NASA/CP—2018-219955

Propulsion-Airframe Integration Technical Interchange Meeting

Mary Jo Long-Davis, Compiler
Glenn Research Center, Cleveland, Ohio

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December 2018

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Propulsion-Airframe Integration Technical Interchange Meeting

Mary Jo Long-Davis, Compiler
Glenn Research Center, Cleveland, Ohio

Proceedings of a technical interchange meeting held at the Ohio Aerospace Institute
organized by NASA and the Air Force Research Laboratory
Cleveland, Ohio
May 30–31, 2018

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National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

December 2018

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Preface

The 1st Propulsion-Airframe Integration Technical Interchange Meeting (PAI–TIM) was held in Cleveland, Ohio, at the Ohio Aerospace Institute from May 30 to 31, 2018. The meeting was organized by representatives from the National Aeronautics and Space Administration (NASA) aeronautics research centers (i.e., Ames, Armstrong, Glenn, and Langley) and the Air Force Research Laboratory and was sponsored by NASA's Advanced Air Vehicle Technology project. The purpose of the PAI–TIM was to exchange information and ideas amongst this community of researchers in a workshop-type setting. At this meeting, results were shared in the form of presentations only (i.e., no papers were required) regarding ongoing research efforts in both the experimental and modeling areas associated with propulsion-airframe integration for advanced subsonic and supersonic vehicles. During the 2-day meeting, a total of 22 presentations were made and organized into three sessions: (1) Vision and PAI Challenges of Future Air Vehicles, (2) PAI Modeling and Simulation: State-of-the-Art and Challenges/Needs, and (3) PAI Testing: Test Techniques, Results and Challenges/Needs. In addition to the technical presentations, panel sessions were conducted each day at the conclusion of the morning and afternoon presentations during which time audience members posed general questions (using an online audience response system) that were then discussed by the panel. All but two of the presentations made at the PAI–TIM are included in this publicly available conference proceedings document.

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Propulsion-Airframe Integration Technical Interchange Meeting

Abstract

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During the 2 day meeting, a total of 22 presentations were made and were organized into three sessions: (1) Vision and PAI Challenges of Future Air Vehicles, (2) PAI Modeling and Simulation: State-of-the-Art and Challenges/Needs, and (3) PAI Testing: Test Techniques, Results and Challenges/Needs. All but two of the presentations made at the PAI–TIM are included in this publicly available conference proceedings document. The presentations were made by representatives from industry, academia, and Government agencies. In addition to the technical presentations, panel sessions were conducted each day at the conclusion of the morning and afternoon presentations during which time audience members posed general questions (using an online audience response system) that were then discussed by the panel.

Overviews of the Three Sessions Follow:

Vision and PAI Challenges of Future Air Vehicles

These presentations covered strategic thinking by the NASA Aeronautics Research Mission Directorate regarding the potential emerging concepts and the associated PAI challenges for subsonic "fixed-wing" aircraft as well as subsonic vertical lift and supersonic commercial vehicles. There were also presentations by industry highlighting requirements for advanced commercial and military vehicles that will inform PAI challenges.

PAI Modeling and Simulation: State-of-the-Art and Challenges/Needs

These presentations covered work being done at NASA and the Air Force Research Laboratory (AFRL). A presentation on NASA's Single-aisle Turboelectric AiRCraft with Aft Boundary Layer propulsion (STARC–ABL) provided a description of the concept, a performance benefits assessment, and a summary of enabling technologies. A presentation on the CFD analysis performed by NASA for the D8 "Double-bubble" subsonic transport concept provided insight into the potential benefit of boundary-layer-ingestion. A presentation by United Technologies Research Center outlined the design challenges and

approaches employed in developing a boundary layer ingesting inlet and distortion-tolerant fan. An aeropropulsion analysis and design framework (referred to as ModelCenter) was presented by NASA. ModelCenter Framework has capabilities to facilitate conceptual and preliminary design for aircraft concepts exhibiting high aerodynamic and propulsion coupling. AFRL presented results from their CFD efforts (e.g., development of rapid, repeatable meshing, and solution and adaptation methodology) conducted in support of testing distortion generators in their compressor aero research lab (CARL). Another presentation by NASA highlighted recent results of a coupled aeropropulsive design optimization of a boundary-layer-ingesting propulsor relevant to the STARC–ABL concept. These results indicate that aeropropulsive coupling has a strong impact on the overall propulsion system design for boundary-layer-ingesting concepts. NASA presented results from several PAI analyses performed using the Launch, Ascent, and Vehicle Aerodynamics (LAVA) code highlighting that different PAI challenges call for different gridding strategies such as structured curvilinear overset, unstructured, and cartesian adaptive mesh refinement. NASA presented challenges with accurately predicting the inlet recovery and distortion using adaptive mesh refinement for a supersonic inlet tested in the NASA Glenn 8- by 6-Foot Supersonic Wind Tunnel (8×6 SWT).

PAI Testing: Test Techniques, Results, and Challenges/Needs

These presentations covered work being done at NASA, AFRL, industry, and academia. The first presentation in this session was made by NASA on the experimental setup, results, and lessons learned from testing a boundary-layer-ingesting-inlet/distortion-tolerant fan (BLI^2DTF) in the NASA Glenn 8×6 SWT. Results from the University of Texas at Austin aimed to provide a basic understanding of the vibroacoustic loads that form on the aft deck and sidewalls of a planar multistream nozzle through testing and examination of measured wall static pressures, aft deck wall dynamic pressures, force measurements, and far-field acoustics, as well as accompanying CFD analyses. NASA presented results from previous high Mach number (M = 0.85) tests successfully conducted on boundary-layer-ingesting inlet flow control technologies on a 2.5%-scale model. AFRL presented results from experiments performed in the CARL facility in which they have developed reconfigurable flow-path hardware appropriate for both clean inlet and distorted inflow testing through reconfigurable upstream ducting and rotators. This presentation also highlights the challenges associated with incorporating instrumentation to adequately characterize the flow field and aeromechanics, as well as implementing swirl distortion generators (i.e., StreamVanes™ developed by Virginia Tech). NASA presented plans to test StreamVanes™ in its single-stage axial compressor facility (W8) to investigate the aerodynamic performance and operability of fans in the presence of swirl distortion. A presentation on the acoustic considerations for PAI highlighted the need going forward for propulsion airframe integration/propulsion aeroacoustics specific tests (with accurate propulsion simulation), which will require that test methods for airframes and propulsors be harmonized. AFRL presented results from the calibration of an innovative flow angularity probe with a real-time pressure sensor which aimed to have similar accuracy as historical probe designs, with a diameter smaller than 0.125 in., and low cost to manufacture/calibrate. NASA highlighted its current capabilities in PAI flight test instrumentation and capabilities that will be needed to address future PAI flight testing.

The following sections contain the approved-for-public-release presentations provided by the participants. Some represent snapshots in time of ongoing work, and some may contain a list of references in case the reader wants additional information.

Technical Interchange Meeting Agenda

WEDNESDAY, 30 MAY 2018

8:30 **CHECK-IN AND REFRESHMENTS**—OAI Lobby

9:00 **INTRODUCTORY REMARKS**—OAI Auditorium

- Mary Jo Long-Davis, NASA Glenn Research Center, Cleveland, OH

9:20 **SESSION I—VISION AND PAI CHALLENGES OF FUTURE AIR VEHICLES**

- Vision and Propulsion Airframe Integration (PAI) Challenges of Future Air Vehicles
  Richard Wahls, NASA HQ, Washington, D.C.
- Vision for and PAI Challenges with Advanced Vehicles- Boeing Perspective
  John Bonet, Boeing Research and Technology, Huntington Beach, CA
- Vision for and PAI Challenges with Advanced Vehicles- Aurora Perspective
  David Hall, Aurora Flight Sciences, Cambridge, MA

10:20 **BREAK**

- Lockheed Martin: Propulsion-Airframe Integration Challenges Justine Li, Lockheed Martin, Palmdale, CA
- Northrop Grumman Perspective on Vision & Propulsion-Airframe Integration Challenges of Future Air Vehicles
- Chris Harris, Northrop Grumman, Los Angeles, CA

11:30 **PANEL SESSION QUESTION AND ANSWER**

12:00 **LUNCH**

- Lunch for PAI-TIM Attendees in the OAI Sunroom

1:00 **SESSION II—PAI MODELING AND SIMULATION: STATE-OF-THE-ART AND CHALLENGES/NEEDS**

- Overview of the NASA STARC-ABL (Rev. B) Advanced Concept
- Jason Welstead, Mark Guynn, Irian Ordaz, Jesse Quinlan, and Brian Mason, NASA Langley Research Center, Hampton, VA; Jim Felder, Bill Haller, Mike Tong, Scott Jones, Justin Gray, Irian Ordaz, Sydney Schnulo, and Ajit Sil, NASA Glenn Research Center, Cleveland, OH; Mark Guynn,
- D8 CFD Overview: An Aerodynamics Study of Boundary Layer Ingestion Benefit + Overview of Tail Cone Thruster WT Test
- Shishir Pandya, NASA Ames Research Center, Moffett Field, CA
- Development of a Robust Distortion Tolerant Low-Pressure-Ratio Fan for Boundary-Layer-Ingesting Engines
- William Cousins, United Technologies Research Center, East Hartford, CT

2:30 **BREAK**

- Aero-Propulsion Analysis and Design Framework
- Irian Ordaz, NASA Langley Research Center, Hampton, VA
- CARL Computational Results and Challenges
- Darius Sanders, Air Force Research Laboratory, Dayton, OH
- Coupled Aero-Propulsive Design Optimization Of a Boundary Layer Ingestion Propulsor
- Justin Gray, NASA Glenn Research Center, Cleveland, OH and Gaeten Kenway, NASA Ames Research Center, Moffett Field, CA

4:15 **PANEL SESSION QUESTION AND ANSWER**
6:30 **NO-HOST DINNER**—Hansa Brewery, Cleveland, OH

THURSDAY, 31 MAY 2018

8:30 **CHECK-IN AND REFRESHMENTS**—OAI Lobby

9:00 **SESSION II—PAI MODELING AND SIMULATION: STATE-OF-THE-ART AND CHALLENGES/NEEDS (CONTINUED)**

- Computational Strategies to Support Propulsion-Airframe Integration Applications
  Francois Cadieux and Cetin Kiris, NASA Ames Research Center, Moffett Field, CA
- Numerical Simulations (and Test Methods) of a Quiet Supersonic Technology (QueSST) Aircraft Preliminary Design
  David Friedlander, Ray Castner and Chris Heath, NASA Glenn Research Center, Cleveland, OH
- Tailor-Mate Supersonic Forebody Inlet Analysis Using Overflow Code
  Brock Pleiman and Will Humphreys, Air Force Research Laboratory, Dayton, OH

10:30 **BREAK**

10:45 **SESSION III—PAI TESTING: TECHNIQUES, RESULTS AND CHALLENGES/NEEDS**

- Boundary-Layer-Ingesting Inlet/Distortion-Tolerant Fan (BLI2DTF) Testing in the 8'x6'
  John Wolter, NASA Glenn Research Center, Cleveland, OH
- Vibroacoustic Loads on the Aft Deck and Sidewalls of a Planar Multistream Supersonic Nozzle
  Charles Tinney, The University of Texas at Austin, Austin, TX

11:45 **PANEL SESSION QUESTION AND ANSWER**

12:15 **LUNCH**

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- CARL Experimental Results and Challenges
  Chase Nessler, Air Force Research Laboratory, Dayton, OH
- W8 Test Plans with Streamvanes
  Julia Stephens, Chris Hughes and Mark Celestina, NASA Glenn Research Center, Cleveland, OH

2:30 **BREAK**

- Acoustic Considerations for PAI
  Dale Van Zante, NASA Glenn Research Center, Cleveland, OH
- Calibration of a Flow Angularity Probe with a Real-time Pressure Sensor
  Brock Pleiman, Air Force Research Laboratory, Dayton, OH
- Propulsion-Airframe Integration Flight Test Instrumentation
  Stephen Cumming and Hyun Dae Kim, NASA Armstrong Flight Research Center, CA

4:15 **PANEL SESSION QUESTION AND ANSWER**

Technical Interchange Meeting Organizing Committee

Jack Benek, Air Force Research Laboratory

Ray Castner, NASA Glenn Research Center

Mark Celestina, NASA Glenn Research Center

Jeff Flamm, NASA Langley Research Center

Eric Hendricks, NASA Glenn Research Center

Chris Hughes, NASA Glenn Research Center

Kevin James, NASA Ames Research Center

Hyun Dae Kim, NASA Armstrong Flight Research Center

Cetin Kiris, NASA Ames Research Center

Michael List, Air Force Research Laboratory

Mary Jo Long-Davis, NASA Glenn Research Center

Brock Pleiman, Air Force Research Laboratory

Jon Tinapple, Air Force Research Laboratory

Vision & Propulsion Airframe Integration (PAI) Challenges of Future Air Vehicles

Dr. Richard A. Wahls (Rich)
Strategic Technical Advisor, Advanced Air Vehicles Program
Aeronautics Research Mission Directorate
NASA

Propulsion Airframe Integration TIM
Ohio Aerospace Institute
Cleveland, OH
May 30-31, 2018

Outline

NASA Aeronautics Context

Propulsion Airframe Integration

Traditional Subsonic “Fixed Wing” Markets

Emerging Aviation Markets

- Supersonic
- Vertical Lift (VL)

Concluding Remarks

NASA Aeronautics

NASA Aeronautics Vision for Aviation in the 21st Century

ARMD continues to evolve and execute the Aeronautics Strategy *https://www.nasa.gov/aeroresearch/strategy*

6 Strategic Thrusts

- Safe, Efficient Growth in Global Operations
- Innovation in Commercial Supersonic Aircraft
- Ultra-Efficient Commercial Transports
- Transition to Alternative Propulsion and Energy
- In-Time System-Wide Safety Assurance
- Assured Autonomy for Aviation Transformation

U.S. leadership for a new era of flight

www.nasa.gov

NASA Aeronautics Strategic Implementation Plan (SIP)

Mega Drivers and Strategic R&D Thrusts

T1 — **Safe, Efficient Growth in Global Operations**
- Enable full NextGen and develop technologies to substantially reduce aircraft safety risks

T2 — **Innovation in Commercial Supersonic Aircraft**
- Achieve a low-boom standard

T3A ST, **T3B VL** — **Ultra-Efficient Commercial Vehicles**
- Pioneer technologies for big leaps in efficiency and environmental performance

T4 — **Transition to Alternative Propulsion and Energy**
- Characterize drop-in alternative fuels and pioneer low-carbon propulsion technology

T5 — **In-Time System-Wide Safety Assurance**
- Develop an integrated prototype of an in-time safety monitoring and assurance system

T6 — **Assured Autonomy for Aviation Transformation**
- Develop high impact aviation autonomy applications

Each Strategic Thrust has associated community outcomes – targeted impacts at 10, 20, and 30 years out.

www.nasa.gov

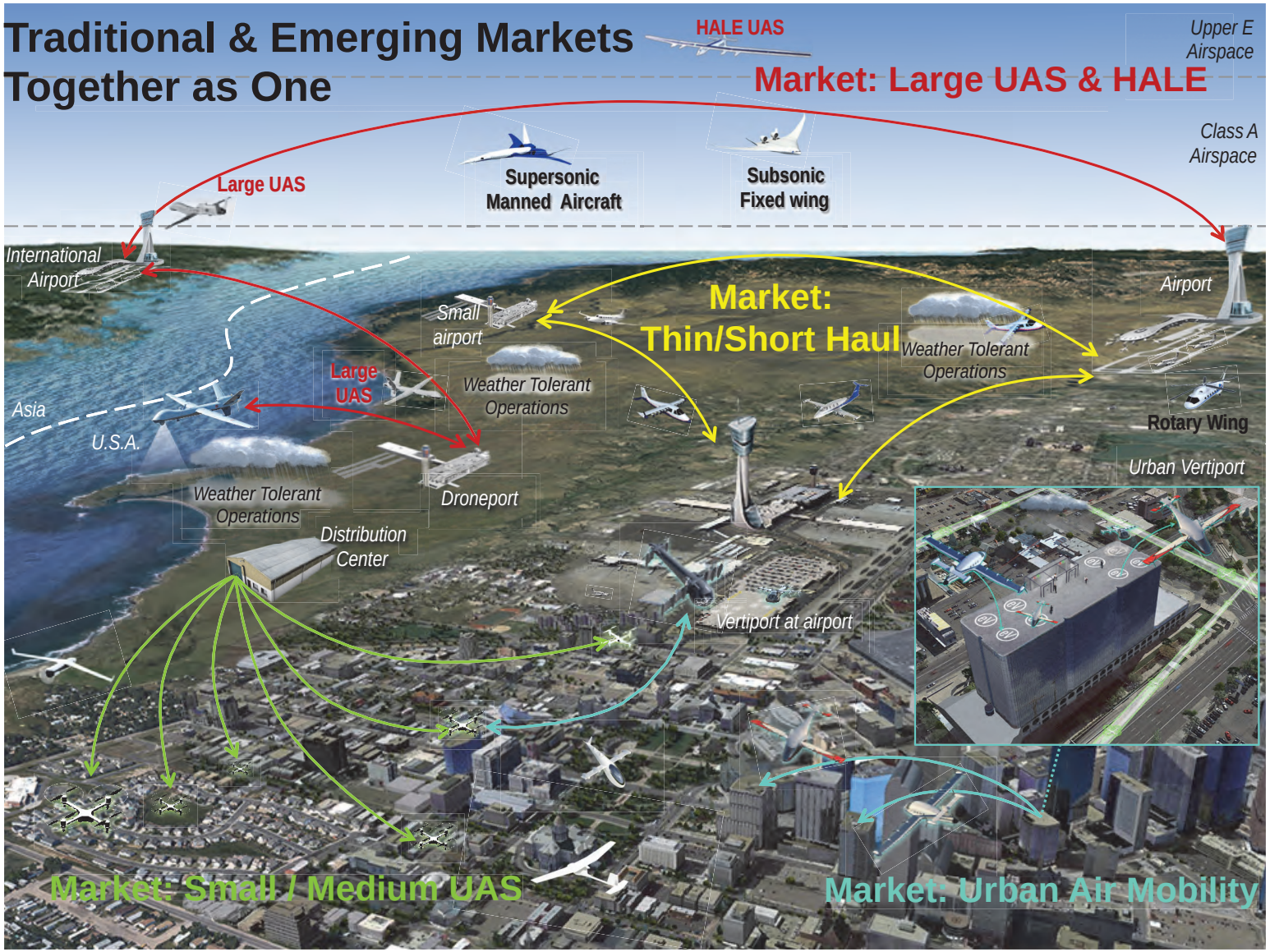
NASA Aeronautics Priorities

from Congressional Briefing on President's FY19 Budget Request (February 2018)

