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

Dr. William T. Cousins
United Technologies Research Center
East Hartford, CT USA

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ATA Aerospace Testing Alliance

Acknowledgements

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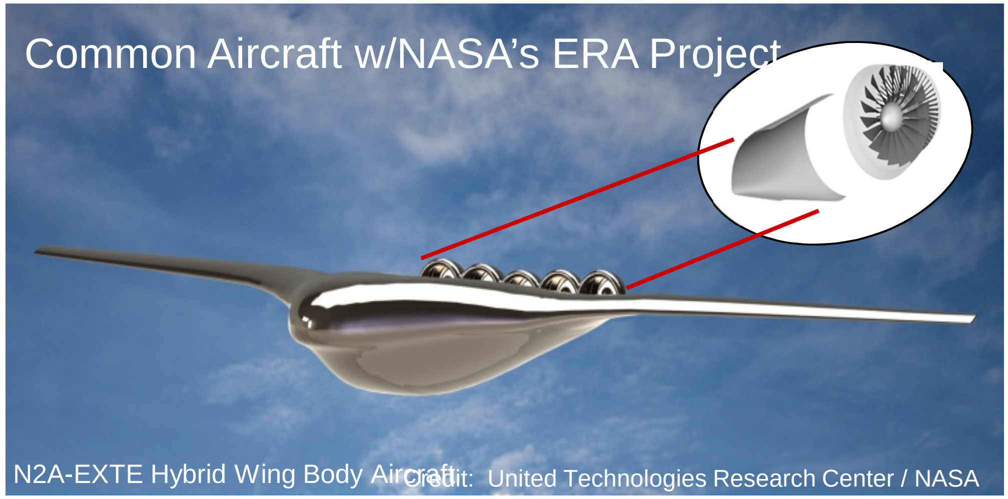
The work presented here will be published in a NASA Contractor Report (NASA CR) entitled "Robust Design for Embedded Engine Systems"

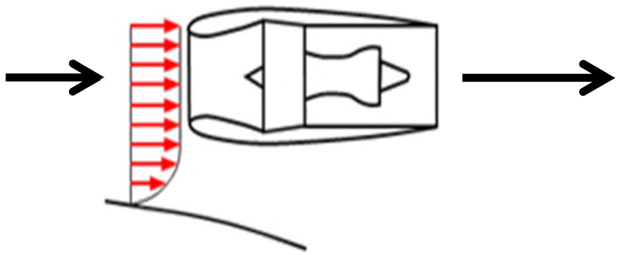
BLI Propulsor Technology Genesis and Applications



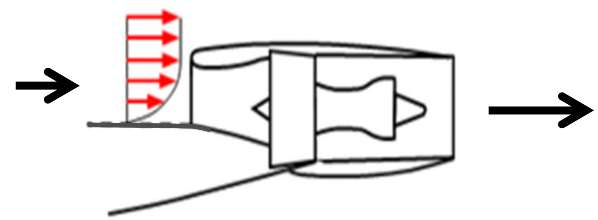
Technology Potentially Applicable To

Future BLI Aircraft

Propulsion Benefits of Boundary Layer Ingestion



Conventional Propulsion



Boundary Layer Ingesting Propulsion

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

Power: $P = \dfrac{\dot{m}}{2}\left(U_j^2 - U_{in}^2\right)$

$$P = T\left(\frac{U_{in}+U_j}{2}\right) = T\left(U_{in} + \frac{\Delta U}{2}\right)$$

where $\Delta U = \left(U_j - U_{in}\right)$

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

Propulsive Efficiency:

$$\eta_{p,conv} = \frac{2U_0}{U_0 + U_{j,conv}}$$

$$\eta_{p,BLI} = \frac{2U_0}{\overline{U}_{in,BLI} + U_{j,BLI}}$$

$$\eta_{p,BLI} = \left(\frac{U_0 + U_{j,conv}}{\overline{U}_{in,BLI} + U_{j,BLI}}\right)\eta_{p,conv}$$

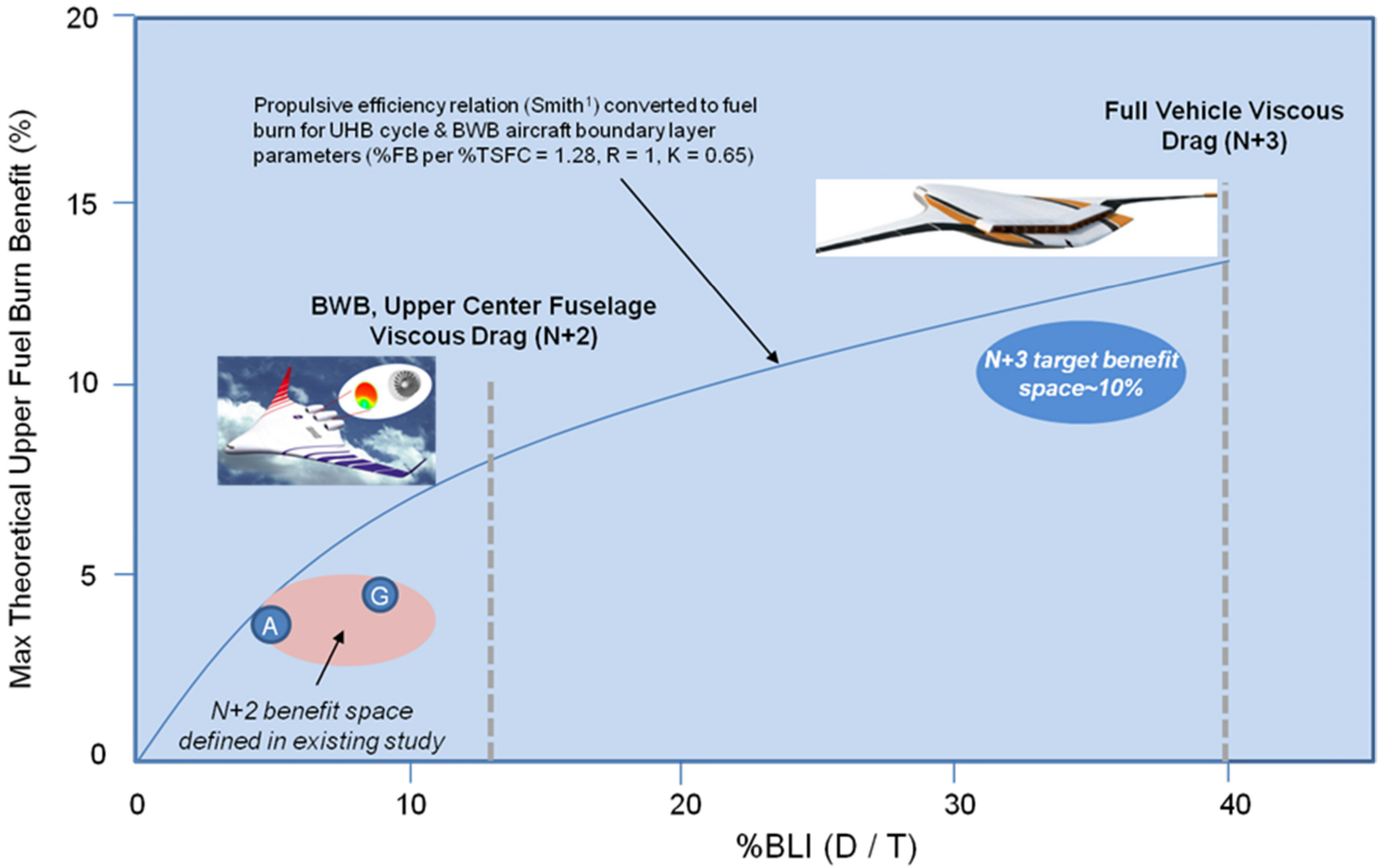
$$\Longrightarrow \eta_{p,BLI} > \eta_{p,conv}$$

Thrust is Maintained With Reduced Power Input Due to Higher Propulsive Efficiency

Ref: Plas, A.P., *Performance of a Boundary Layer Ingesting Propulsion System*, M.S. Thesis, MIT, 2006.
Plas, et al, *Performance of a Boundary Layer Ingesting (BLI) Propulsion System*, AIAA Paper 2007-0450, p. 22.

