against an advanced technology baseline propulsion system (Pylon Mounted BPR = 16, FPR = 1.35 UHB Turbofan)

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Ref:  
Design Goals

- Design and deliver a distortion-tolerant fan to perform in the boundary-layer ingestion environment, for a demonstration test in the NASA 8’x6’ wind tunnel
  - Perform design at sea level, Mach 0.78 conditions
  - Mechanical integrity is a top priority
  - Performance and stability behavior must be considered
- Inlet, fan rotor, and EGV must be designed
Design Challenges

Some items outside “normal” design space must be considered

- Many elements impact the operation of a BLI propulsion system
  - Characteristics of incoming swirl and total pressure distortion
  - Large fan incidence angle variation
  - Features required to meet aeromechanics & structural concerns
  - Inlet total pressure losses
  - Performance of the fan, EGV, and duct components
- Inlet and fan integrated design required
- High-dynamic flow impact on the fan design
Design Path Followed

Some aspects of the design path are unique

- Design a low-loss inlet
- Begin design with a basic “reference” blade
- Design the EGV and flow path to assist in smoothing the exiting distortion
- Examine the integrated inlet/rotor/EGV design
- Design for the dynamic response of the fan rotor
Program Evolution

Program evolved as learning & tool capability progressed over time

Program Start

- P&W Aero-1 Fan with tip shroud
- JT15D w/mid-span shroud
- NASA tip-turbine fan (TDI 1109)

Complete redesign required due to operability limitations

G4 Fan Recommended

- L/D = 0.6

Redesign decision after Research Design Review

- G4 Fan unshrouded
- L/D = 3

New blade designed for over 1000 hours of HCF life at ADP

- L/D = 1.5
- Performance drop to meet mechanical constraints

Recognition that solidity could be increased

- Not done due to program time constraints

~100 hours of HCF life at ADP

Final Inlet L/D = 0.6 (managed distortion profile)

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Inlet Design

Final design shaped to provide operational distortion pattern

Original Inlet “A”

Low Pressure

L / D = 3
\( \Delta P_T = 1.8\% \)

Designed BLI Inlet

Low Pressure

L / D = 0.6
\( \Delta P_T = 0.3\% \)
Distortion Intensity and Incidence Swing are Significant

Maximum Values: $\Delta P_c/P \sim 10\%$  $\Delta P_r/P \sim 4\%$  Extent $\sim 125^\circ$
Reference Blade in BLI Environment Not Acceptable

Inlet refinement for distortion shaping had a major influence
“Standard” Blade Modified to Accommodate Distortion

Unique features implemented to develop “distortion tolerant blade”

- Camber & thickness distribution managed
- Tip chord reduced for structural tolerance to loading shifts
- Dynamic design through camber & work distribution
- Blade stacking modified

- Under platform stress managed by dove-tail adjustments
- Shot peening for static stress reduction
- Modified leading & trailing edge for high incidence & Mach number distribution

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Rapid Loading Changes Require Unique Dynamic Design

Blade designed to stall and recover on every revolution, due to incidence swing

Distortion tolerance of the airfoil can be enhanced through control of the reduced frequency and thus the time constant of the airfoil response

\[ k = \beta \omega / \nu \]

where
- \( \beta \) = 1/2 the rotor chord length (or the meridional distance for consistency),
- \( \omega \) = frequency of the disturbance in radians per second, and
- \( \nu \) = the average relative velocity.

Rapid Loading Changes Require Unique Dynamic Design

Blade designed to stall and recover on every revolution, due to incidence swing

Duplicate of Page 15 showing excursion of D-factor w/blade position

Distortion tolerance of the airfoil can be enhanced through control of the reduced frequency and thus the time constant of the airfoil response

\[ k = \beta \frac{\omega}{v} \]

where
- \( \beta = \frac{1}{2} \) the rotor chord length (or the meridional distance for consistency),
- \( \omega \) = frequency of the disturbance in radians per second, and
- \( v \) = the average relative velocity.

Approximate Throat Position of the Center Blade

Reference Plane for the Center Blade

Approximate Distance Traveled at Relative Velocity Between Blade Senses a Change in Pressure Rise Ability

Rapid Loading Changes Require Unique Dynamic Design

Blade designed to stall and recover on every revolution, due to incidence swing

Duplicate of Page 15 showing excursion of D-factor w/blade position

Typical range of stalling behavior

\[ k = \frac{\beta \omega}{\nu} \]

where

- \( \beta \) = 1/2 the rotor chord length (or the meridional distance for consistency),
- \( \omega \) = frequency of the disturbance in radians per second, and
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Distortion tolerance of the airfoil can be enhanced through control of the reduced frequency and thus the time constant of the airfoil response.

Resulting Blade/Inlet Integrated Design with Dynamics

Mechanical design criteria achieved and dynamic operation satisfied
Stress Level Criteria Met with Integrated Design

Goodman Diagram – Fan Blade at 100% ADP

Goodman Diagram – Fan Blade at 105% ADP

Component Stresses

Component Stresses

Worst Case Superposition
52% Goodman Limit

Worst Case Superposition
58% Goodman Limit

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Boundary Layer Ingesting Inlet/Distortion Tolerant Fan Test Article

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NASA 8’x6’ Supersonic Wind Tunnel
(6.5’x6’ Embedded Propulsor Test Bed Configuration)

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• BLI Propulsor Operability “Good” (Away From Campbell Crossings)

• Robustness of Distortion Tolerant Fan Demonstrated

• Significant Stability Margin Achieved
Conclusions

• First distortion tolerant fan stage designed and successfully tested at realistic Mach number

• Stability margin to flutter ~12% achieved at 100% corrected speed, exceeding pre-test goals

• Stability margin to stall ~18% and higher across the map

• Design process using 3-D unsteady RANS and structural codes demonstrated to achieve performance objectives with guidance from “experienced designers and researchers”

• Extensive amount of numerical and experimental data acquired in this program will provide guidance for the design of high performance propulsion systems for aircraft using boundary layer ingestion concepts.