- Focus Topics
  - Low Boom Flight Demonstrator
  - Subsonic Aircraft Technologies
  - Hypersonic Technology
  - UAS Traffic Management and Urban Air Mobility
  - Air Traffic Management
  - System Wide Safety
  - Energizing the U.S. Aeronautics Innovation Pipeline

Focus Topic list indicative of ARMD priority areas

PAI critical for all vehicles


Traditional & Emerging Markets Together as One
HALE UAS
Upper E Airspace
Market: Large UAS & HALE
Class A Airspace
Large UAS
Supersonic Manned Aircraft
Subsonic Fixed wing
International Airport
Small airport
Market: Thin/Short Haul
Airport
Weather Tolerant Operations
Large UAS
Weather Tolerant Operations
Asia
U.S.A.
Rotary Wing
Urban Vertiport
Weather Tolerant Operations
Droneport
Distribution Center
Vertiport at airport
Market: Small / Medium UAS
Market: Urban Air Mobility

Propulsion Airframe Integration

integration of the key subsystems that most define the aircraft

- What system? For this presentation:
  - Vehicle system
  - Vehicle as a subsystem within the air transportation system
  - Vehicle as a system compromised of major subsystems
    - airframe, propulsion, control, communication, navigation, …

- Propulsion Airframe Integration
  - Integration of two major subsystems that most define what we see as the aircraft configuration <u>externally</u>, but also includes much that is <u>internal</u>
    - Example: fuel subsystem is internal, integrated within airframe and propulsion subsystems
  - Includes Propulsion Airframe Acoustics (PAA) challenges & opportunities

The Dawn of Propulsion Airframe Integration

1902 glider

1903 powered flight

www.nasa.gov

“Current” Propulsion Airframe Integration

Subsonic Transport – under wing pylon mount

- Challenge
  - Efficient integration
  - Propulsion system growth for efficiency/noise
  - Nacelle weight/drag growth
- Design Process Advances
  - Isolated wing & nacelle
  - Wing with influence of nacelle
  - Simultaneous wing/nacelle
  - Simultaneous wing/nacelle/fan?
- Design Considerations
  - ground clearance, roll, nose gear collapse, water ingestion, rotor burst, loads/aeroelastics, ETOPS, engine out, full env operability, fuel system integ, secondary power extraction & distrib, etc

PAI IS HARD AND GETTING HARDER

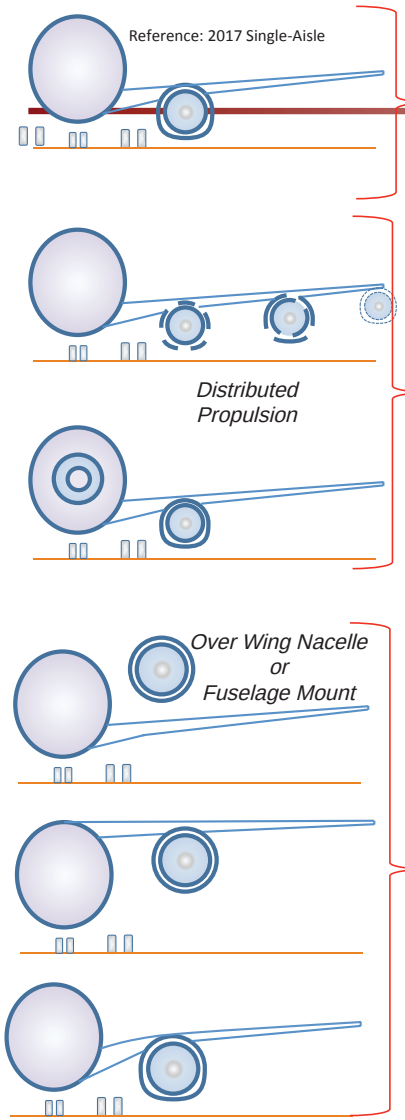
Schlosser et al. Chart 5
http://www.aflonext.eu/files/CEAS%202017/AFLoNext_CEAS2017_DesignTestingFlowControl_Airbus_Dassault.pdf

Boeing 737-700 (left) vs B737 MAX 8 (right)

Figure courtesy Brian Yutko

Overcoming the PAI Challenge

Subsonic Transport – options



1 – No physical size growth (outer mold line (OML)) compared to state-of-the-art (SOA) propulsion system

- fits under existing low wing

1.1) Small core, high efficiency without growing OML

1.2) Partial hybrid system

2- Reduce physical size (OML) compared to SOA propulsion system

- fits under existing wing with room for growth
- more than 2 propulsors, equal or less number of cores than propulsors

2.1) > 2 engines, propulsor to core 1:1, each smaller than equivalent twin

2.2) Distributed propulsion system #fans > #cores. Explore trade space of propulsor distribution and power transmission (electrical or mechanical)

Example: Boundary Layer Ingestion (**BLI)** tail cone thruster (to enable smaller thrust requirement for under wing engines)

3- Accept physical size (OML) growth compared to SOA propulsion system

- doesn't fit under existing wing, unless landing gear grows (weight/noise)
- requires reconfiguration/relocation of propulsion, nontraditional airframe

3.1) Over Wing Nacelle

3.2) Fuselage Mount (side or above)

3.3) High wing / Gull Wing

3.4) **BLI** or flush mount w/diverter derivative of any pylon mounted configure above

Graphics Credit: Scott Anders

Overcoming the PAI Challenge

Subsonic Transport – opening a range of future possibilities?

- Sample Configuration Possibilities with unique PAI

Boeing BWB

Lockheed Martin HWB

Dzyne BWB

- Sample Configuration Possibilities with unique PAI including BLI
  - 180 Degree Distortion

NASA N3X

MIT/Cambridge SAX-40

MIT/Aurora D8

  - 360 Degree Distortion

Boeing SUGAR

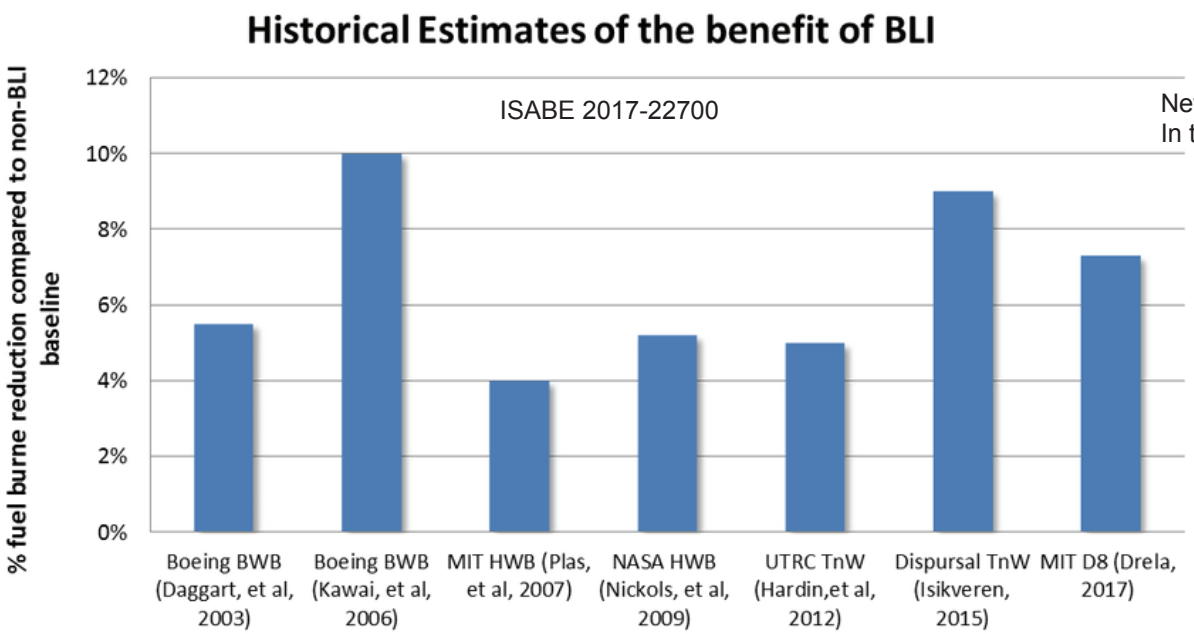
NASA STARC-ABL

Bauhaus Luftfarht Propulsive Fuselage

So what about BLI?

Is there really a benefit when considering all the penalities?

- Potential Benefits
  - Variation, uncertainty in benefit, dependent on application and assumptions



New results in 2018
In the range of 3-6% benefit

So what about BLI?

Is there really a benefit when considering all the penalities?

- Understanding details and minimizing penalties
  - Distortion Tolerant Fan
    fan efficiency, weight, ….

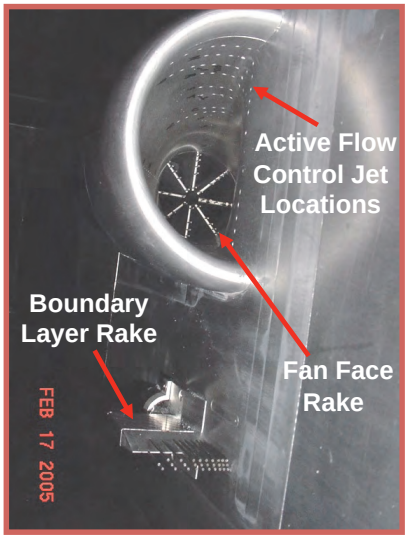
    See Arend, et al. AIAA 2017-5041

  - NASA GRC 8x6

Inlet Flow Conditioning
forward of or within inlet

See Owens, et al. AIAA J. of Aircraft vol. 45, no.4. pp1431

NASA LaRC 0.3m TCT



Propulsion Airframe Integration

Safe, Efficient, Quiet Vertical Lift Aircraft

"Traditional" helicopter design is already challenging and PAI fundamental

Wide range of concepts in development (Hirshberg, www.vtol.org, January 2018 lists 51!) up to and including in flight test that are even more challenging

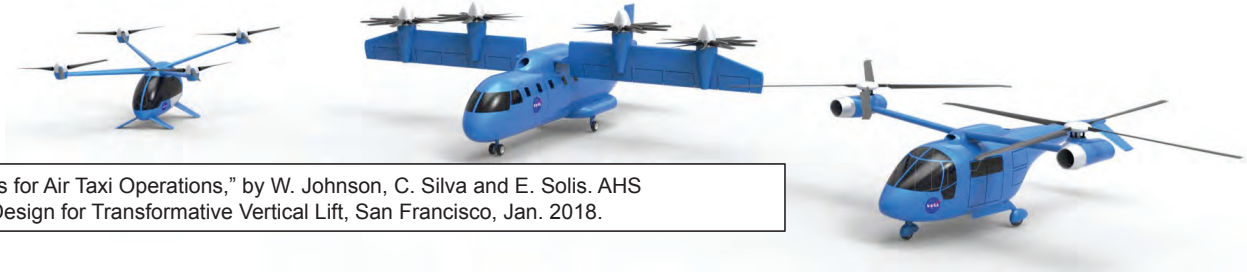
Image credit: Joby Aviation

Image credit: Kitty Hawk

Image credit: Aurora Flight Sciences

Image credit: Airbus A^3

NASA representative suite of reference vertical lift aircraft/missions for research



"Concept Vehicles for Air Taxi Operations," by W. Johnson, C. Silva and E. Solis. AHS Aeromechanics Design for Transformative Vertical Lift, San Francisco, Jan. 2018.

www.nasa.gov

Propulsion Airframe Integration

Civil Supersonic Aircraft

Practical civil supersonic aircraft are emerging

Full vehicle shaping including PAI is critical for quiet, efficient supersonic flight

NASA Low Boom Demonstrator and several other aircraft concepts in development heading towards flight test

Image credit: Boom

Image credit: Aerion

NASA Low Boom Flight Demonstrator

Concluding Remarks

- Exciting times in Traditional and Emerging Aviation Markets
  - Many opportunities … many challenges
  - Modern technology/capabilities lead to expanded design/trade space (but the devil is in the detail)
- NASA Aeronautics working on PAI Challenges and exploring opportunities across vehicle classes
  - External and internal integration challenges
  - Complexity of design, test, and analysis grows
  - Subsonic FW: PAI challenges may drive configuration change
    Vehicle-integrated BLI-propulsion warrants further study
  - Subsonic VL: PAI challenges in breadth and complexity of new configurations
  - Supersonic: PAI challenges inherent in low boom and conventional designs

NASA/CP—2018-219955

www.nasa.gov

Lockheed Martin: Propulsion-Airframe Integration Challenges

30 May 2018

Justine Li

Propulsion-Airframe Integration Technical Interchange Meeting (PAI-TIM)
Cleveland, OH

LOCKHEED MARTIN

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Preface

Advanced vehicle design with increasing capability depends on limited, relevant reliable data for increasingly complex systems

Lockheed Martin leverages experience in air vehicle design and integration to improve capability

P-80	F-104	D-21B	SR-71

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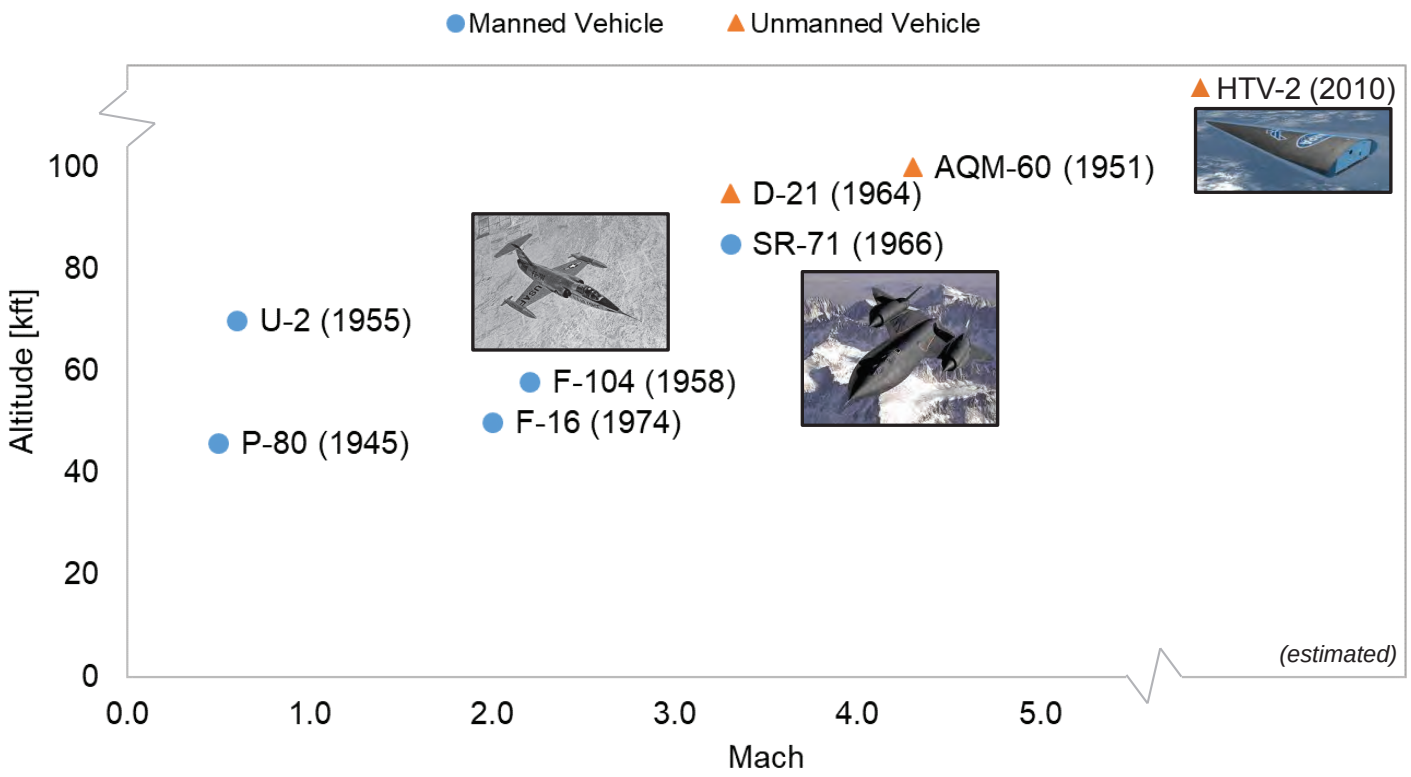
Historical Perspective



LM Skunk Works builds upon 75 years of air vehicle design

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Major Challenges of Advanced Vehicle Design

Air Vehicle Capability
- Speed, Altitude
- Range, Endurance
- Payload

Propulsion System
- Engine
- Inlet
- Nozzle

Air Vehicle Systems
- Structures, Loads
- Materials
- Thermal management
- Fuel, Power
- Lift, Drag

Increased air vehicle capability increases system dependencies

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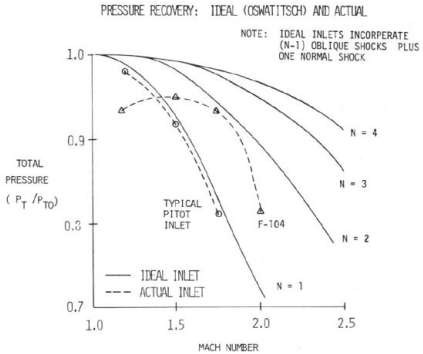
Propulsion System and Integration

F-104 Starfighter (M2+)

- General Electric J79

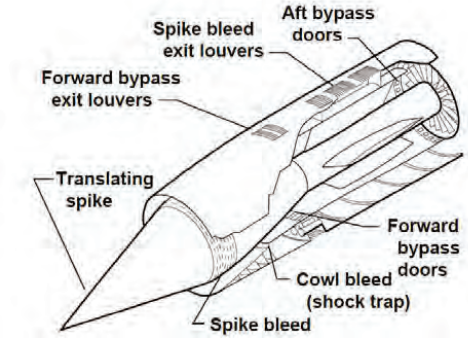
Courtesy Surber & Tinapple, 2012

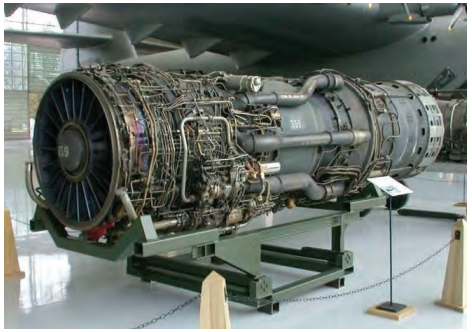


Courtesy Surber & Tinapple, 2012

SR-71 Blackbird (M3+)