Fuel Burn Benefits Obtained from Boundary Layer Ingestion

N+2 benefit space addressed in present program



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System Studies Defined Technology Needs

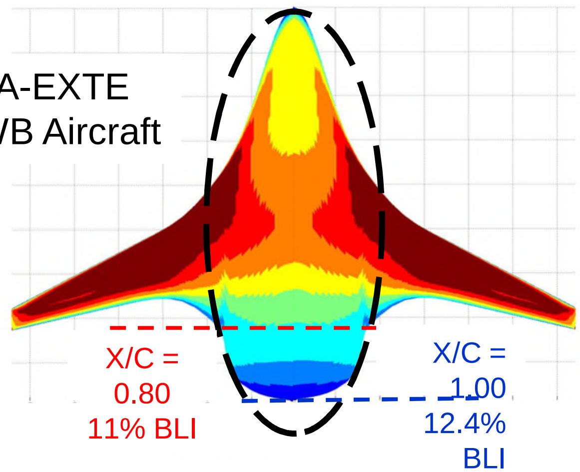
- High Level System Study[1,2]: Significant System-Level benefits can be achieved (~3-5% fuel Burn for HWB Aircraft)

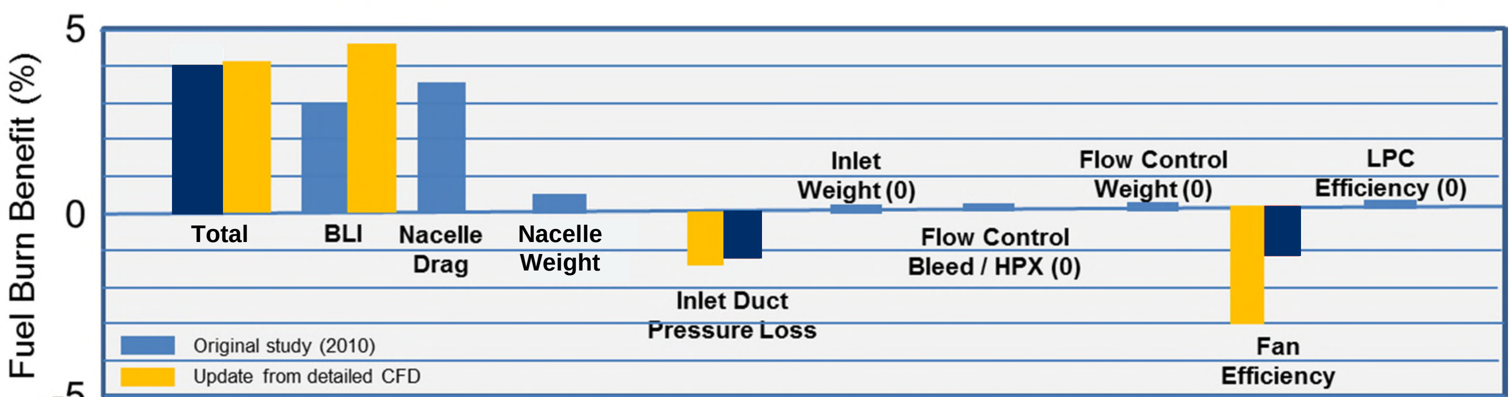
  Benefits on the order of ~10% possible for configurations with larger ingested drag fractions

  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)

N2A-EXTE
HWB Aircraft

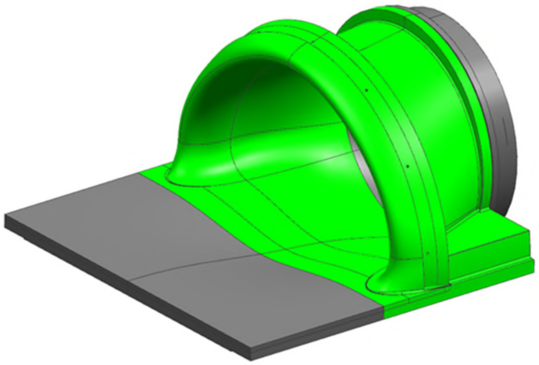




Ref: [1]Hardin, et al., *Aircraft System Study of Boundary Layer Ingesting Propulsion*, AIAA Paper 2012-3993, p. 12.
[2]Ochs, S.S., et al., *CFD-Based Analysis of Boundary Layer Ingesting Propulsion*, AIAA Paper 2015-3800, p. 15.
[3]Smith, L.H., *Wake Ingestion Propulsion Benefit*, AIAA Journal of Propulsion and Power, Vol. 9, No. 1, Jan-Feb, 1993, pp. 74-82.

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

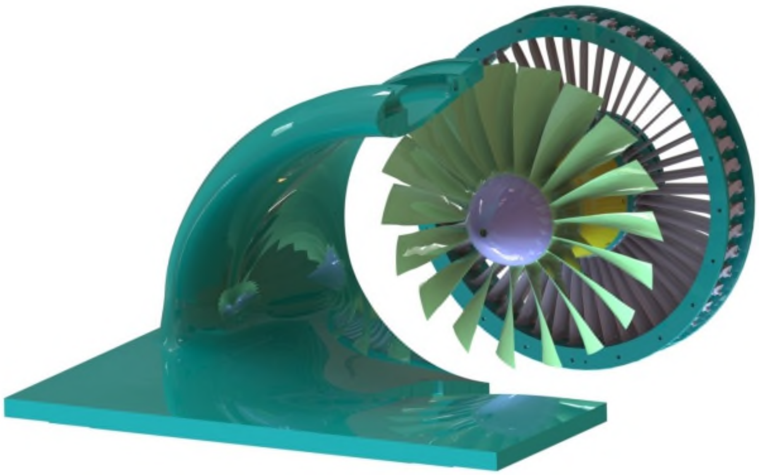
Some items outside “normal” design space must be considered

- 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

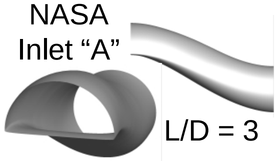
Program evolved as learning & tool capability progressed over time

Program Start

P&W Aero-1 Fan with tip shroud

Fan not available

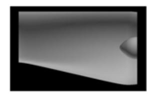
NASA Inlet "A"



L/D = 3

JT15D w/mid-span shroud

Turbine change required for same operating line



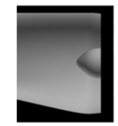
L/D = 1.5

NASA tip-turbine fan (TDI 1109)

Complete redesign required due to operability limitations

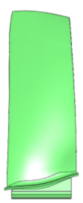
P&W Aero-1 Fan

G4 Fan Recommended



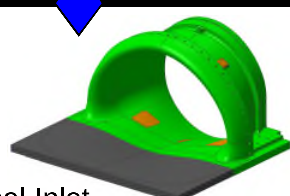
L/D = 0.6

G4 fan unshrouded



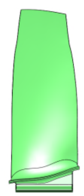
~100 hours of HCF life at ADP

Redesign decision after Research Design Review



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

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

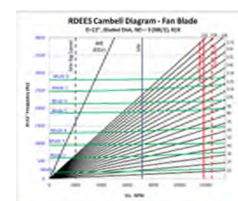


Performance drop to meet mechanical constraints

Recognition that solidity could be increased

Not done due to program time constraints

Main focus on structural integrity



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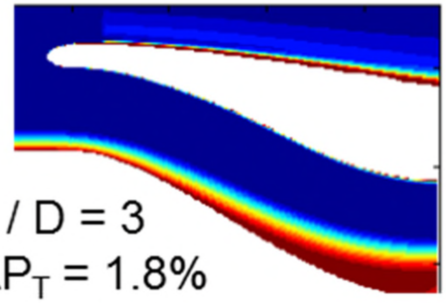
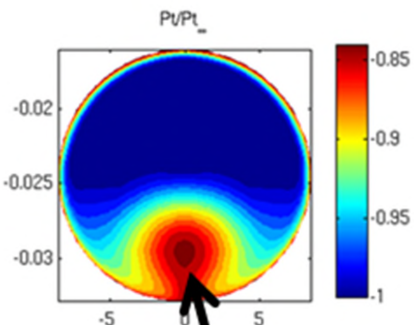
Inlet Design