- Pratt & Whitney J-58





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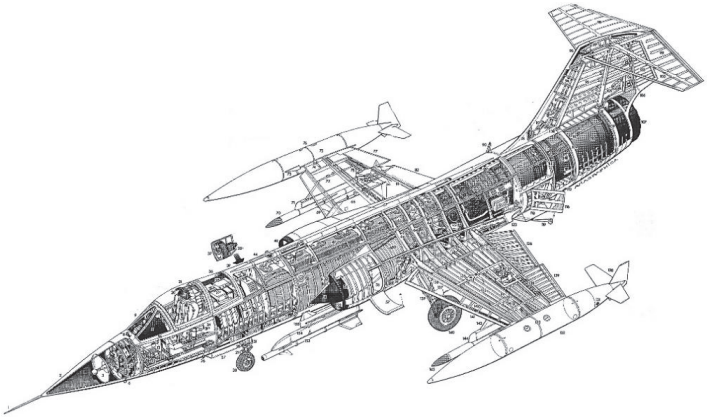
Air Vehicle Systems: Structures, Materials

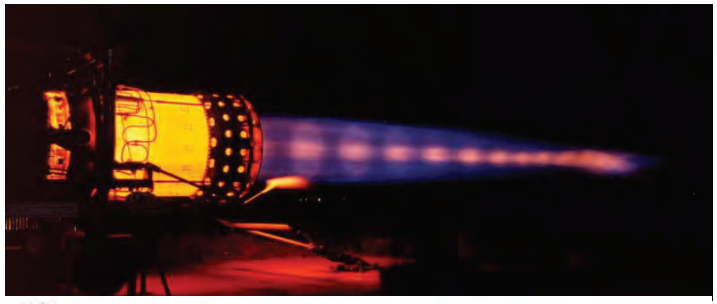
F-104 Starfighter (M2+)

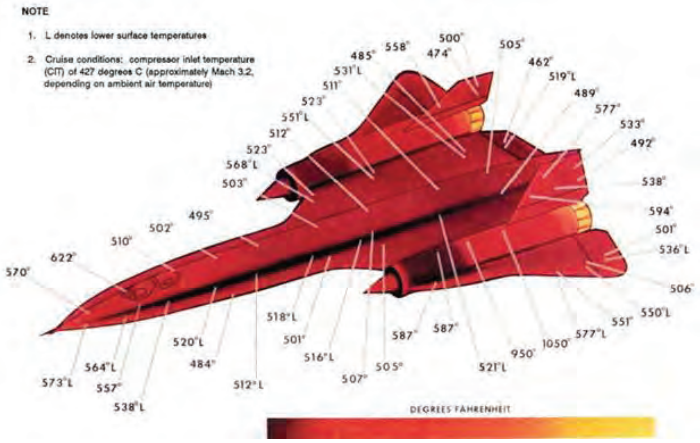
- Conventional all-aluminum construction



SR-71 Blackbird (M3+)

- Titanium and composite construction





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Air Vehicle Systems: Subsystems

F-104 Starfighter (M2+)

- Thermal Management:
  Bypass air
- Power generation:
  two 20 kVA generators
  - INS,TACAN
  - UHF radio

SR-71 Blackbird (M3+)

- Thermal Management:
  Bypass air & Fuel heat exchanger
- Power generation:
  two 60 kVA generators
  - INS & ANS,TACAN
  - UHF radio

NAS-14V2
Astroinertial
Navigation System

  - Optical/IR systems
  - ELINT & ECM
  - ASARS-1

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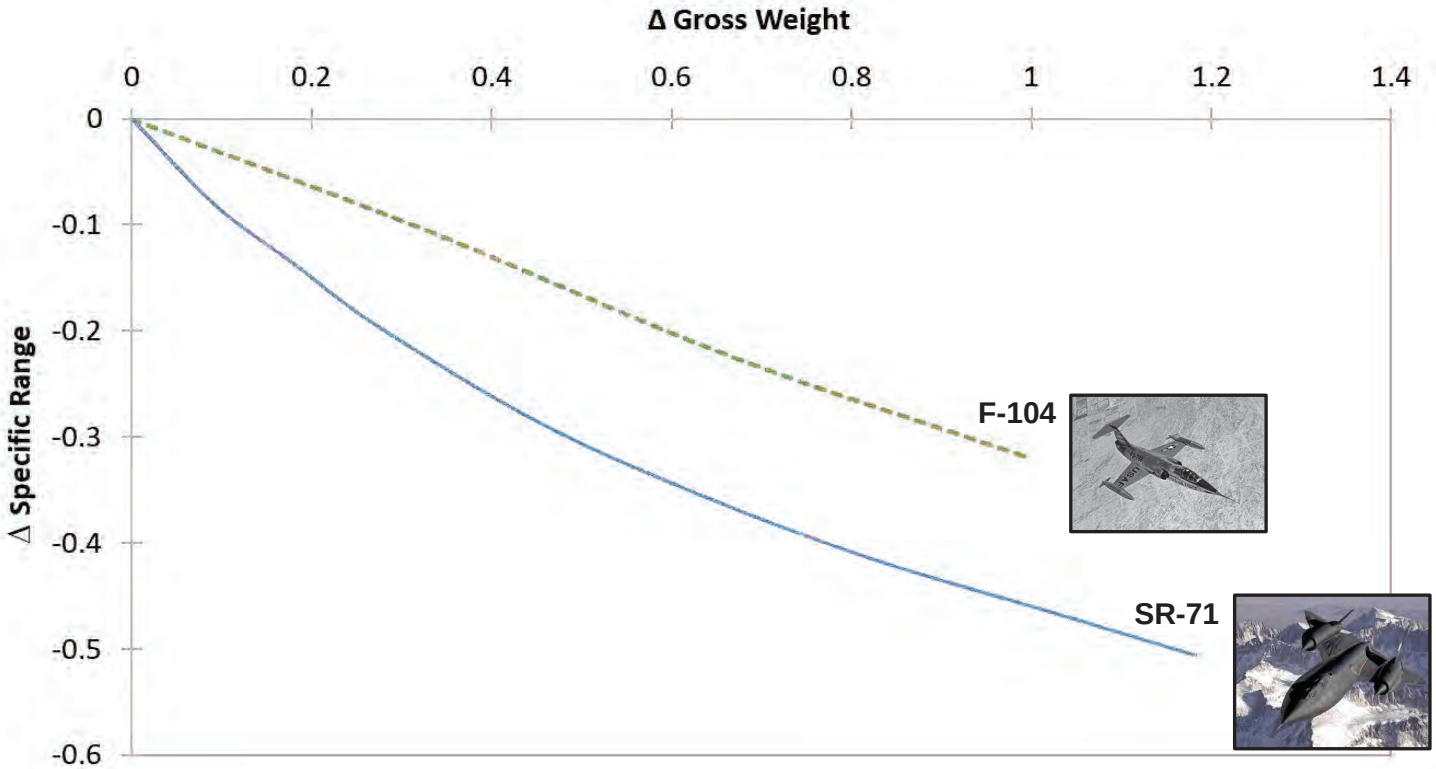
Air Vehicle Capability



Advanced vehicle capability more sensitive to system complexity

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Challenges to Address

Near term challenges

- High temperature apertures
- High temperature actuators
- Additive manufacturing

Long term challenges

- High Mach turbine engines
- High temperature seals
- Regenerative power generation

Collaboration will advance the state of the art

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Conclusion

Future air vehicle capabilities depend on increased propulsion, other vehicle discipline advancements, and understanding their interactions

Lockheed Martin is positioned to extend the capability of high-speed future aircraft

F-104

SR-71

Future Aircraft

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1943 2018

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Northrop Grumman Perspective on Vision & Propulsion-Airframe Integration Challenges of Future Air Vehicles

PAI-TIM 2018

Session 1: Vision & PAI Challenges of Future Air Vehicles

May 30, 2018

Christopher A. Harris

Inlet and Exhaust Systems Design & Analysis Manager
Northrop Grumman Corporation

Briefing Objective & Outline

NORTHROP GRUMMAN

Objective: Provide a perspective vision on future air vehicle systems requirements and the challenges levied on propulsion-airframe integration to enable those future air vehicle capabilities

Outline:

- Background & History
- Vision Systems Capabilities
- Capability Pressures on Propulsion
- Propulsion Integration Specific Challenges
- An Example Response to the Challenges
- Discussion & Questions

Northrop Grumman Products

Approved For Public Release, #18-0874; Unlimited Distribution

Rev. 041816

Autonomous Design Center of Excellence

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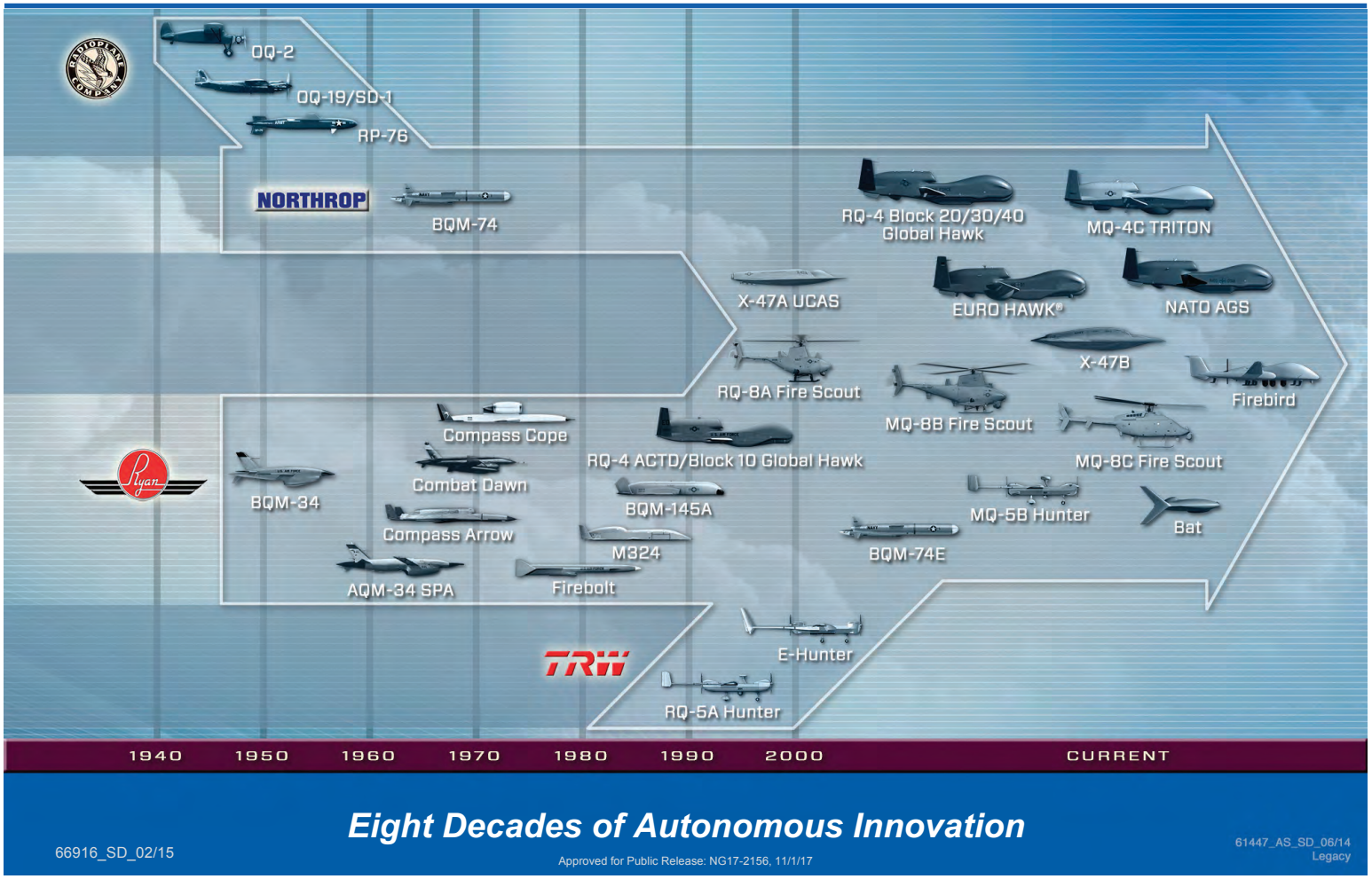
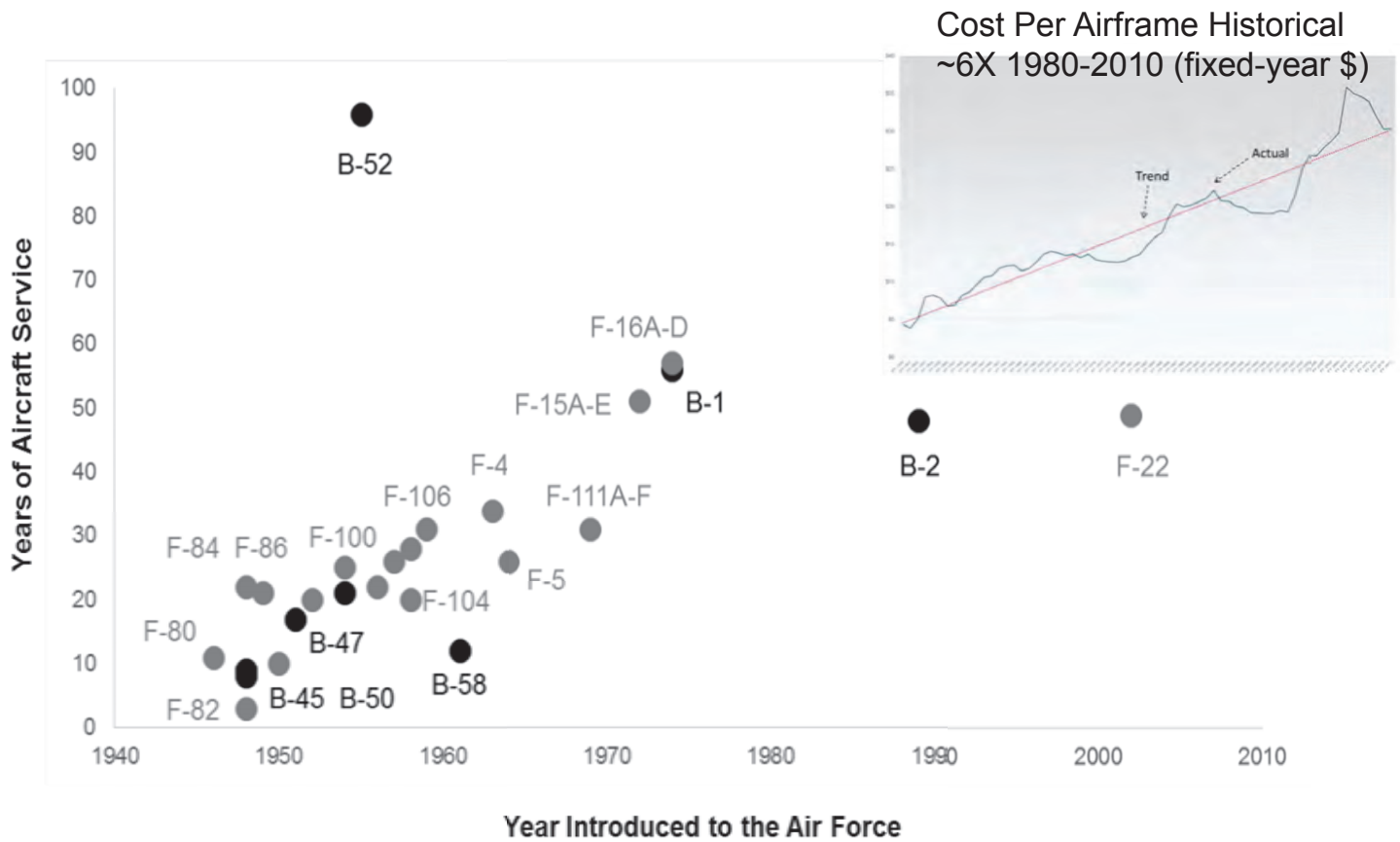
Heritage



Perspectives on Combat Aircraft Service Lives



More Capability, More Expensive, Fewer Air Combat Systems Trend

Vision for Future Systems

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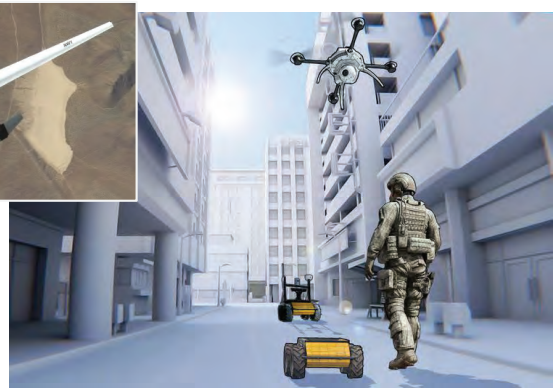
- More capable systems
  - Continue to improve mission & systems-level performance
  - Embedded propulsion will be key to most capable systems
  - More electronic systems & payloads will drive integration of power/thermal and propulsion
  - Integration of commercially developed turbines/motors

- More systems (at lower cost)
  - Smaller systems that provide some fractional capability of large UAS
  - Less sophisticated air vehicle requirements, specialized functions
  - Operate in teams or swarms of systems
  - Requires affordable airframe/propulsion



Future Advanced Military Capability Pressures that Will Impact Propulsion Integration

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How We Got to Today's Capabilities

- Thermal efficiency improvements
- Aerodynamic efficiencies (3D aero)
- Cycle optimization (Bypass Increases)
- Materials (Alloys, CMCs, Composites)
- Seals & bearings for high OPR's
- Low loss, low distortion inlets designed with heavy CFD use
- Inlet/engine compatibility testing methods
- Leveraging of commercial technology

- Higher Specific Power Generators
- Oil & Cooling Systems
- Better Power Electronics
- Better Engine Controls

- Computational Modeling
- Digitization of Testing

Today's Vehicle Level Capability Pressures

Mission Payload-Radius
Drivers: Missions and Payloads

Endurance
Drivers: Missions and Value of Assets Operating on Station

Electrical Power
Drivers: Compactness / Increasing Specific Power of Mission Systems

System Effectiveness
Drivers: Missions and Value of Assets

Future Propulsion Integration Challenges

- Thermal efficiency limitations are asymptoting (choose volume or weight)
- Military systems FPRs are diverging more from civil powerplants
- Volumetric integration of higher bypass turbines is limited by configuration
- Weight of variable systems can be high
- HALE systems need more thrust and power at altitude

- Power available reaching limits (or has) on multiple platforms
- Low spool power needs military specific
- Thermal management may need to be integrated with propulsion due to many real-world mission limitations

- Propulsion drives vehicle configurations
- Advanced configurations need to be proven and flight tested ($$$)
- Both technologies and concepts are new

Approaches that led to today's capabilities are reaching limits…

Future Vehicle Requirements: Propulsion Integration Derived Requirements

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- Greater mission radius, endurance and payload capabilities
  - Continued demand for increasing range and persistence: high inlet performance
  - Better specific range to reduce logistics fuel cost & burden: embedded low FPR fans
  - Asymptoting engine thermal efficiency: integration, propulsive efficiency ($\dot{m}$ / F)
- Greater mission-capable system requirements
  - Minimize volume integration challenges: compact inlets
  - Integration of low pressure-ratio fans: advanced inlet & fan compatibility design/test
- Support for 5X power and thermal management extraction/rejection
  - Power needs growing for VMC's, LRU's, etc., at the same time electronic mission systems are miniaturizing, increasing power density, leading to more higher-power systems that can be volumetrically integrated into aircraft: heat rejection via bypass
  - E.g., Distributed or Hybrid-Electric systems: power & thermal integration
  - Directed energy systems deployment: power & thermal integration

New mission systems and "legacy" drivers of mission radius, payload will require new approaches to develop more capable systems

NG Approach Towards Enabling Engine/Inlet Compatibility for Future Systems

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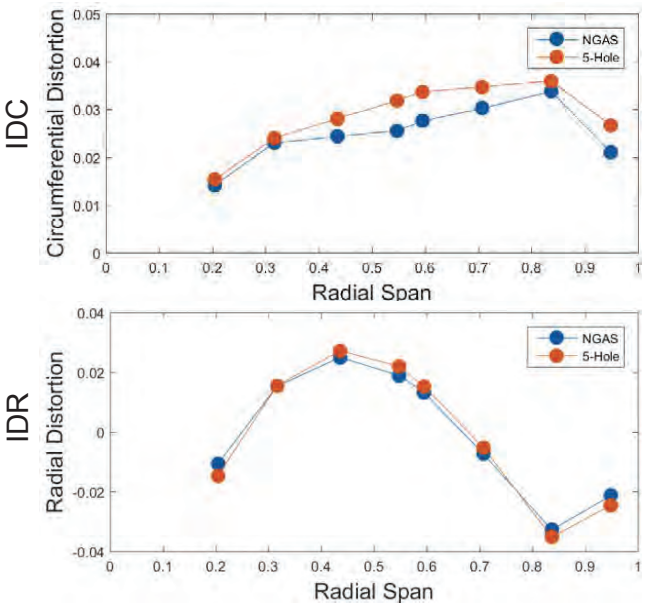
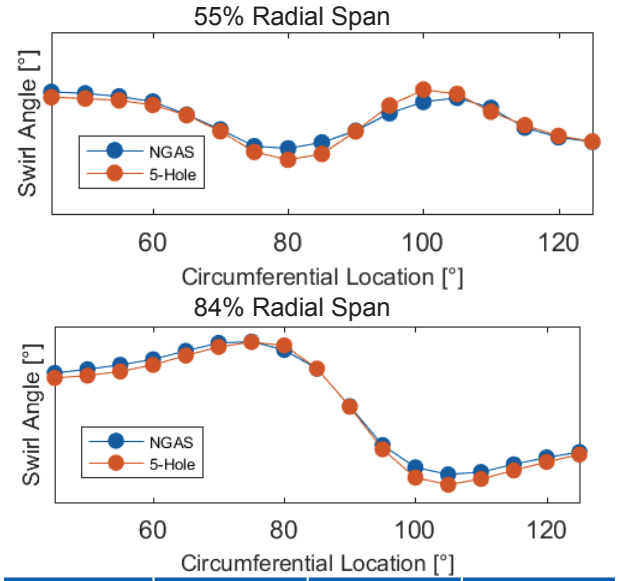
Total Pressure Distortion

- Slight under-prediction by NGAS probe for IDC
- Great agreement between NGAS and five-hole probe results for IDR



Swirl Angle and Distortion

- NGAS swirl angles closely match five-hole probe results

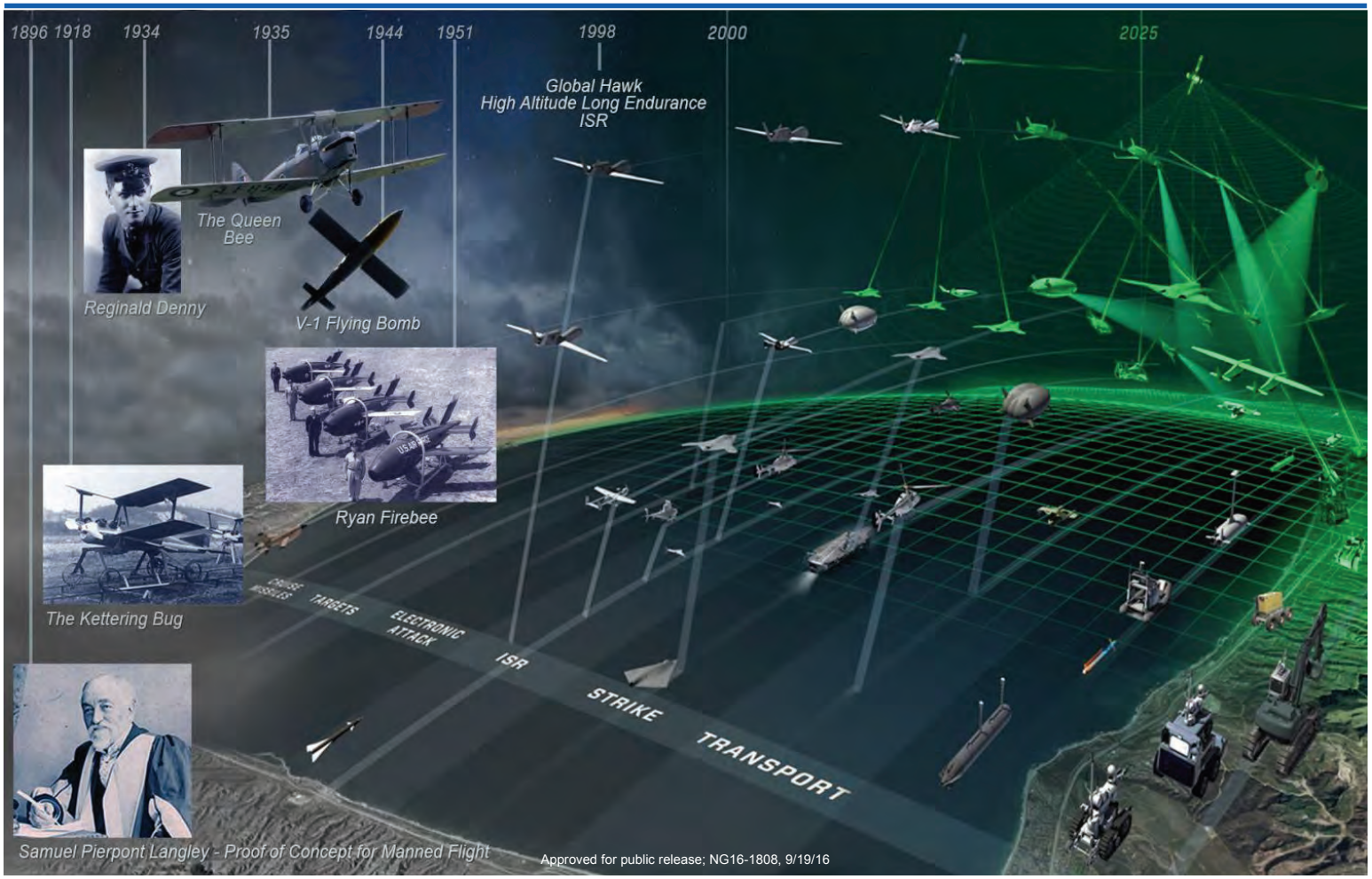


Span	ΔSI	ΔSD	ΔSP
55%	-0.105°	0.134	-0.080
84%	0.082°	0.000	0.000

NGAS compact dynamic distortion + swirl probe for use through EMD

Approved for public release; NG17-1145, 5/25/17

The Unmanned Systems Revolution…



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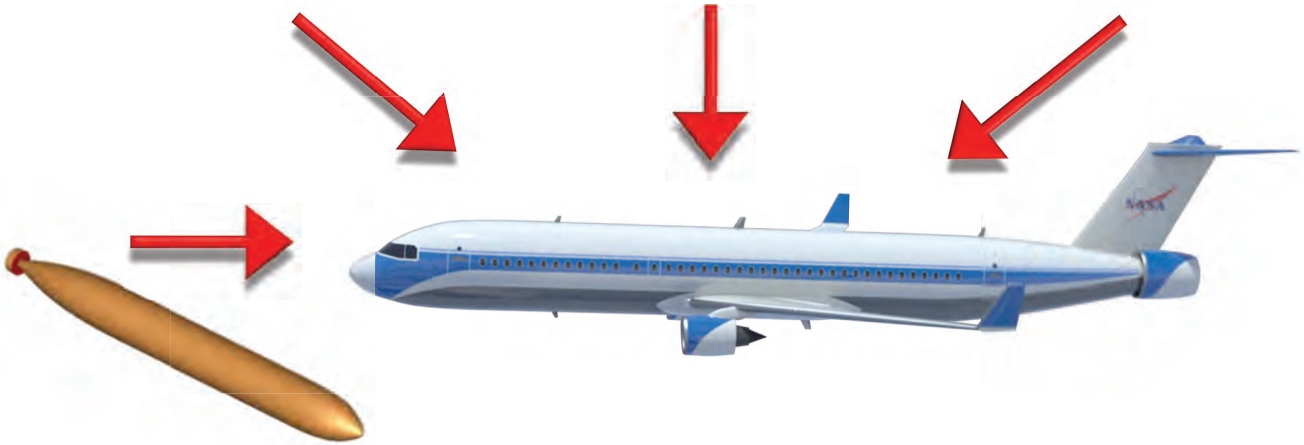
Overview of the NASA STARC-ABL (Rev. B)
Advanced Concept
Jason Welstead – PI, Aeronautics Systems Analysis
Jim Felder – Propulsion Systems Analysis
Mark Guynn – Aeronautics Systems Analysis
Bill Haller – Propulsion Systems Analysis
Mike Tong – Propulsion Systems Analysis
Scott Jones – Propulsion Systems Analysis
Justin Gray – Propulsion Systems Analysis
Irian Ordaz – Aeronautics Systems Analysis
Jesse Quinlan – Aeronautics Systems Analysis
Brian Mason – Structural Mechanics
Sydney Schnulo – Propulsion Systems Analysis
Ajit Sil – Propulsion Systems Analysis
May 30, 2018

Concept Germination

SUGAR VOLT

SUGAR Freeze

N3X



AIAA-2013-4402

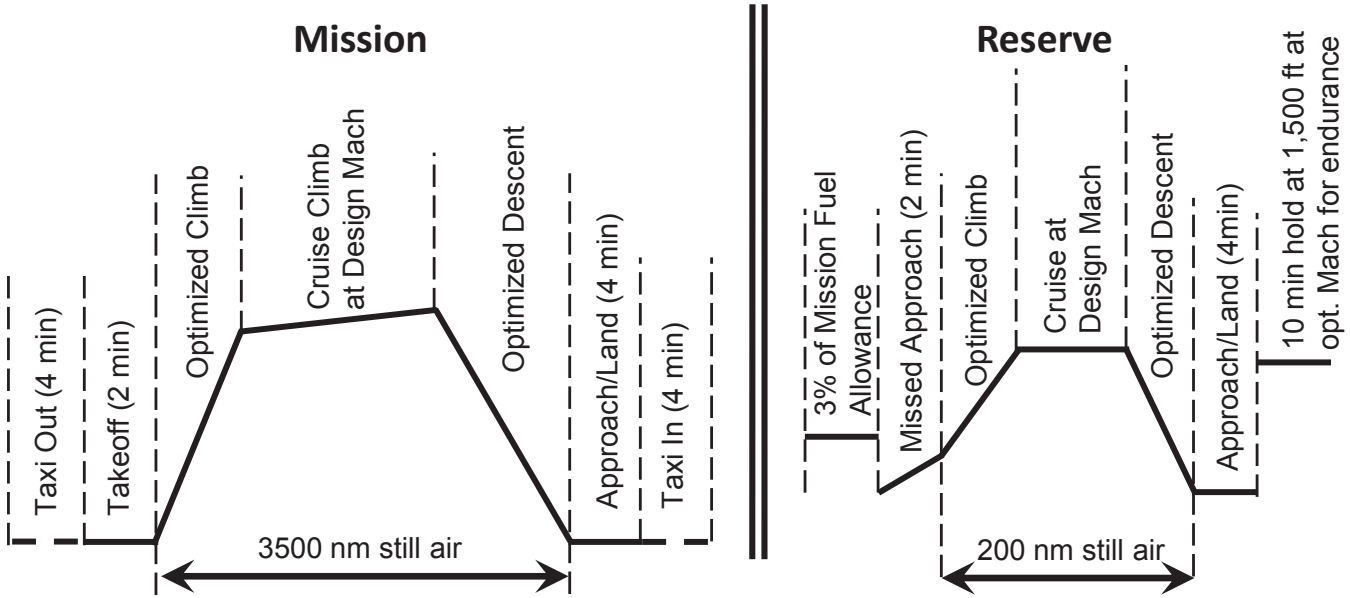
STARC-ABL Rev. B* Concept Description

- STARC-ABL: **S**ingle-aisle **T**urboelectric **A**i**RC**raft with **A**ft **B**oundary **L**ayer propulsion
  - Conventional single aisle tube-and-wing configuration
  - Twin underwing mounted N+3 geared turbofan engines with attached generators on fan shaft
  - Ducted, electrically driven, boundary layer ingesting tailcone propulsor
- Summary of changes from Rev. A to Rev. B
  - Design cruise Mach number increased from 0.7 to 0.785
  - Modified wing sweep angle to accommodate increased Mach number
  - Using NASA Glenn N+3 geared turbofan model (core limited to 2.5 lbm/sec)
  - Empirical estimates for propulsion weight replaced by WATE++ analysis
  - Improved weight estimates of thermal management system
  - Onboard voltage increased from 750 to 1000 volts
  - Underwing engine fan pressure ratio decreased from 1.45 to 1.3
  - Leveraged coupled aero-propulsive analysis for capturing BLI effects
  - Modified mission constraints to provide comparable performance to N3CC

*STARC-ABL Rev. A published in AIAA SciTech 2016 paper (AIAA-2016-1027)

Design Mission Summary

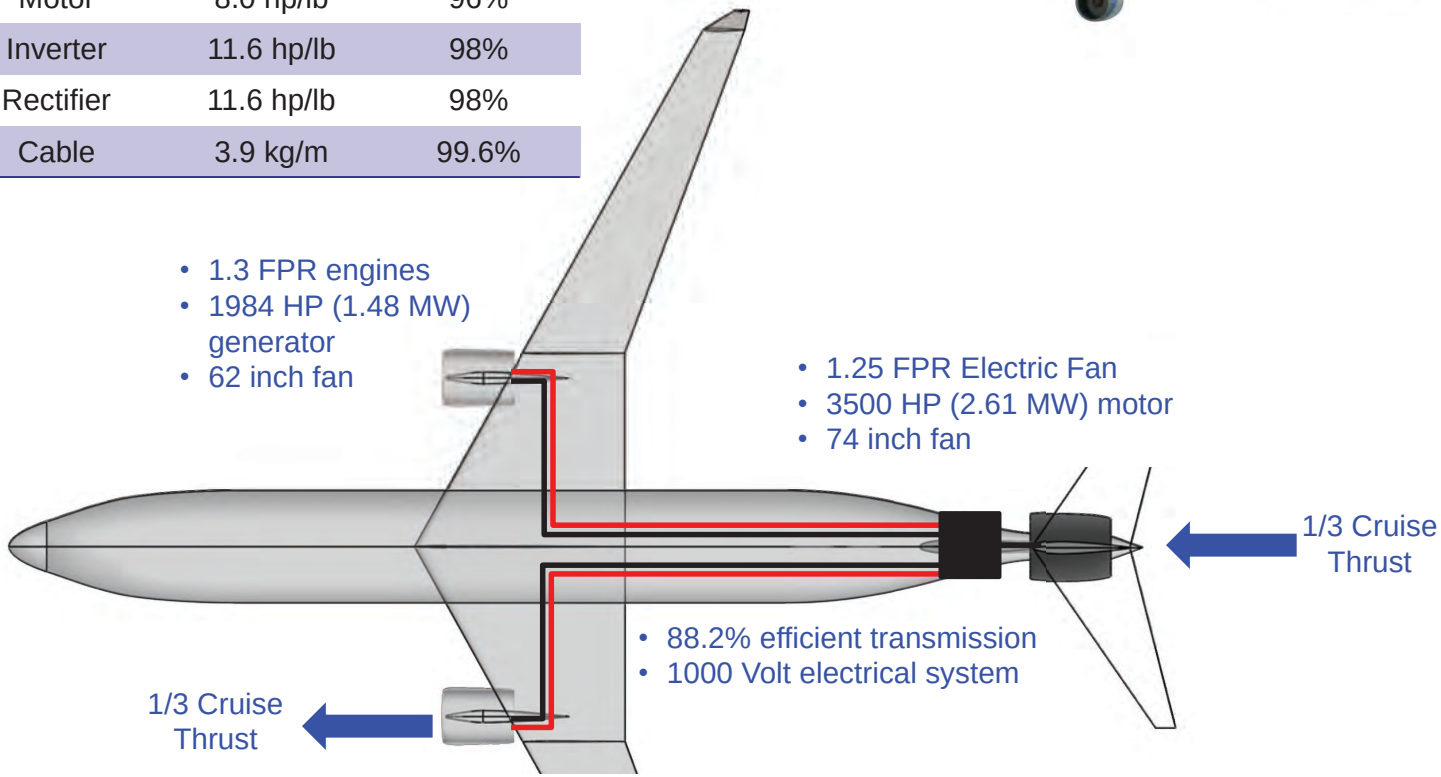
- N+3 (EIS 2035) reference mission assuming improved operations and reduced taxi time.