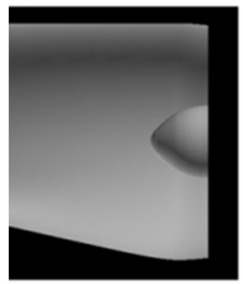
Final design shaped to provide operational distortion pattern

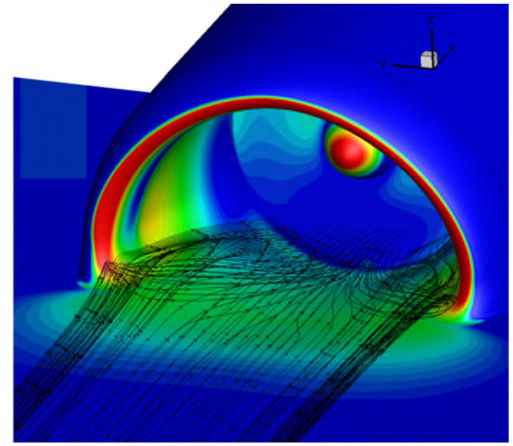


L / D = 3
ΔP_T = 1.8%

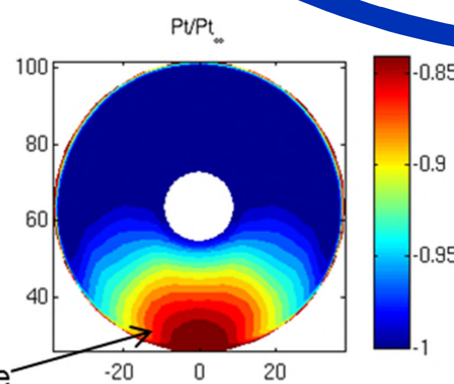


Low Pressure
Original Inlet "A"



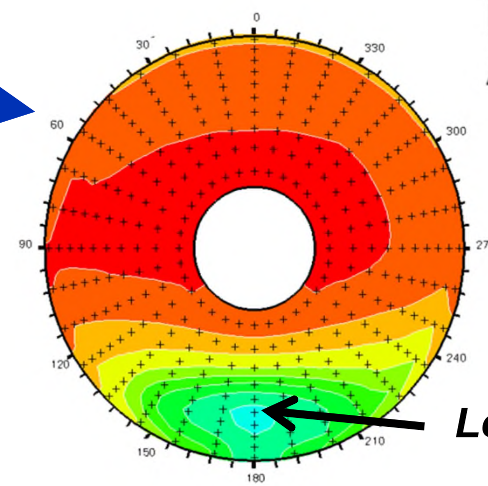


Designed BLI Inlet



Low Pressure

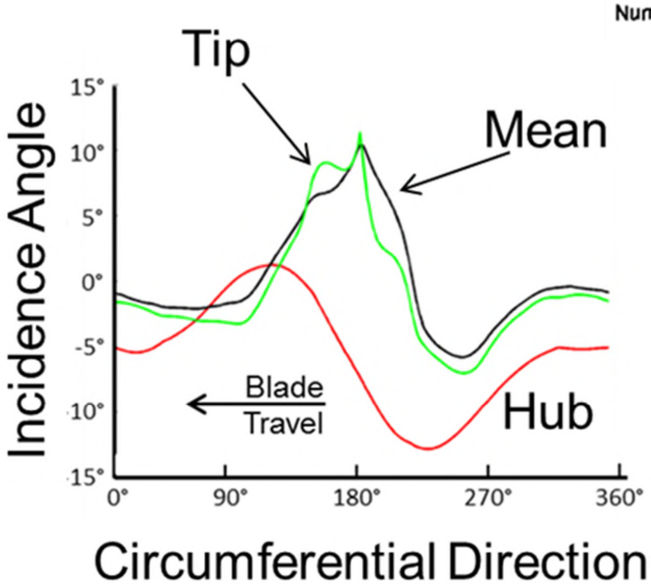
L / D = 0.6
ΔP_T = 0.3%

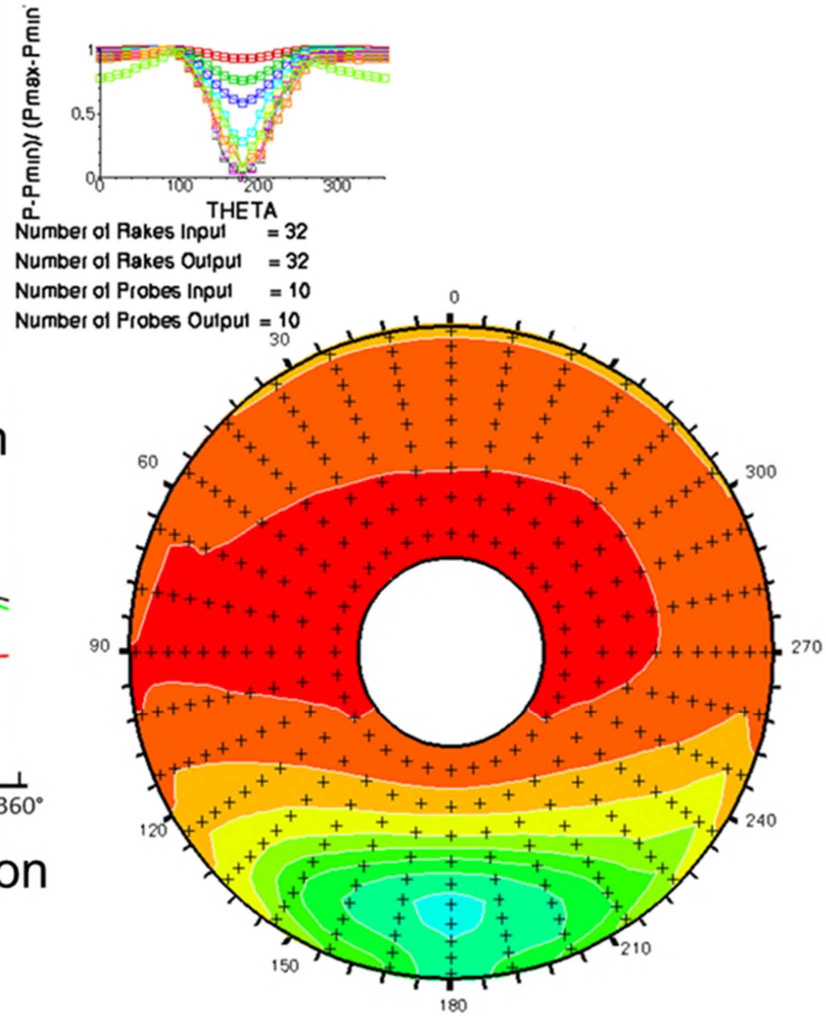


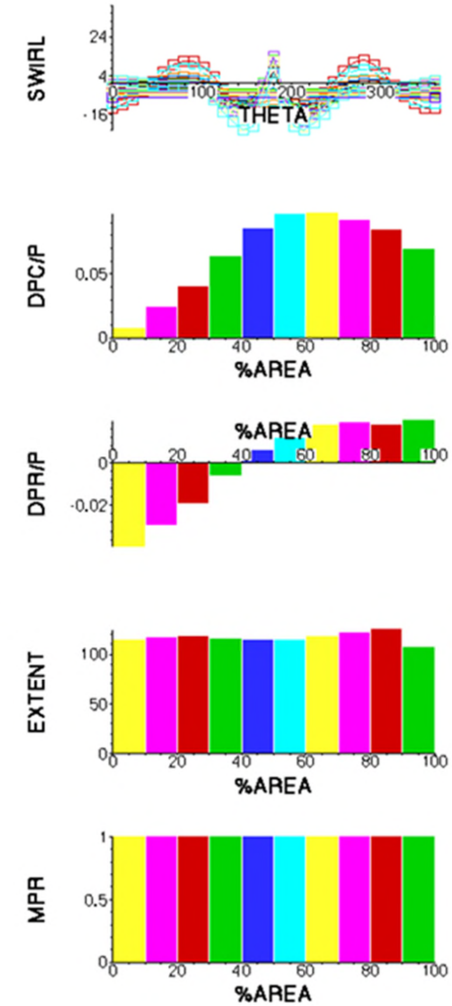
Low Pressure

Distortion Intensity and Incidence Swing are Significant

Maximum Values: $\Delta P_c/P \sim 10\%$ $\Delta P_r/P \sim 4\%$ Extent ~ 125°

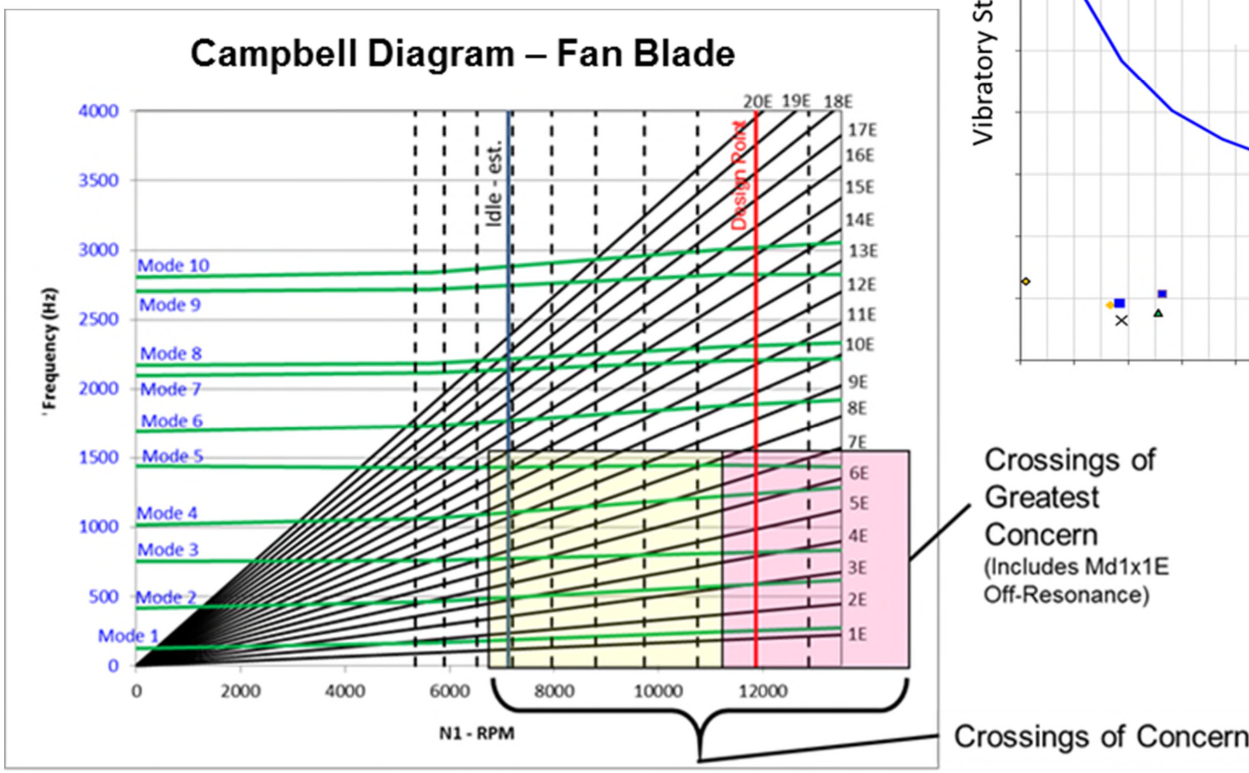


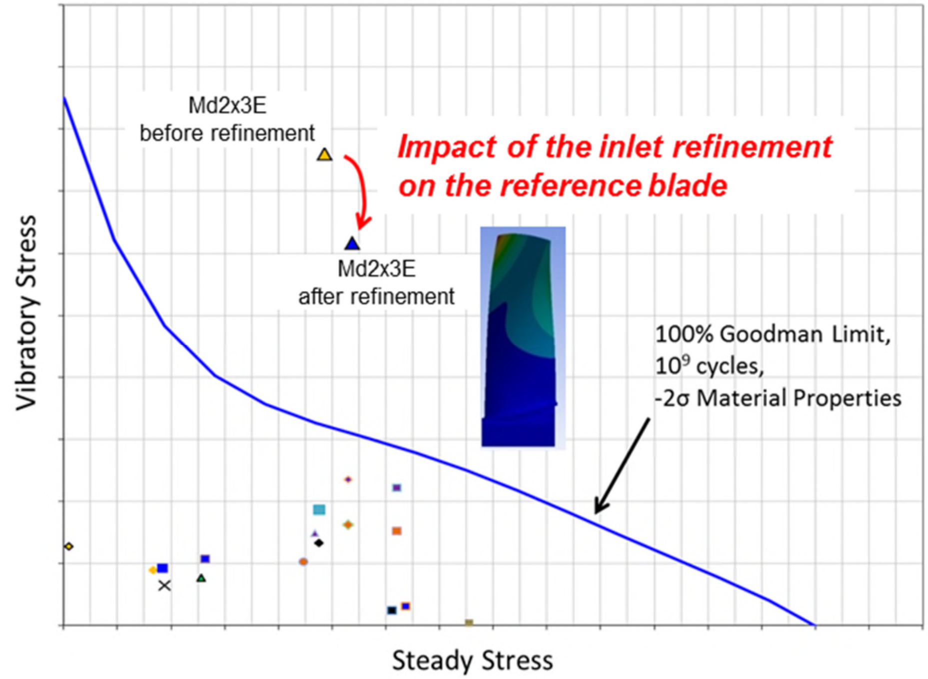




Reference Blade in BLI Environment Not Acceptable

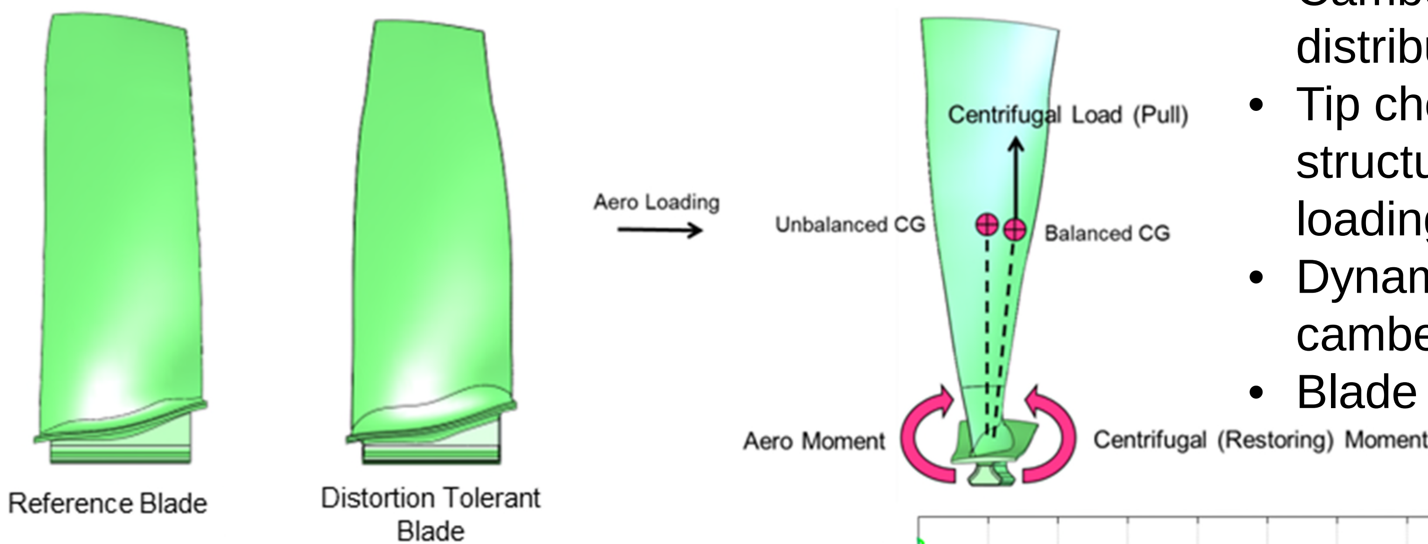
Inlet refinement for distortion shaping had a major influence