STARC-ABL Rev. B Power System Architecture

Electrical Component Assumptions

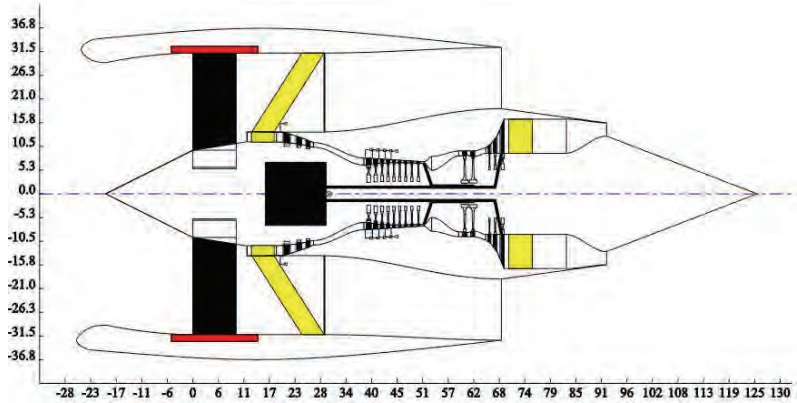
Component	Spec Pwr/Wt	Efficiency
Generator	8.0 hp/lb	96%
Motor	8.0 hp/lb	96%
Inverter	11.6 hp/lb	98%
Rectifier	11.6 hp/lb	98%
Cable	3.9 kg/m	99.6%



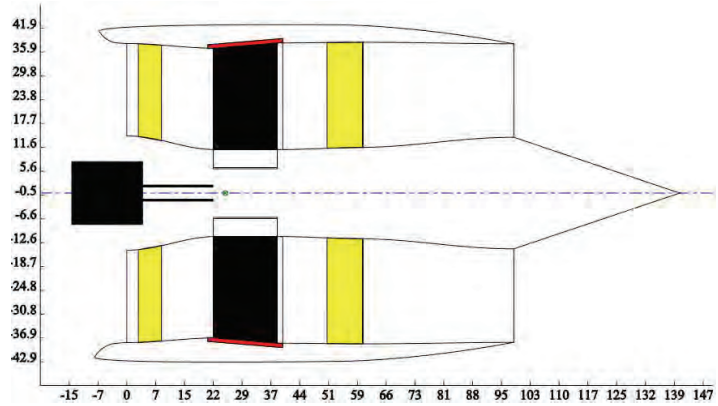
Propulsion System Concept Description

- Normal conduction (non-superconducting) electrical system
- Max 3500 HP to BLI propulsor and throttled back with underwing engines
- Underwing engine fan pressure ratio of 1.30
- Core flow limit set to 2.5 lbm/sec
- BLI propulsor fan pressure ratio of 1.25
- N+3 technology assumptions on propulsion architecture

Underwing GenFan



Tailcone Propulsor



System Performance Comparison

		STARC-ABL Rev B2.0	N3CC Rev. B2.0	Delta
Wing Area (trap)	ft^2	1130	1120	1.4%
Span	ft	118	118	Fixed
Aspect Ratio	-	12.3	12.4	-1.4%
Sweep (LE)	deg	29	29	Fixed
Wing Loading	lb/ft^2	118.7	120.5	-1.5%
Empty Weight	lb	73890	73170	1.0%
Operating Empty Weight	lb	78510	77780	0.9%
Zero Fuel Weight	lb	109310	108580	0.7%
Takeoff Gross Weight	lb	134740	134880	-0.1%
Excess Specific Power	ft/min	480	440	10.4%
Time to Climb	min	26.4	21.7	21.7%
Thrust (Sea Level Static)	lb/eng	21410	21660	-1.1%
Altitude (Start of Cruise)	ft	37280	36400	2.4%
CL (Start of Cruise)	-	0.601	0.585	2.6%
Cruise Mach Number	-	0.785	0.785	Fixed
L/D (Start of Cruise)	-	21	20.7	1.6%
Takeoff Length	ft	8190	8190	0.0%
Landing Length	ft	6050	6120	-1.1%
Approach Velocity	knots	148	149	-0.7%
TSFC (Start of Cruise)	lb/hr/lb	0.468	0.480	**-2.6%**
Design Mission BF	lb	22550	23360	**-3.4%**
Economic Mission BF	lb	6240	6410	**-2.7%**

Propulsion System Weights

- Each propulsion system sized to meeting rolling takeoff and climb thrust requirements
- Sized propulsion systems are similar in sea level static thrust

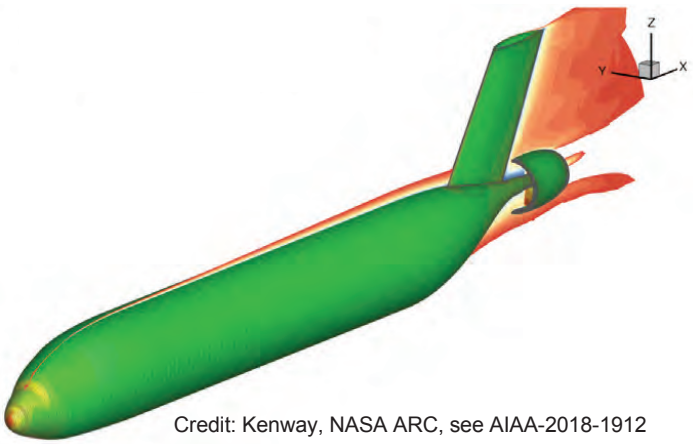
	N3CC Rev. B2.0 (43,320 lb)	STARC-ABL Rev B2.0 (42,830 lb) ← SLS Thrust
Turbofans (2)	12,010	8100
Rectifier (2)	-	330
Generator (2)	-	480
Tailcone w/ gearbox	-	1830
Electric motor	-	440
Inverter	-	300
Cable	-	440
Circuit protection	-	110
Thermal management	-	150
Nominal total	12,010 lb	12,190 lb
Installation weight	5%	5%
Sized SLS thrust	43,320 lb	42,830 lb
Engine scaling	0%	0%
Sized total	12,610 lb	12,800 lb

Quick Summary of Rev. B Results

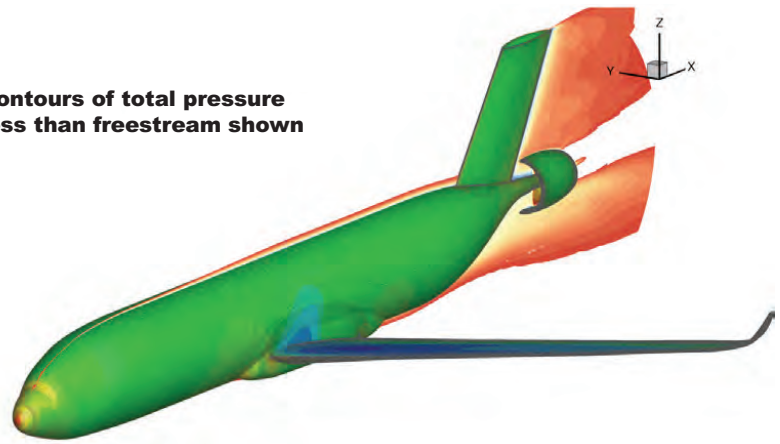
- Significant reductions in system fuel burn
  - **2.6%** reduction in start of cruise (SOC) TSFC
  - **2.7%** reduction in economic mission block fuel
  - **3.4%** reduction in design mission block fuel
  - Fuel burn reduced compared to N3CC RevB 2.0 results
- Fuselage propulsor details
  - Only a portion of the fuselage kinetic energy defect is ingested
  - BLI propulsor placed at most aft fuselage position
  - Driven by an all-electric motor with max power of 3500 HP
  - Electrical system modeled assuming ~12% total system losses
- Partially turboelectric system is not a large weight penalty
  - Downsizing of underwing engines enabled by turboelectric offsets the weight addition of electrical components and tailcone propulsor
- Cable size/weight can become prohibitive if onboard voltage too low
- Electric system specific power based upon current AATT NRA efforts

Observed Trends

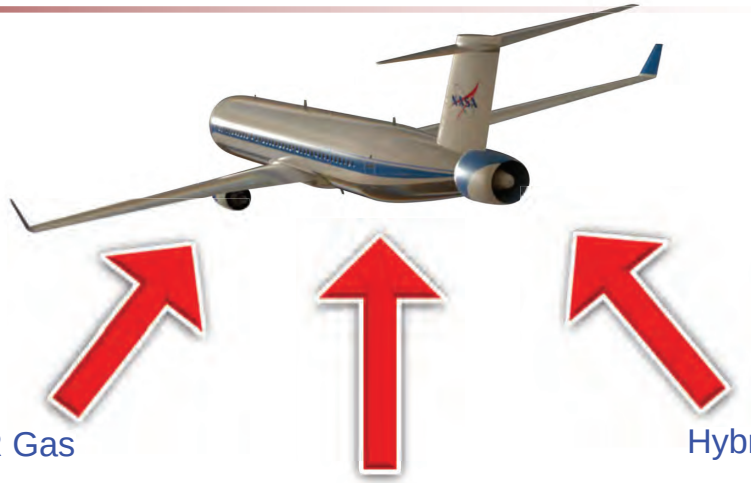
- Eliminating electrical transmission losses results in ~4% fuel burn improvement
- STARC-ABL benefits a function of underwing turbofan technology
  - As the underwing engine efficiency improves the benefits of distribution decrease due to dominating transmission losses
  - STARC-ABL fuel burn benefits grow if N+3 engine technology assumptions are too aggressive
- Wing circulation has significant impact on amount of ingested fuselage boundary layer



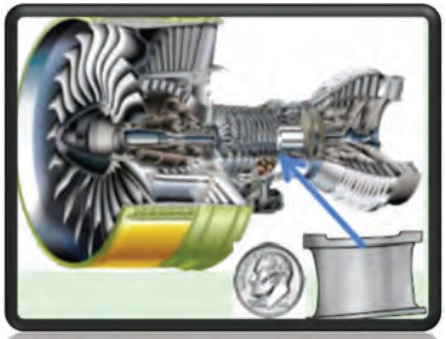
Credit: Kenway, NASA ARC, see AIAA-2018-1912



Related AATT Investments on Enabling Technologies for STARC-ABL

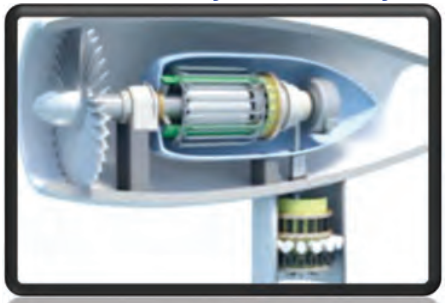


Compact High OPR Gas Generator
SPM: Jim Walker



Unconventional PAI (Tailcone Thruster)
SPM: Chris Hughes

Hybrid Gas-Electric Propulsion
SPM: Amy Jankovsky



Summary of Current and Near Term AATT Research Efforts

SA&I Concept Study and Trades	• Continued systems analysis of STARC-ABL Concept (Rev. B) o Improved propulsion system weight modeling o Increased design cruise Mach to 0.785 o Better estimate of TMS requirements and weights o Higher order analysis (CFD, FEA, etc.) • Analysis of a Single-aisle non-electric distributed propulsion concept o Turbine powered tailcone thruster o Explore the question, “What does electric give you?”
UPAI Tailcone Thruster Task	• Wind tunnel model design for transonic wind tunnel test o Obtain data for benchmarking computational tools for BLI analysis o Quantify the BLI effect from a tailcone propulsor o Investigate impact of propulsor on aft fuselage flow o Inform advanced concept system studies with BLI • Target test date for powered model is currently FY20 • A series of risk reduction tests are being explored in support of the powered test

Questions?

D8 CFD Overview: An Aerodynamics Study of Boundary Layer Ingestion Benefit
+
Overview of Tail Cone Thruster WT Test

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Arthur Huang, MIT, and Alejandra Uranga, USC

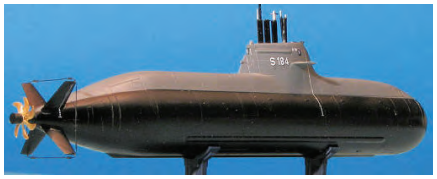
TCT Presentation adapted from Jason Welstead

PAI-TIM, NASA GRC, May 30-31, 2018

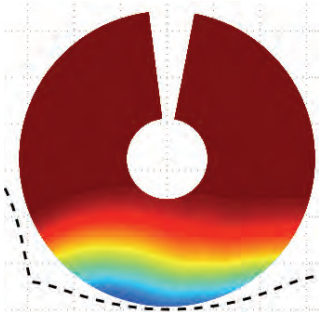
Outline

- Introduction
- CFD Model and validation
- BLI Benefit Computation: Power (P_k)
- BLI Benefit Computation: Dissipation (Φ)
- TCT WT test overview

BLI configurations

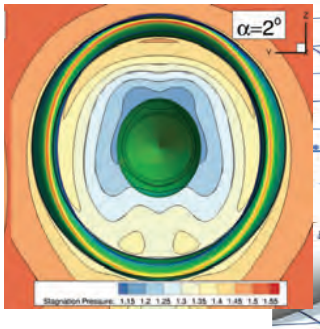


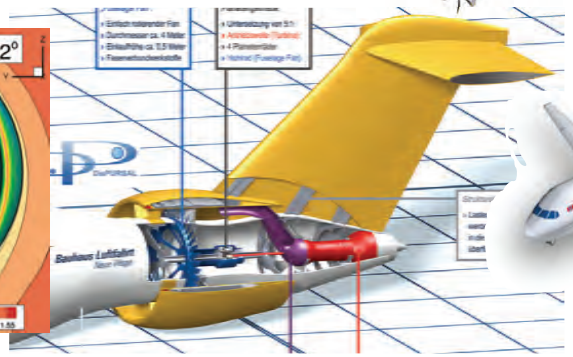
- Type 1 (circumferential distortion)



ESAero Proprietary – ECO-80 Concept

- Type 2 (radial distortion)

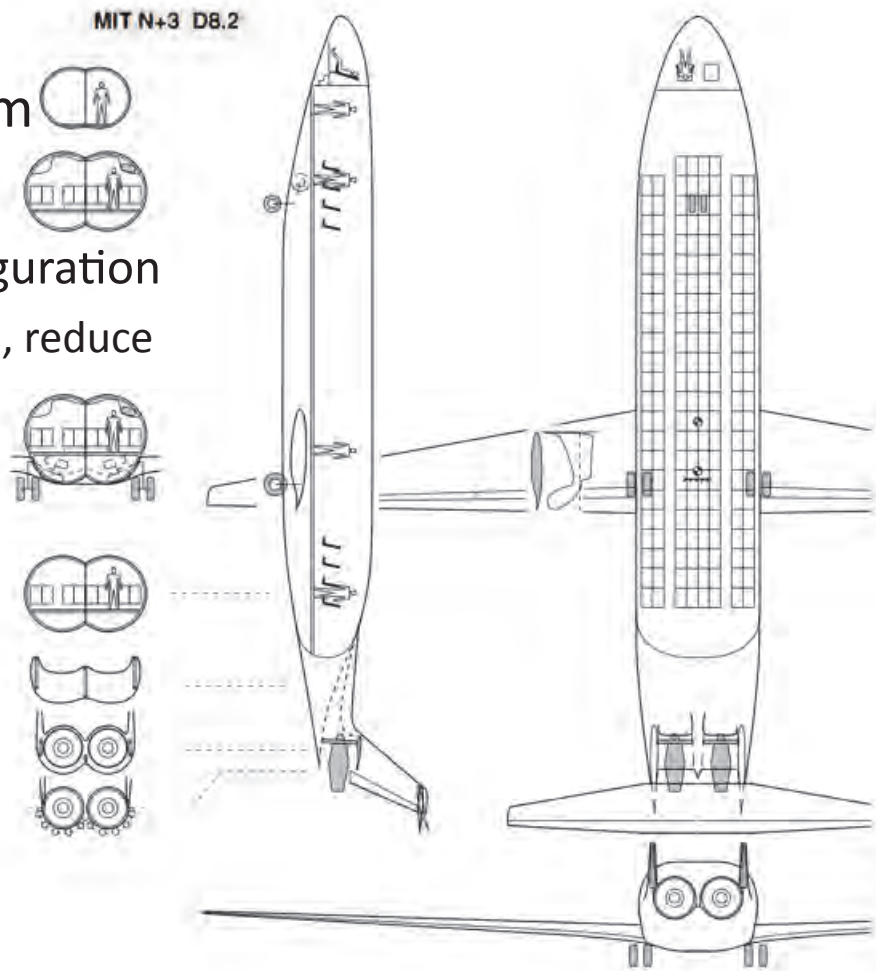




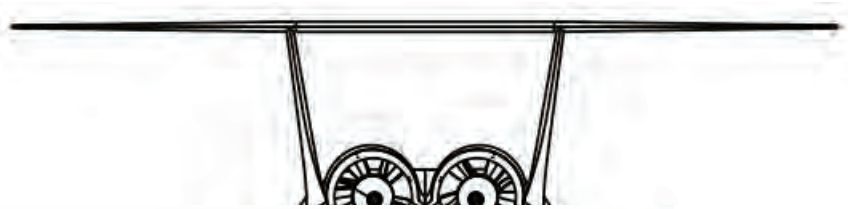
https://www.bauhaus-luftfahrt.net/de/topthema/propulsive-fuselage/

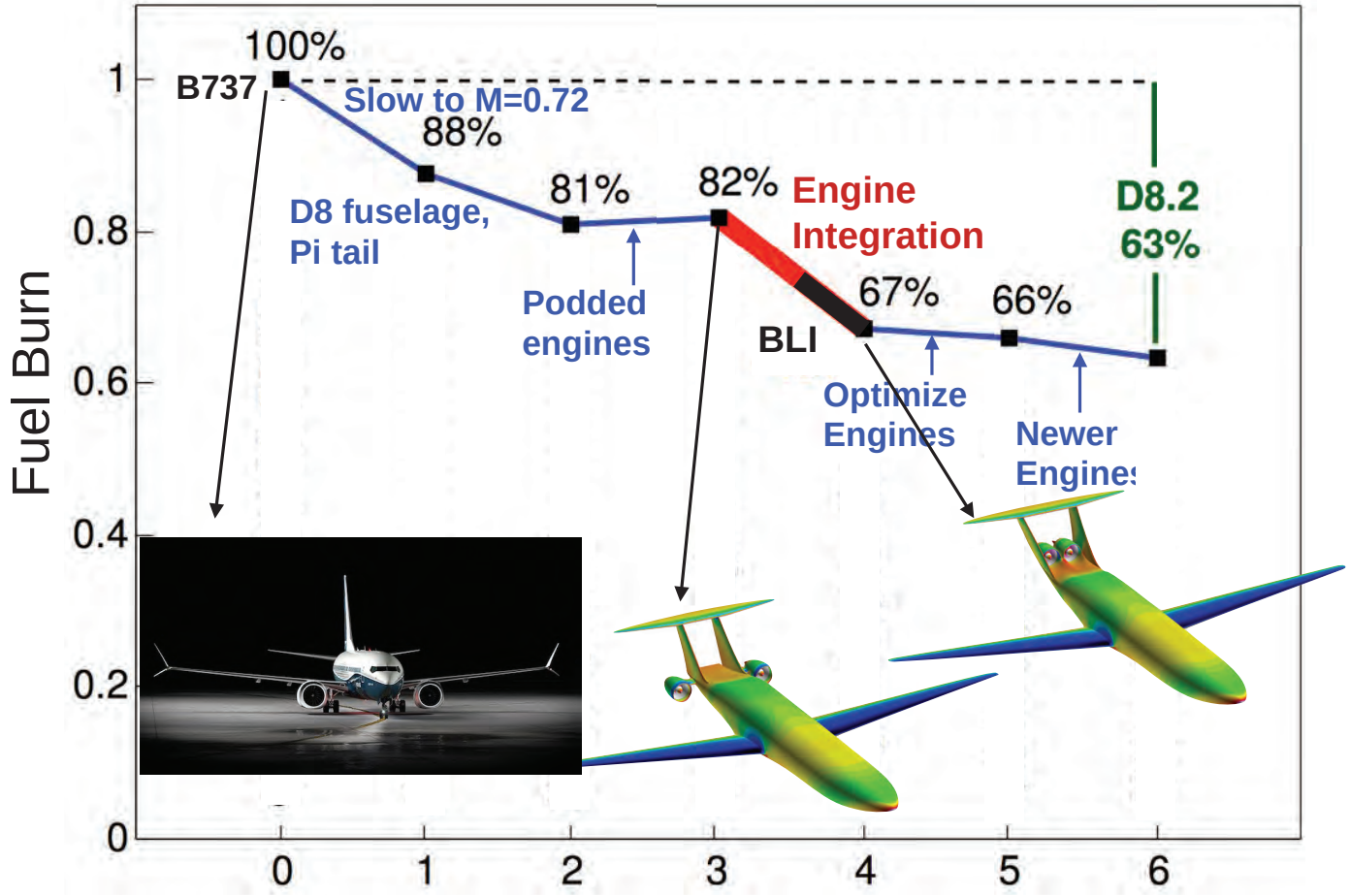
The D8 Aircraft Concept

- Fundamental Aero program
  - Fixed-wing
  - N+3 advanced vehicle configuration
    - Lower fuel burn, lower noise, reduce emissions
- 180 passengers
- 3000 nmi range
- 118 ft span
- Boeing 737/A320 class
- Lifting fuselage, pi-tail
- Flush-mounted engines



B737—>D8
Our Focus: BLI





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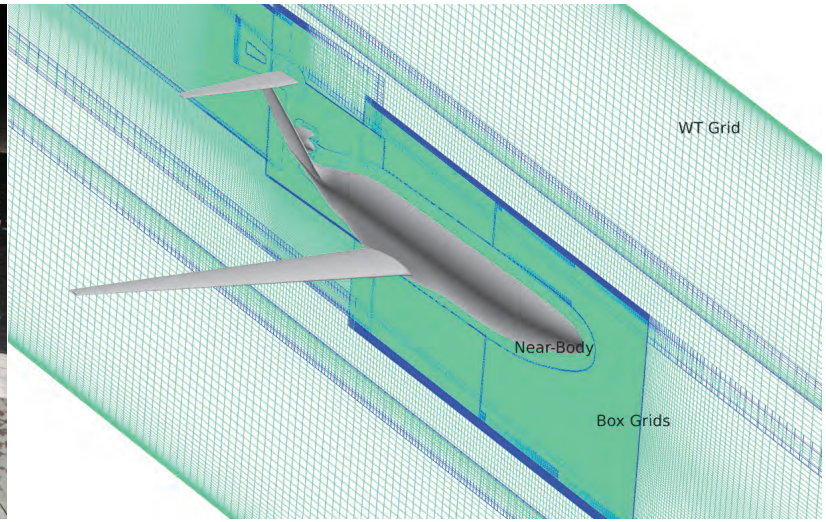
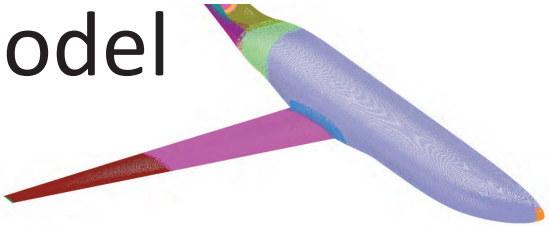
D8 Model

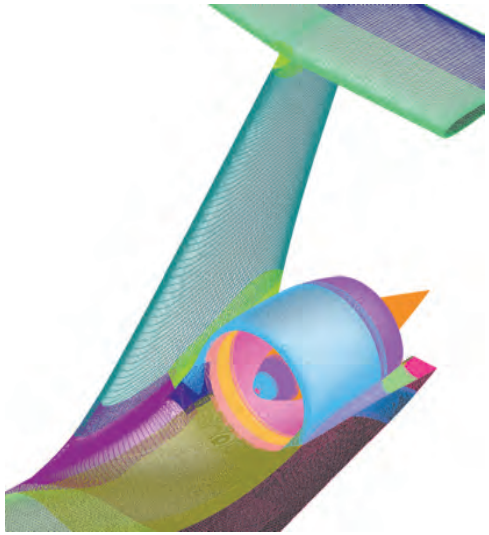


Blue indicates regions of overlap

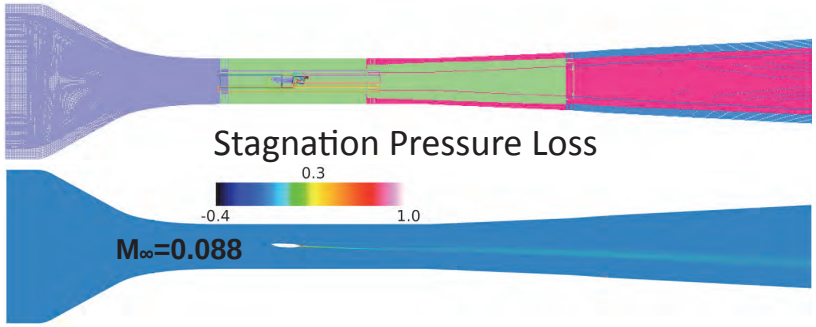
- Larc 14x22 WT model
  - 1:11 scale, Full body
  - Mounting hardware controls AoA
- Computational model
  - 1:11 scale, Half body
  - No mounting hardware
  - Inviscid wind tunnel walls

Computational Model





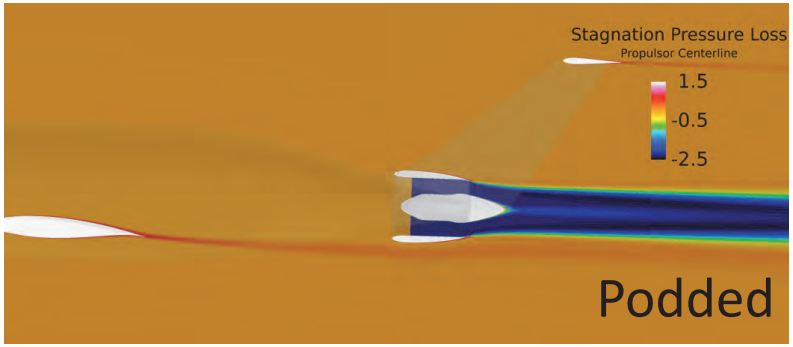
- Chimera Grid Tools
  - Overset surface and volume mesh
    - Same grids for forward fuselage, wing, and WT
  - Unpowered: 36 grids, 113 Million points
  - Podded: 49 grids, 130 Million points
  - Integrated: 64 grids, 135 Million points
- OVERFLOW-2 solver
  - Mach=0.088
  - Re = 44000/in.
  - y+ ≈ 0.7

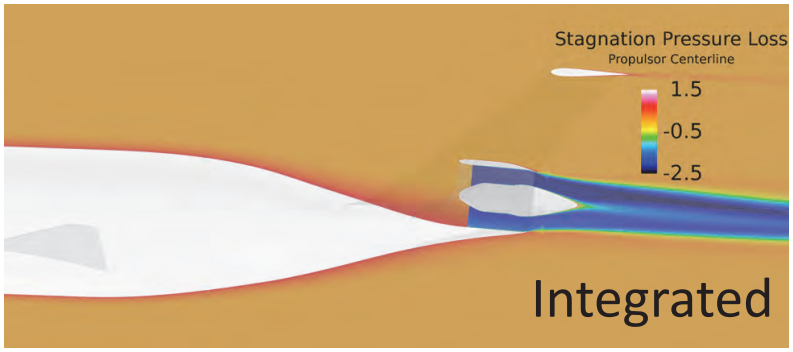


- Inviscid WT wall boundary conditions
- 7 grids (4 wall grids, 3 core grids) + box grids
- Mach and Re number matched at pitot probe

Fan Model and its Effect

- Actuator disk
  - –Uniform pressure jump
- Four cases with increasing pressure jump settings
  - For both podded and integrated
  - Integrated sees a lower mass flow

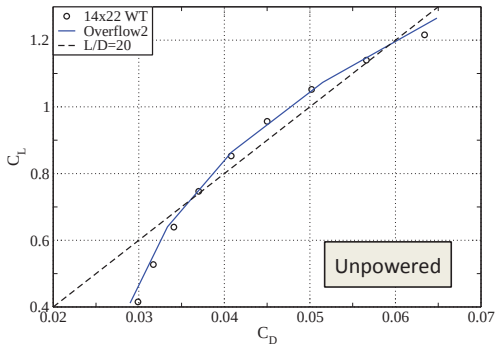




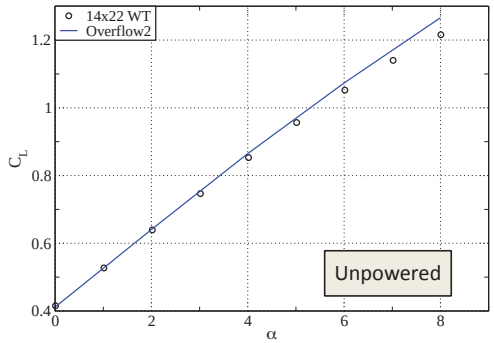
Cut through center of propulsor shown.

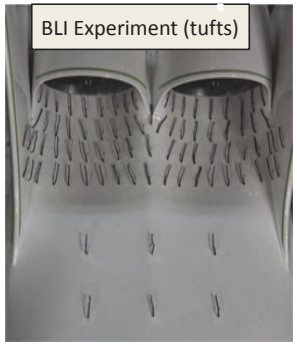
CFD Simulations

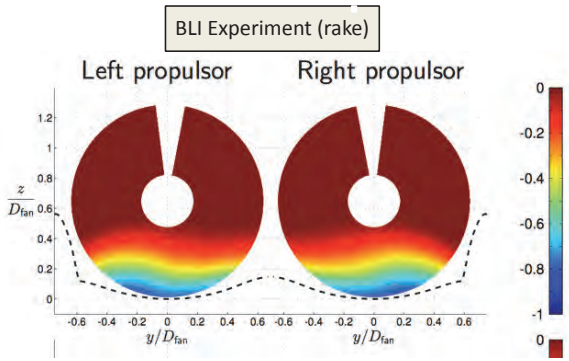
CFD Validation

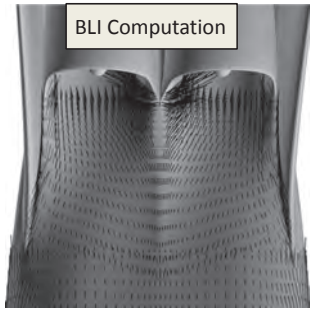


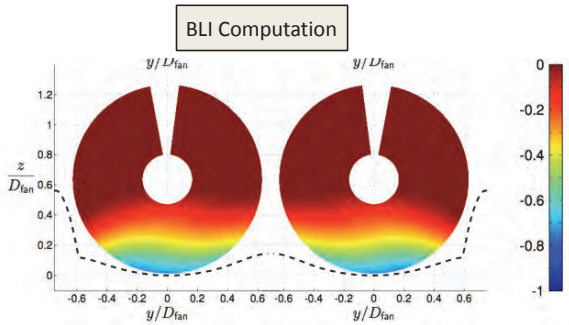
$\alpha = 2°$
$V_\infty = 70$ mph



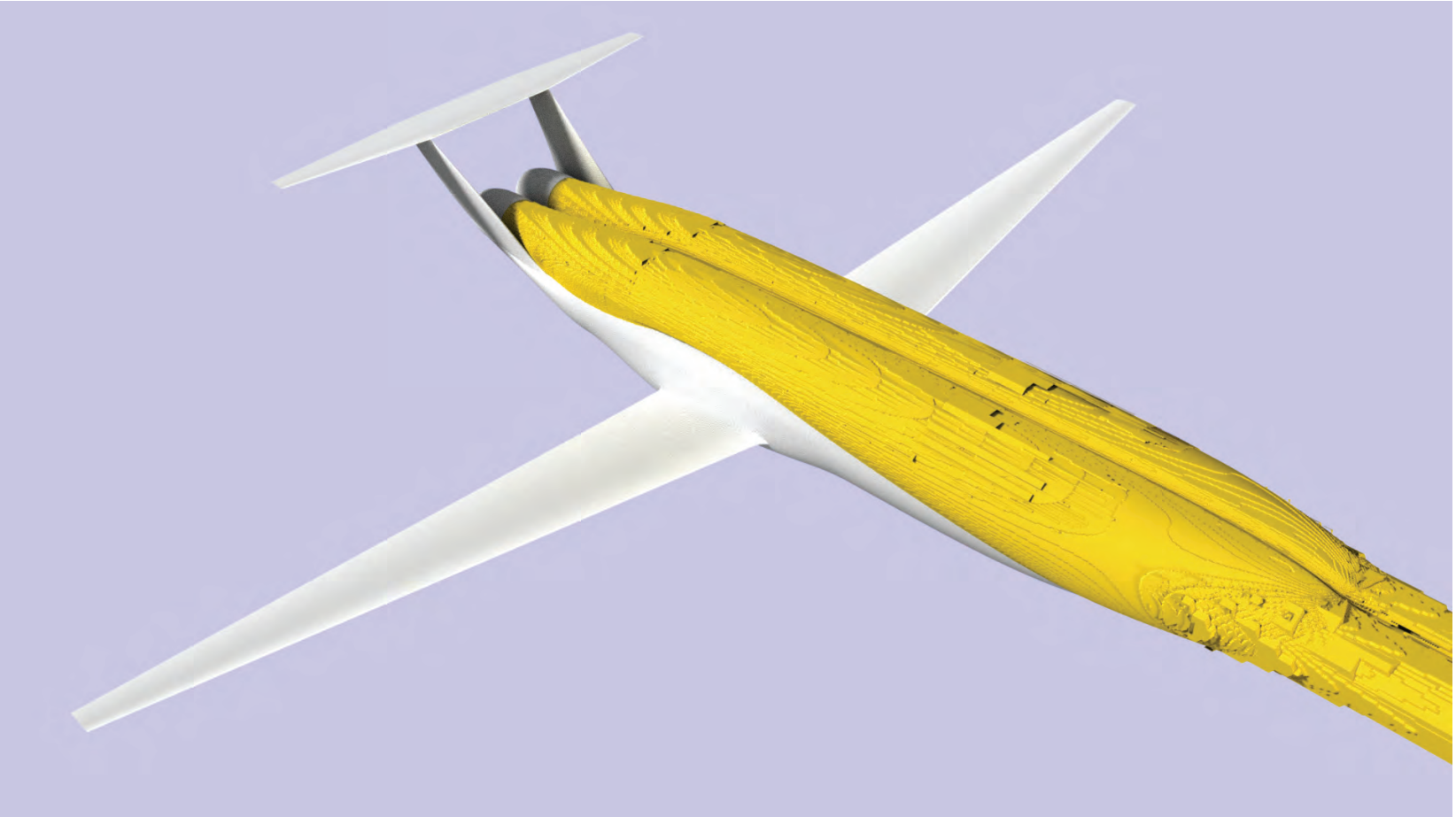








Streamtube



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- Drela, “PowerBalance in Aerodynamic Flows”, AIAA J., July 2009
- Pejian, et. al., “Performance Analysis of Wake and Boundary-Layer Ingestion for Aircraft Design”, AIAA J., V.54
- Hall, et. al. “Boundary Layer Ingestion Benefit for Transport Aircraft”, J. Propulsion and Power, v.33, No.5

BLI Benefit

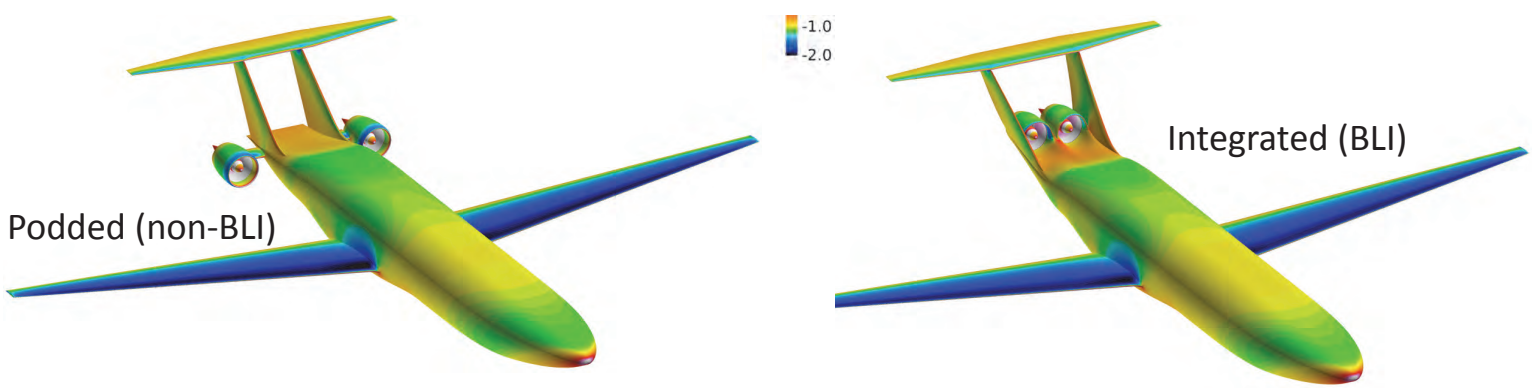
- Compare mechanical flow power:

$$P_K = \oint_{propulsor} (p_{t,\infty} - p_t)\,(\mathbf{V}\cdot\hat{\mathbf{n}})\,\mathrm{d}A\ .$$