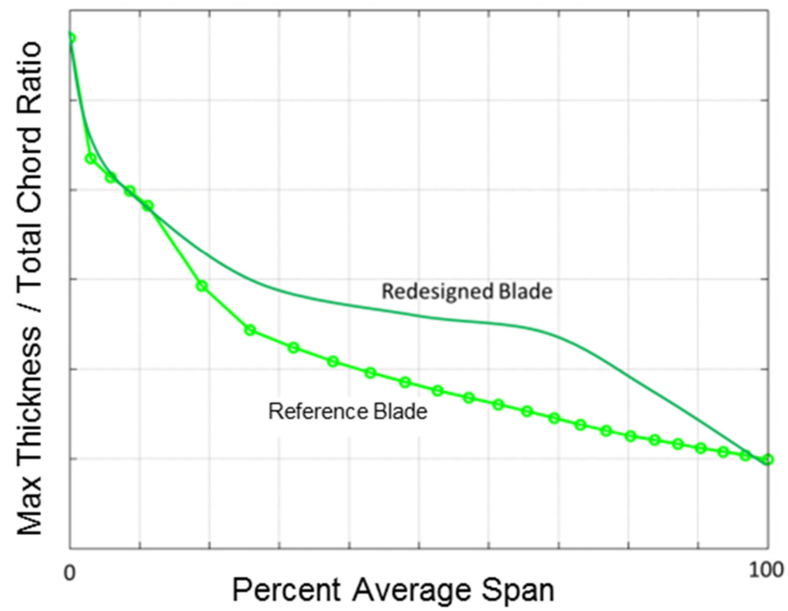
"Standard" Blade Modified to Accommodate Distortion

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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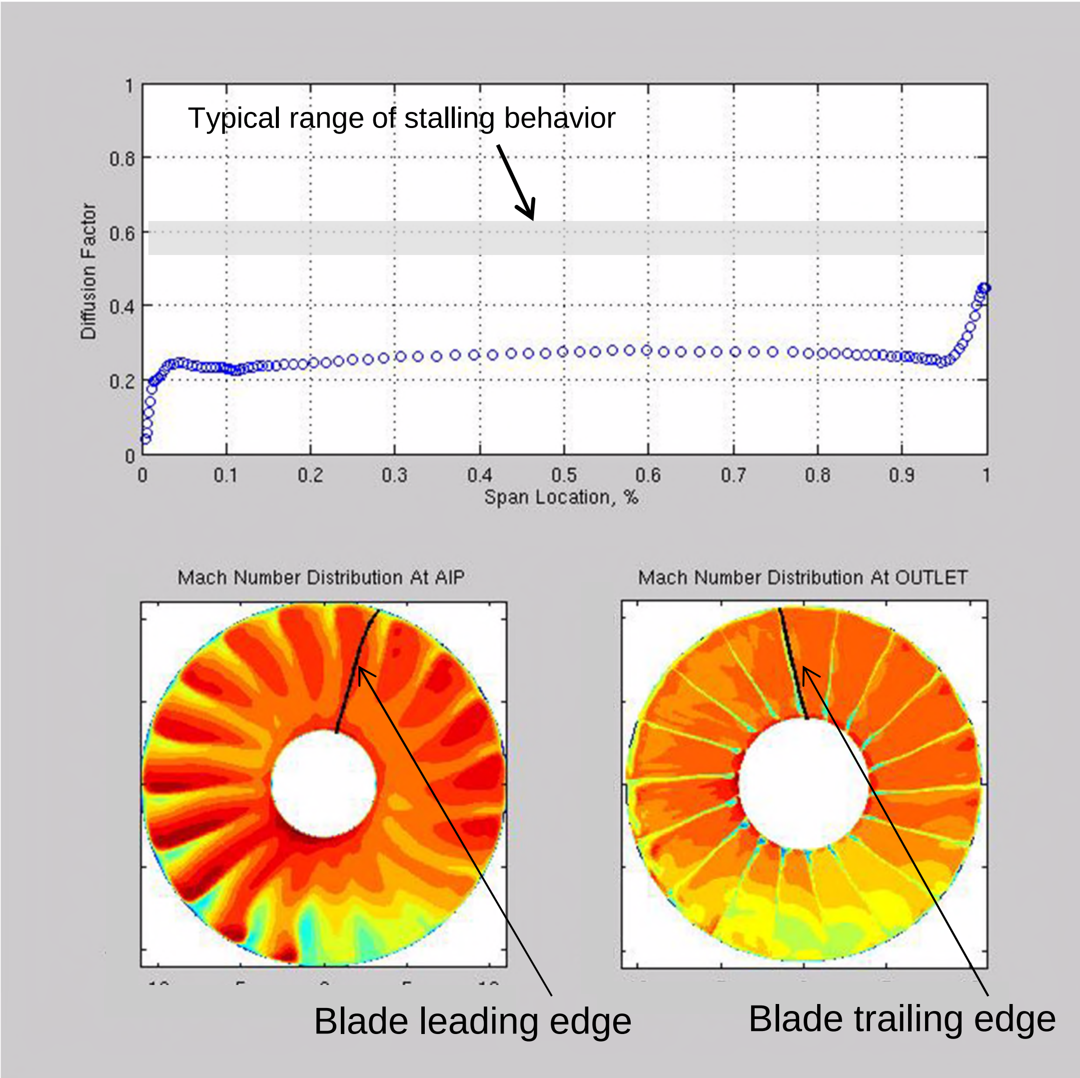
Rapid Loading Changes Require Unique Dynamic Design

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

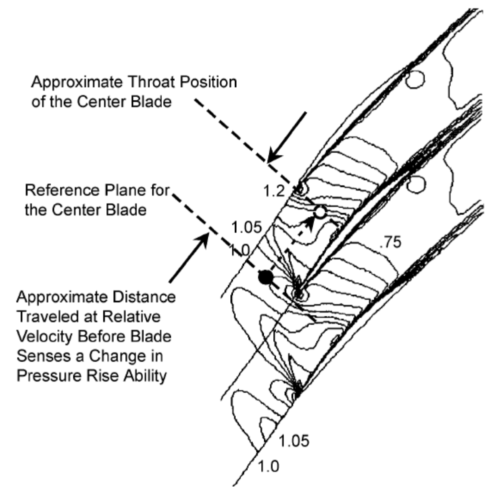


Distortion tolerance of the airfoil can be enhanced through control of the reduced frequency and thus the time constant of the airfoil response

$$k = \beta\,\omega \,/\, v$$

where

- β = 1/2 the rotor chord length (or the meridional distance for consistency),
- ω = frequency of the disturbance in radians per second, and
- v = the average relative velocity.



Ref. Cousins, W. T., “A Theory for the Prediction of Compressor Blade Aerodynamic Response”, AIAA Paper AIAA-98-3308, presented at the 34th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Cleveland, OH, July 13-15, 1998.

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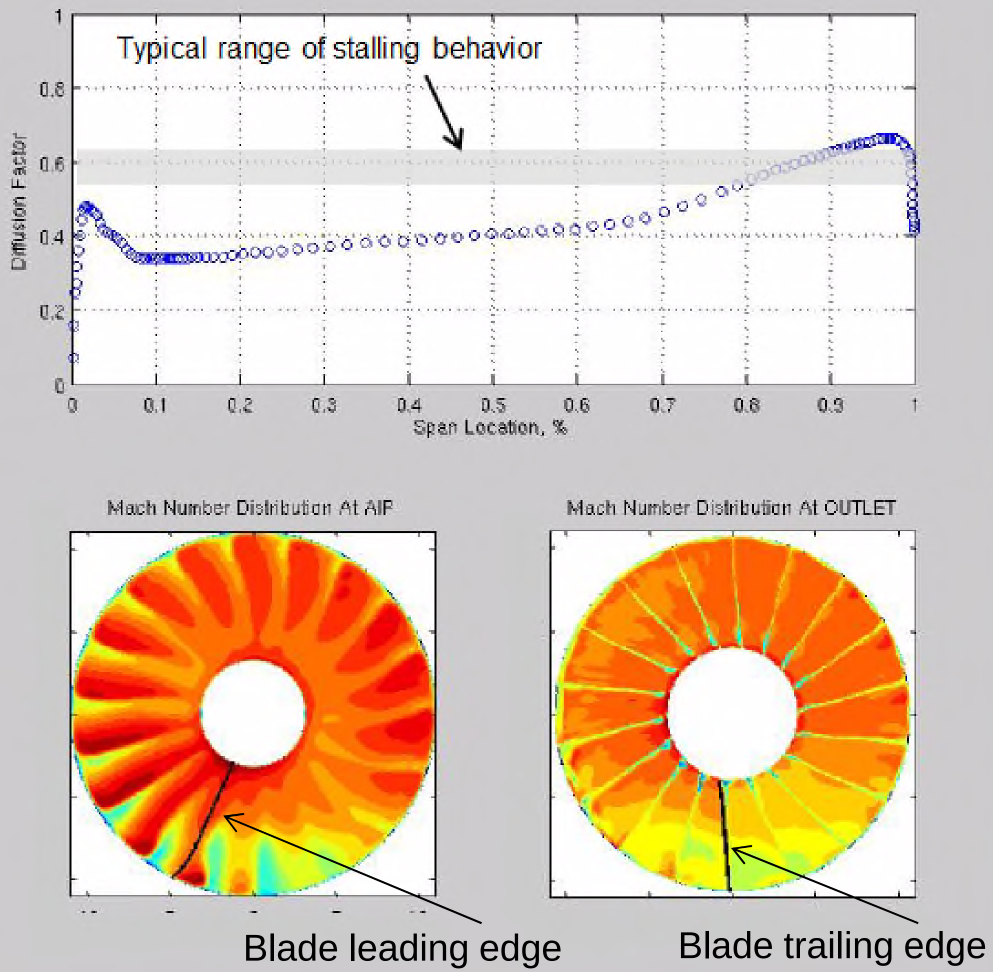
Duplicate of Page 15 showing excursion of D-factor w/blade position



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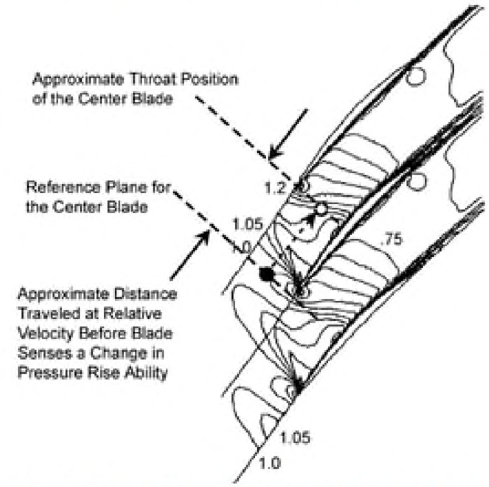

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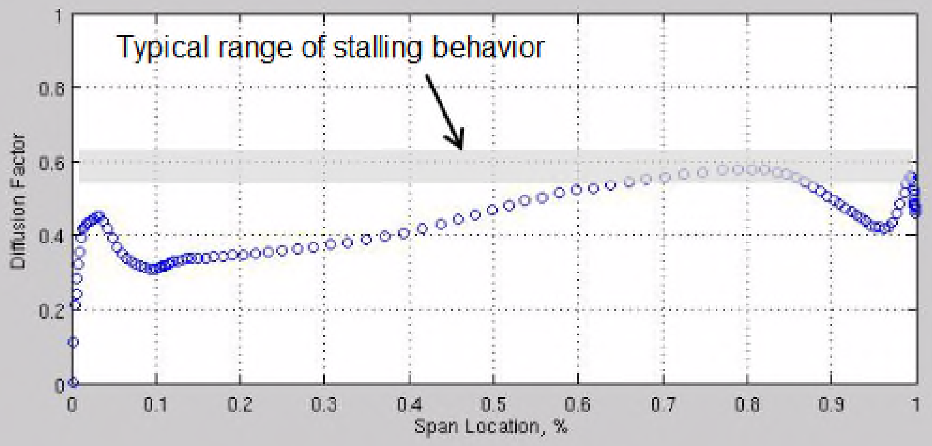

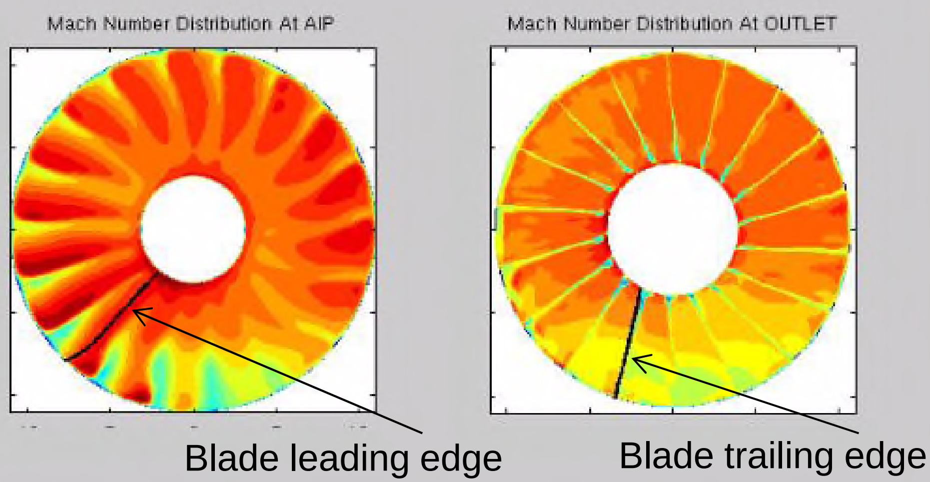

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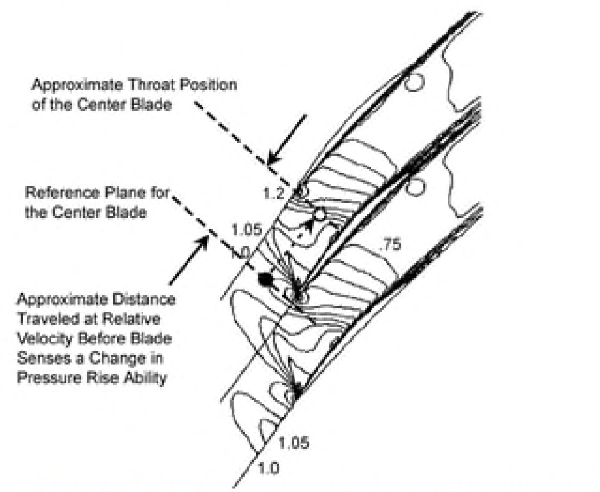