  –Power transmitted by propulsor to the flow

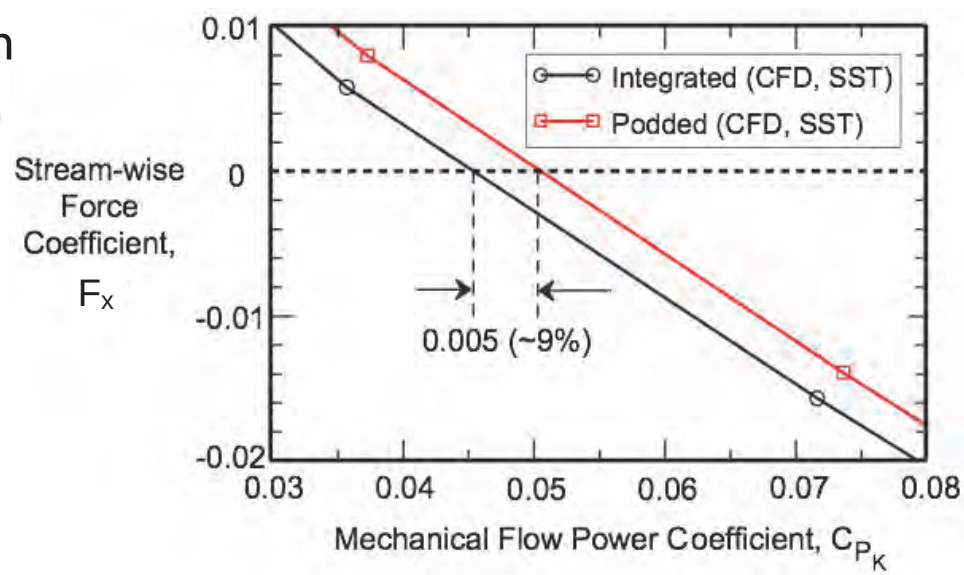
- Savings in power required: integrated vs. podded

$$\text{BLI benefit} \equiv \left.\frac{P_{K_{\text{non-BLI}}} - P_{K_{\text{BLI}}}}{P_{K_{\text{non-BLI}}}}\right|_{\text{at given } F_X}$$



Assessing BLI Benefit

- Plot axial force(F_x) vs. mechanical flow power (P_k)
  - Streamwise net axial force: pressure and viscous force.
    - On airframe solid surfaces + actuator disk
- Compare podded and integrated configs
  - At cruise condition
    - Net axial force = 0



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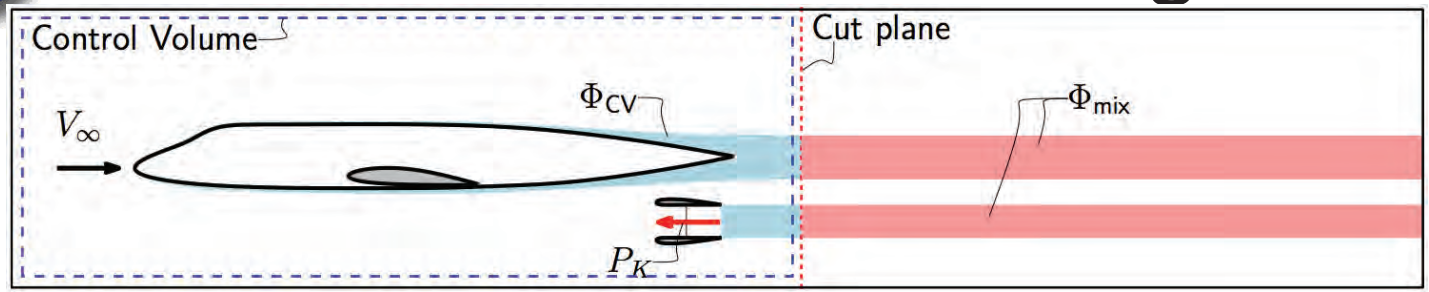
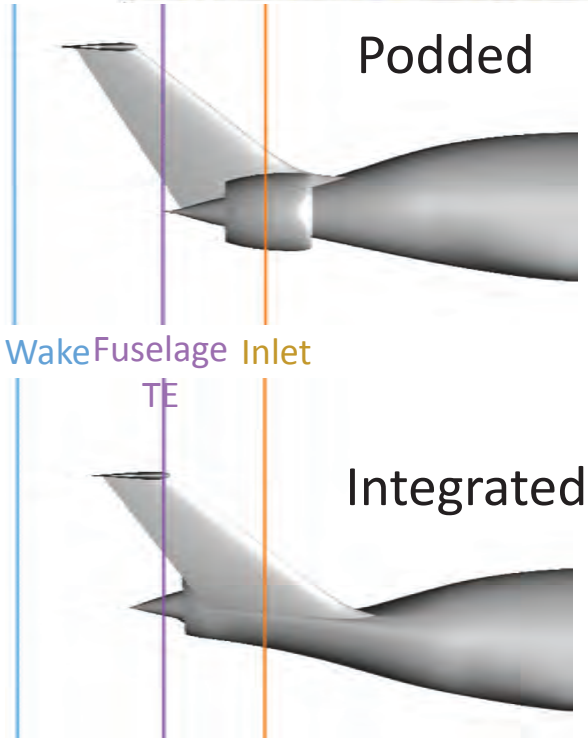
Where is the Benefit Coming From?





- Sources and sinks of power

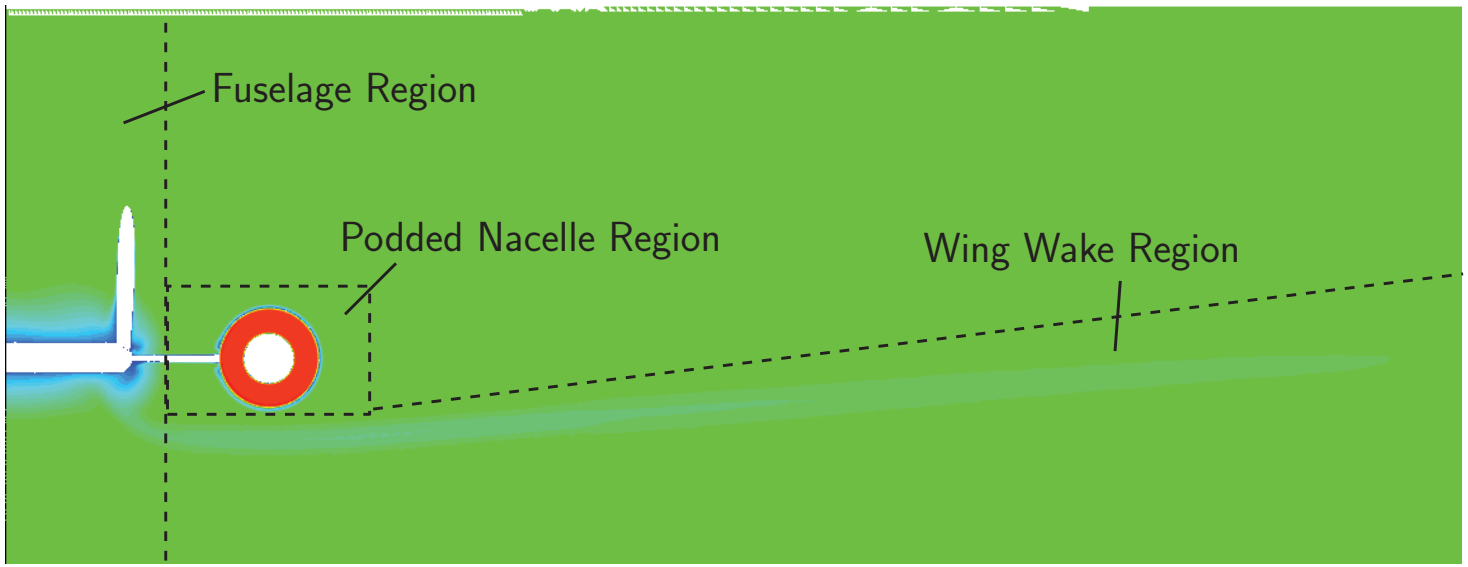
$$P_K + P_V = \Phi + \dot{E} - F_X V_\infty$$

  - Pv=0 for incompressible flow
  - Fx=0 at cruise

$$\Phi = \Phi_{CV} + \Phi_{\mathrm{mix}} = \left(P_K - \dot{\mathcal{E}}\right) + \Phi_{\mathrm{mix}}$$

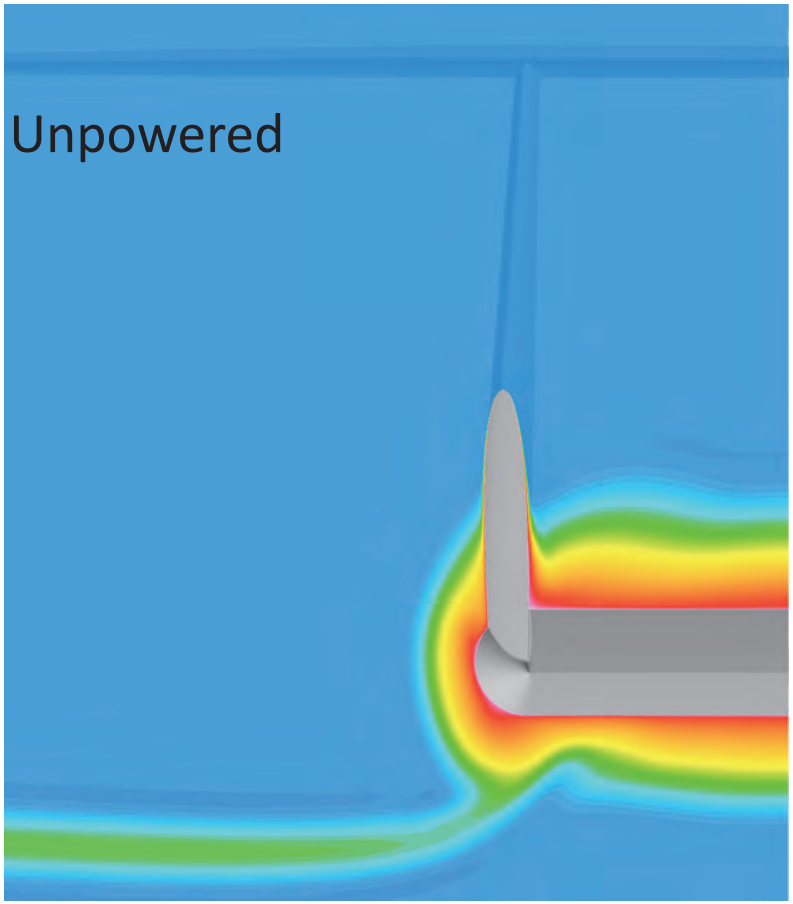
  - Upstream viscous dissipation
    - measured by stagnation pressure flux
    - We can focus on stagnation pressure loss and dissipation

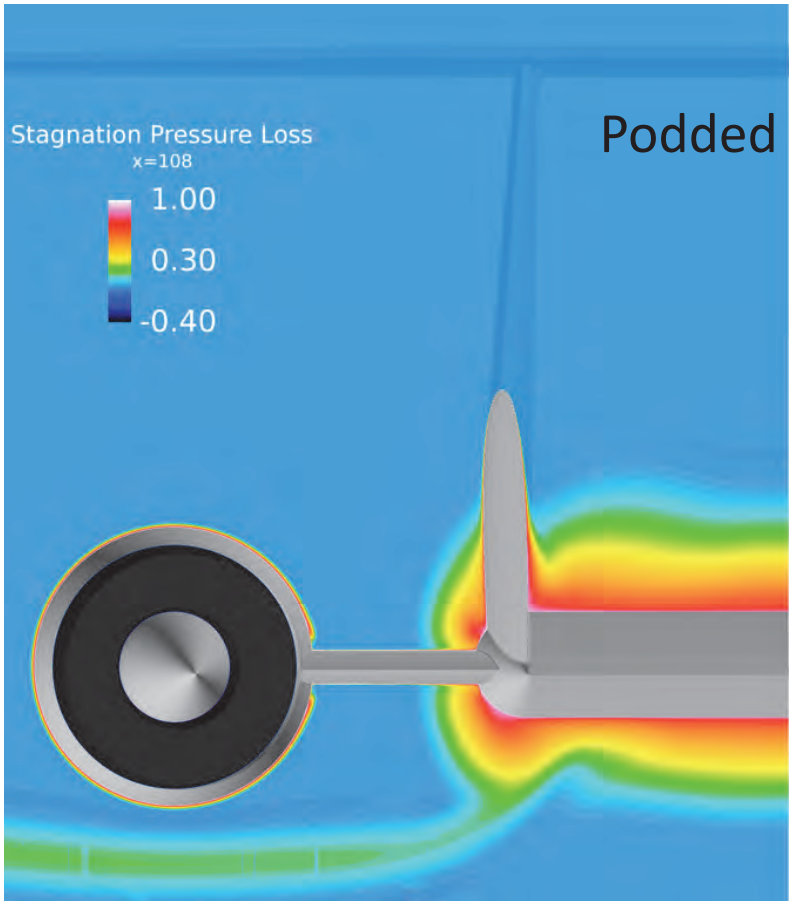
Dissipation Computation



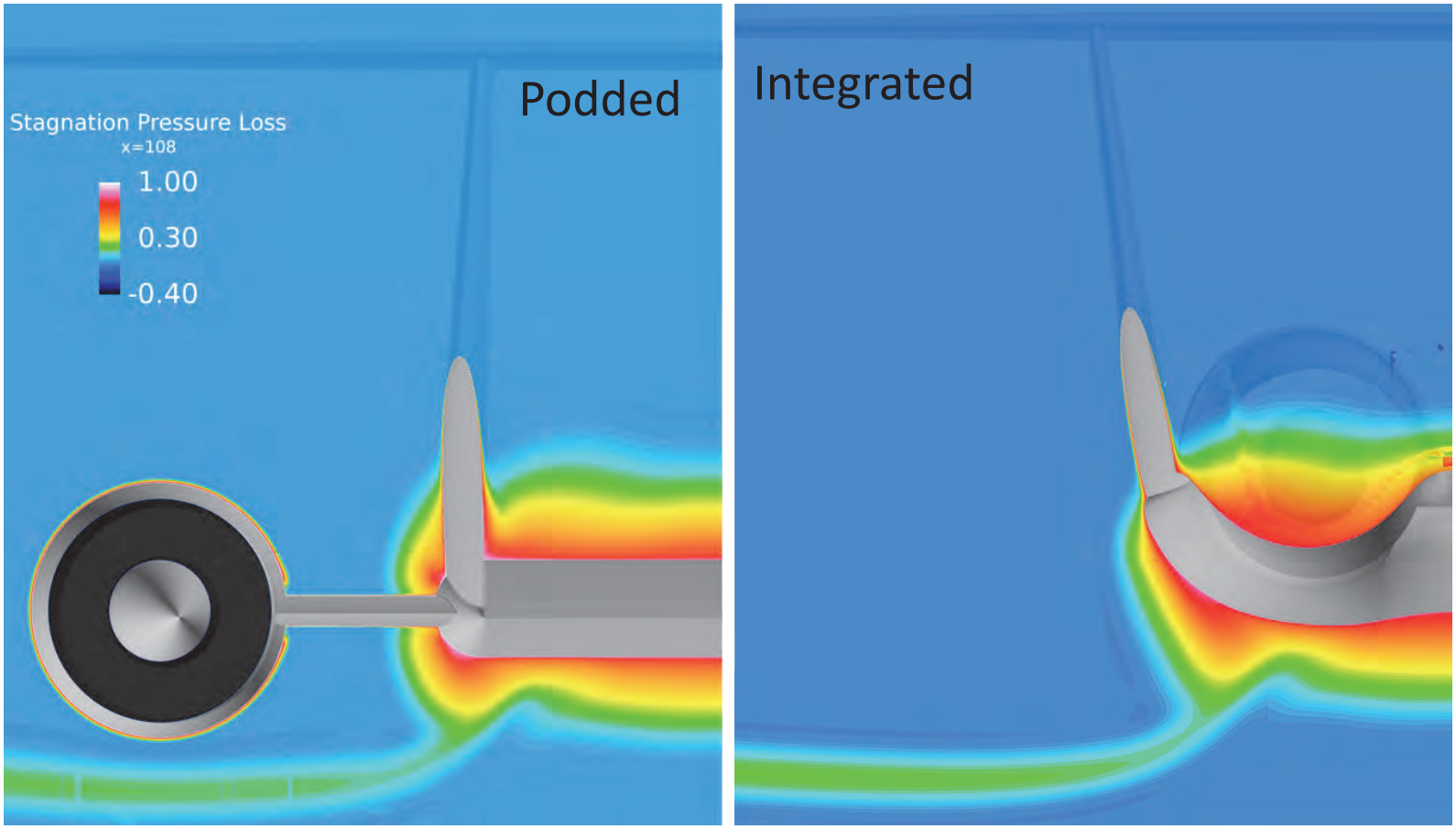
- Dissipation coefficient: $\zeta = \dfrac{\Phi}{q_\infty S V_\infty}$
  - computed in each region
  - No separate nacelle for integrated config

Inlet


Unpowered


Stagnation Pressure Loss
x=108
1.00
0.30
-0.40
Podded

Inlet (cont.)