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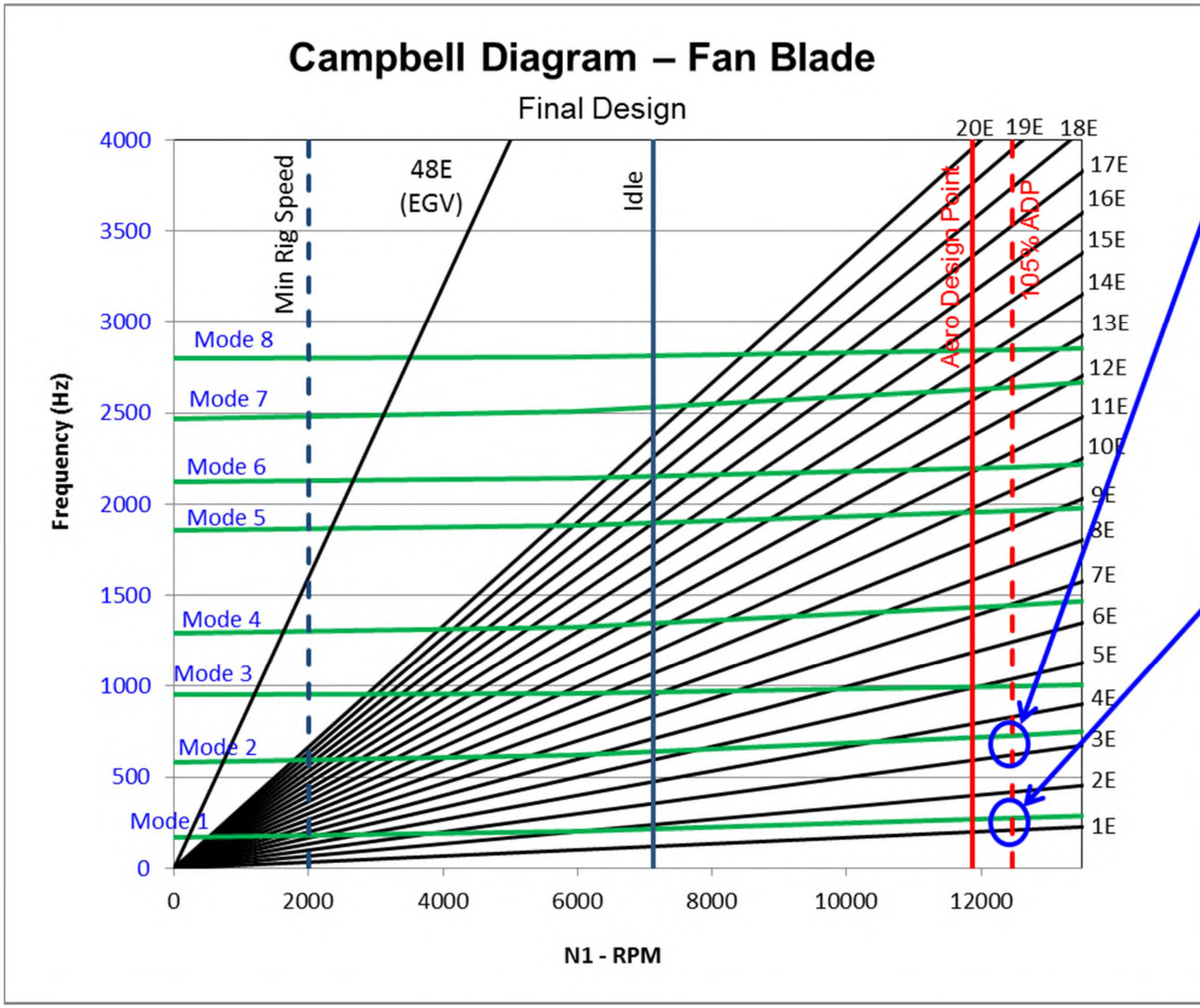
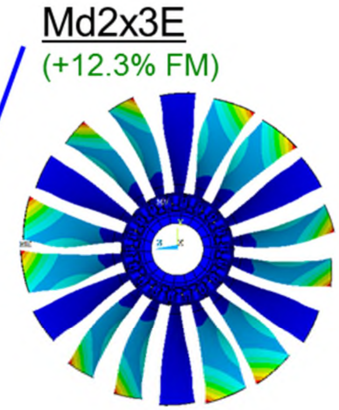
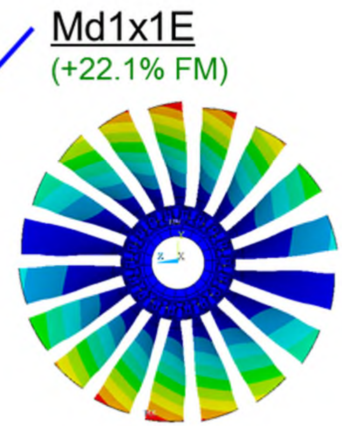
Resulting Blade/Inlet Integrated Design with Dynamics

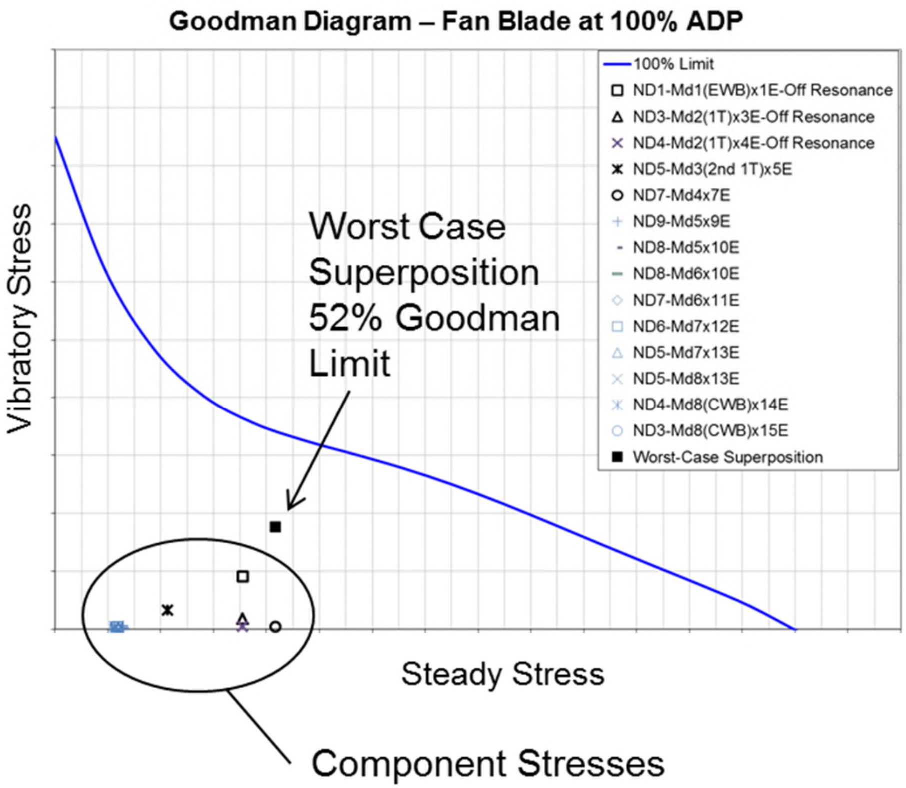
Mechanical design criteria achieved and dynamic operation satisfied

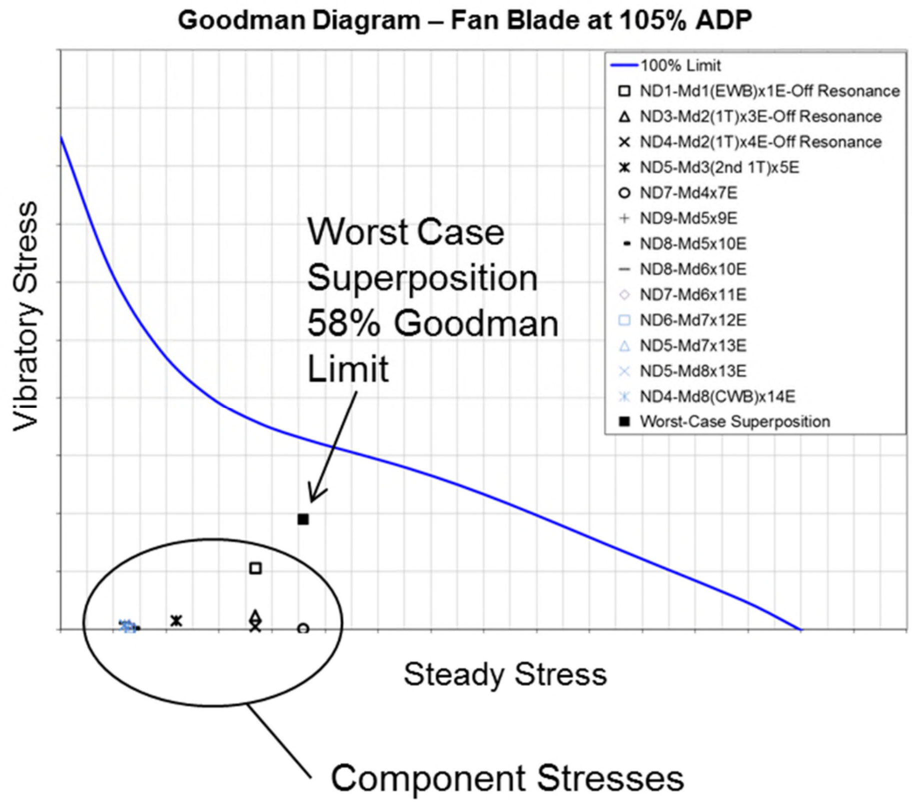




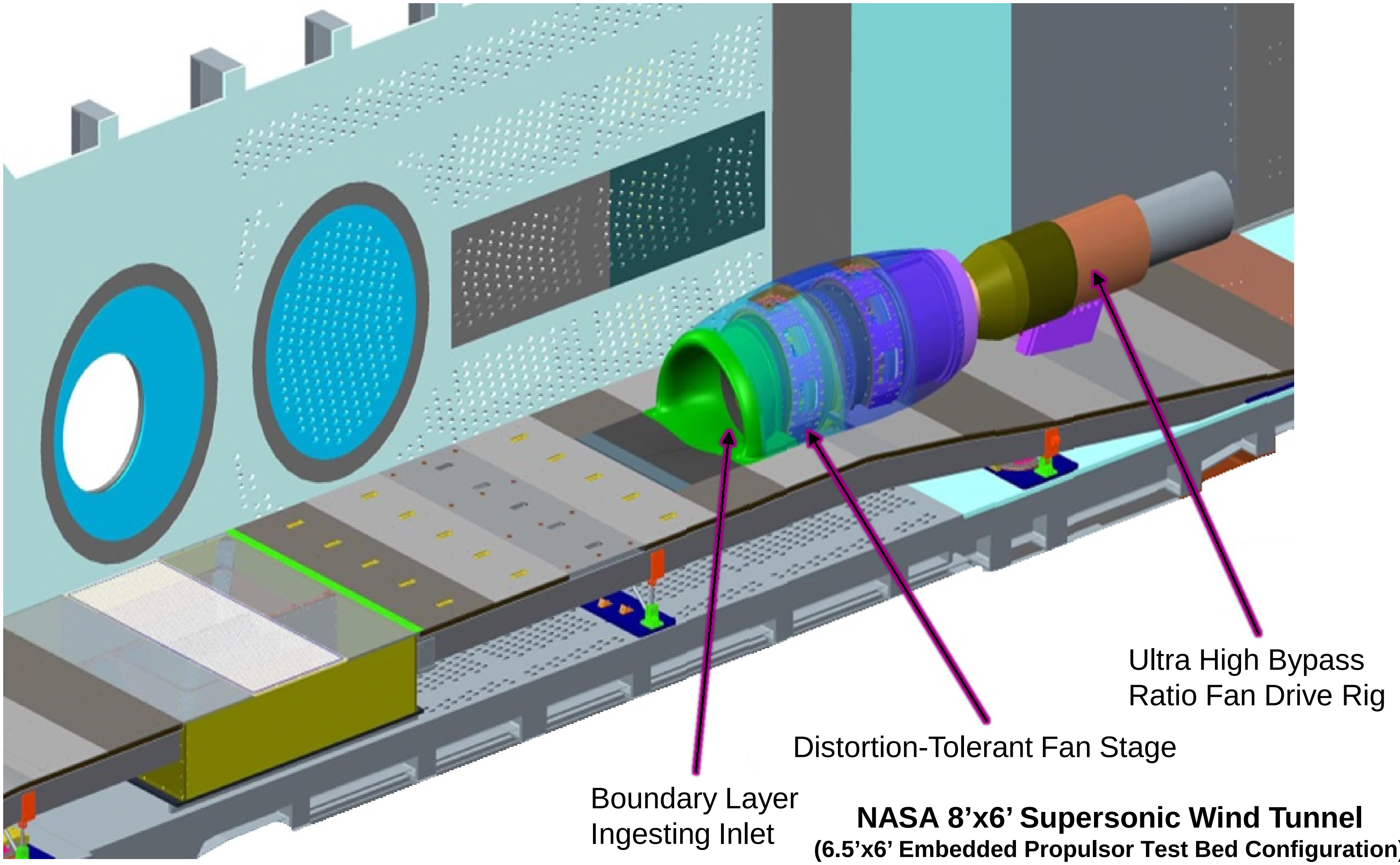


Stress Level Criteria Met with Integrated Design





Boundary Layer Ingesting Inlet/Distortion Tolerant Fan Test Article



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

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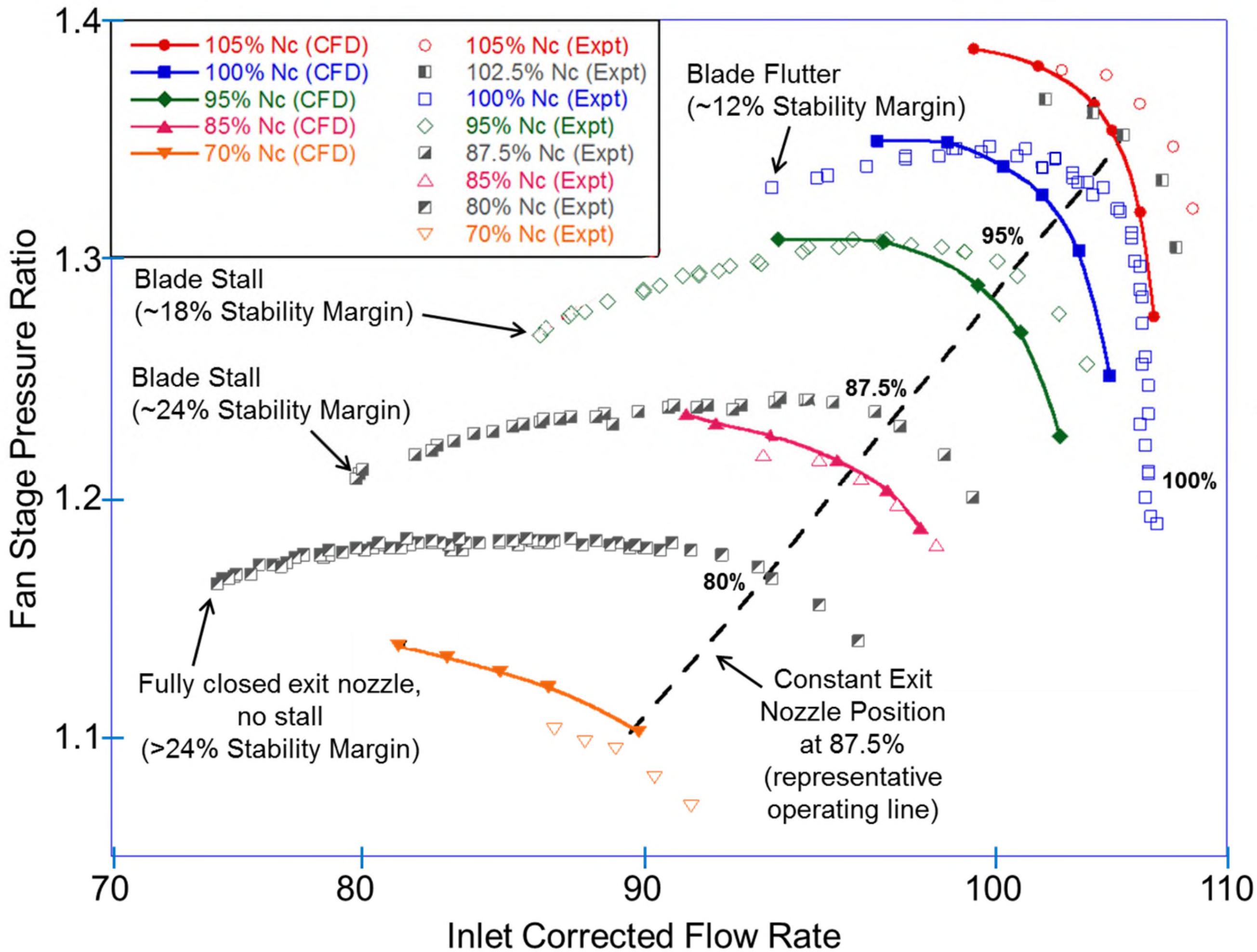
Distortion-Tolerant Fan Stage Stability Margin



- BLI Propulsor Operability "Good" (Away From Campbell Crossings)
- Robustness of Distortion Tolerant Fan Demonstrated
- Significant Stability Margin Achieved

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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.