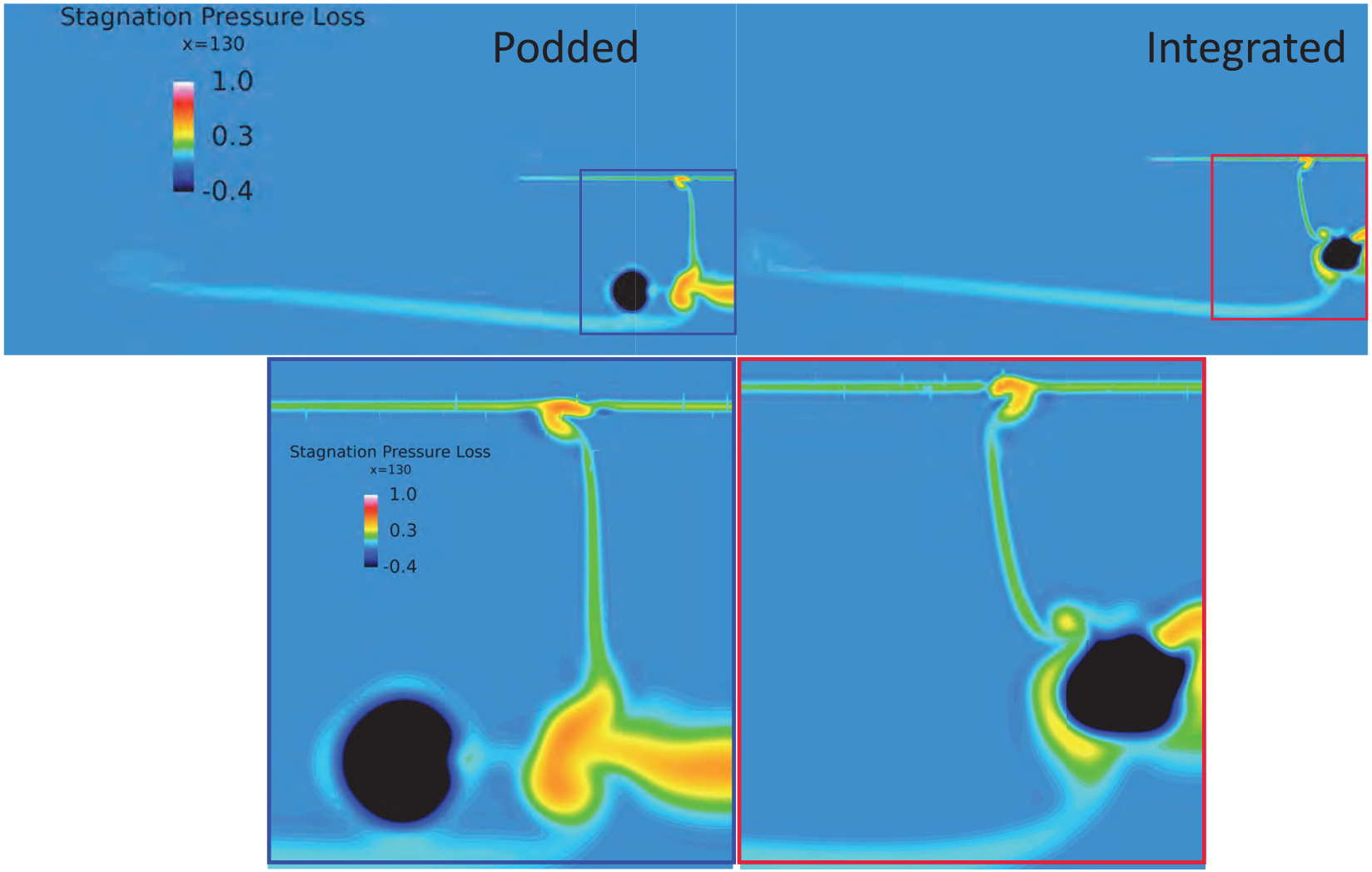

Podded
Stagnation Pressure Loss
x=108
1.00
0.30
-0.40
Integrated

Dissipation at Inlet

	Total	Fuselage	Wing	Nacelle
Unpowered	0.02148	0.01067 (50%)	0.01080 (50%)	0
Podded	0.02425	0.01071 (44%)	0.01132 (47%)	0.0022 (1%)
Integrated	0.02241	0.01129 (50%)	0.01112 (50%)	0
Variation	0.00228	0.00062	0.00052	0.0022

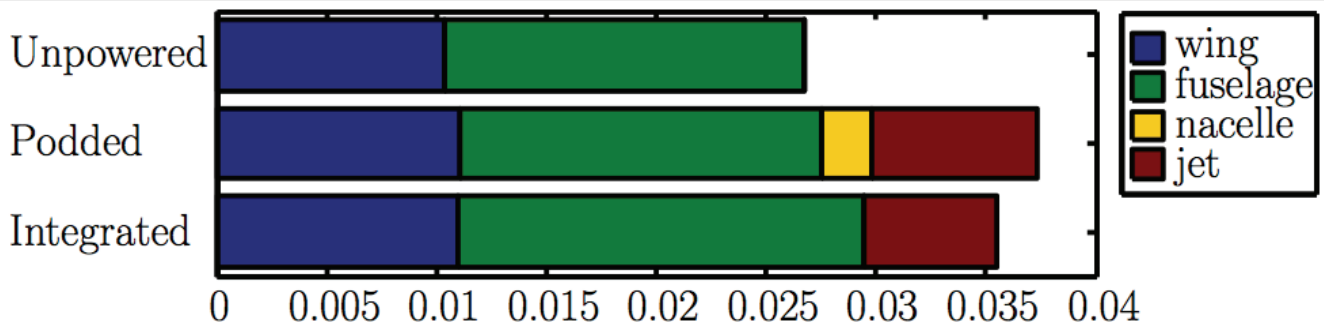
- Minor variations in fuselage and wing regions.
- Only major difference due to presence of podded nacelle.

Wake


Stagnation Pressure Loss
x=130
1.0
0.3
-0.4
Podded
Integrated
Stagnation Pressure Loss
x=130
1.0
0.3
-0.4

Dissipation in the Wake

	Total	ζ_{fuse}	$\zeta_{nacelle}$	ζ_{jet}	ζ_{wing}
Unpowered	0.0240	0.0129 (54%)	0	0	0.0111 (46%)
Podded	0.0345	0.0129 (38%)	0.0025 (7%)	0.00760 (22%)	0.0115 (33%)
Integrated	0.0325	0.0149 (46%)	0	0.00603 (19%)	0.0115 (35%)

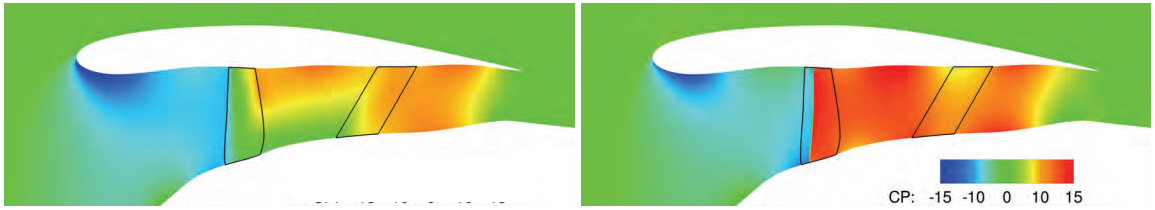


- Wing dissipation not affected by BLI
- Integrated config. has 6% less overall dissipation
  - 3/4 from lower jet velocity
  - 1/4 from lower fuselage/nacelle dissipation

Body Force Model: SDT fan results

Body force | Uniform pressure jump

Static Pressure



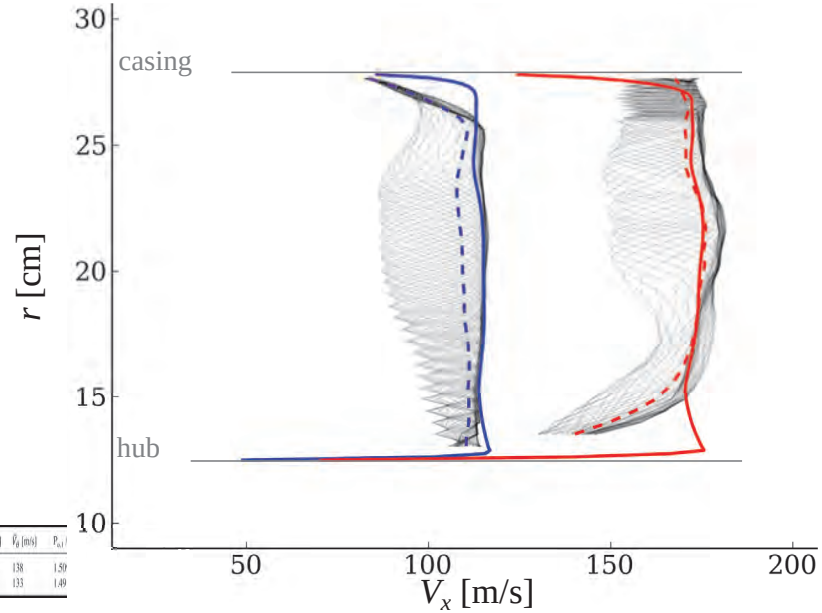
Rotor wake survey:

7,808 rpm 12,657 rpm

Experiment (phase-avg.)

Experiment (mean of phase-avg.)

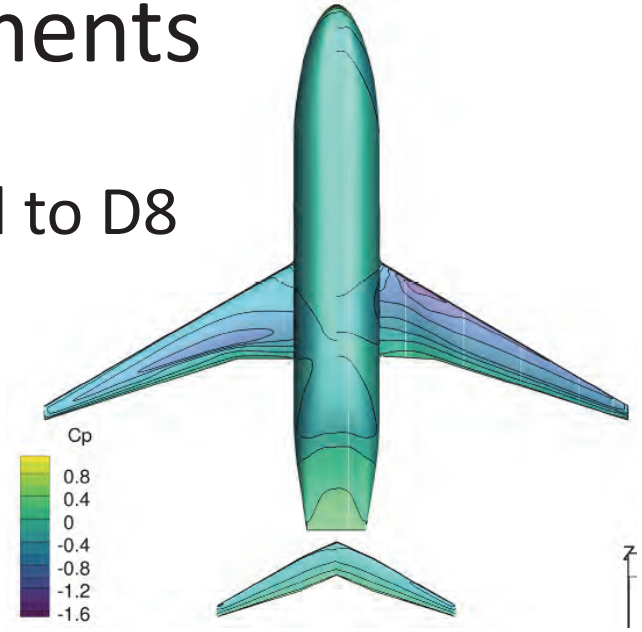
Simulation (body force model)



at 12,657 rpm	$\bar{V}_x$ [m/s]	$\bar{V}_\theta$ [m/s]	$P_{t,1}/P_{t,0}$
Experiment	171	138	1.509
Body Force Model	172	133	1.491

Improvements

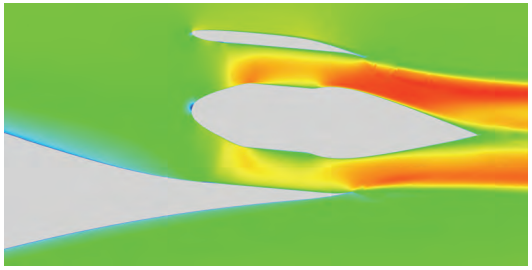
- Apply Body force fan model to D8
  - Reassess BLI benefit
- Design a transonic D8
  - Aurora/In-house
  - Reassess BLI benefit



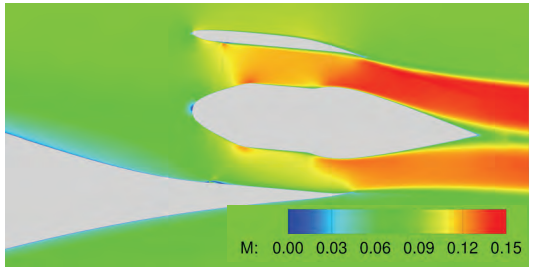
AIAA-2017-4436

Mach number

Body Force



Uniform Pressure Jump



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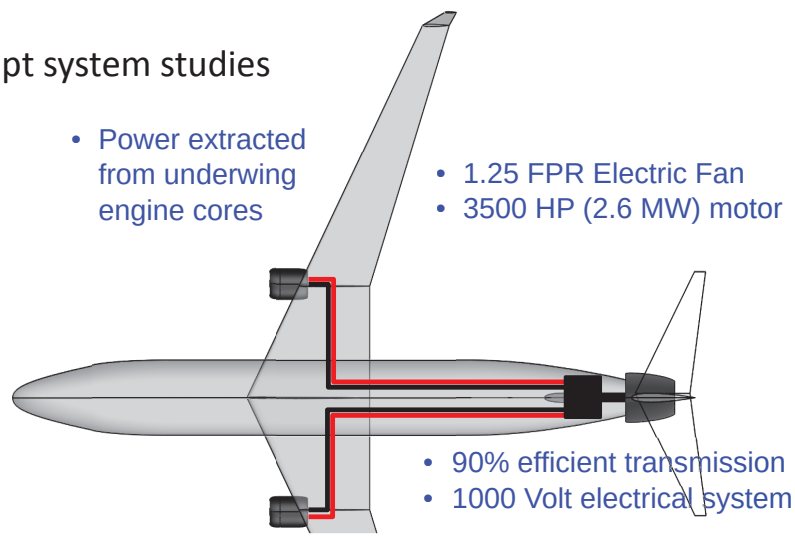
  - Background
  - Test Objectives
  - Test Overview

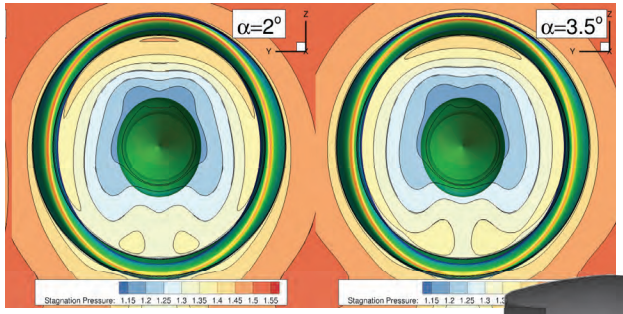
Background

- Problem:
  - BLI is the primary source of system benefit for STARC-ABL
    - significant uncertainty exists in the modeling and prediction of a BLI propulsor
  - No transonic propulsion-airframe integration (PAI) with BLI has been performed
- Goal:
  - Conduct a powered, transonic wind tunnel test of a tailcone thruster
    - benchmarking analysis tools
    - quantify the BLI effect
    - inform advanced concept system studies

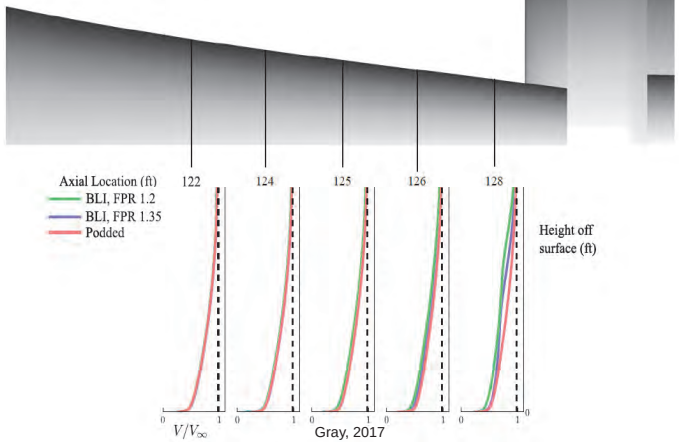


Test Objectives

- Collect sufficient test data
  - benchmark computational models
    - Aerodynamics and propulsion
    - Modeling of PAI
  - Enable BLI modeling improvements
  - Increase confidence in predictions
- Quantify inlet distortion
- Fuselage BLI effect (benefit?)
  - Combination of test data and analysis
- Investigate impact on the aft fuselage flow characteristics due to the presence of a powered fan at multiple throttle conditions.



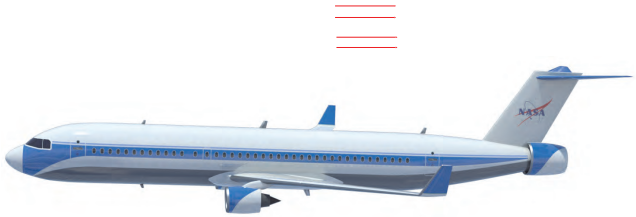
Kenway, 2018



Gray, 2017

Test Objectives

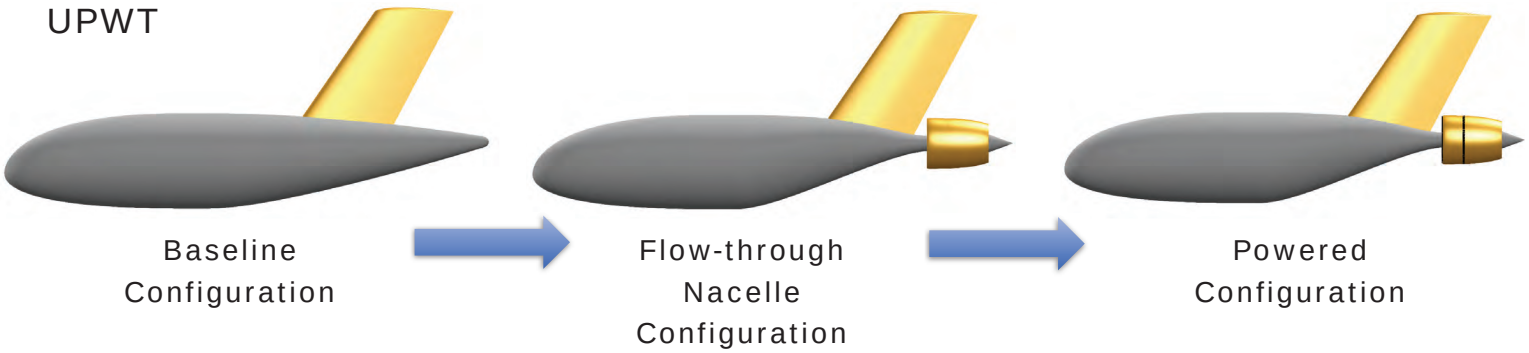
- Inform advanced concept systems analysis with knowledge gained from:
  - Test data
  - Benchmarked numerical analyses
- Increase concept fidelity and maturity
- Quantify the tailcone propulsor system efficiency
- BLI effect

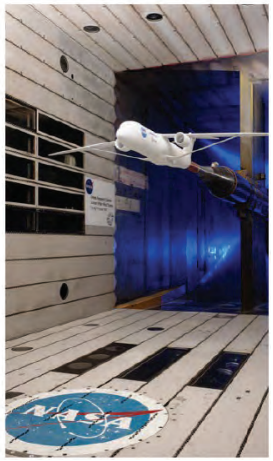


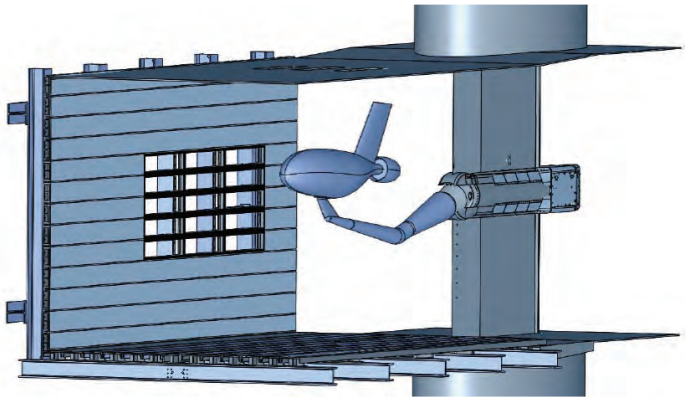
Test Overview

- Geometry buildup approach

Ames 11'
UPWT





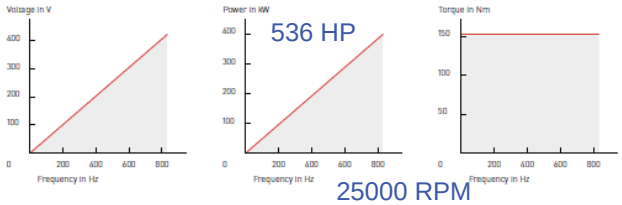


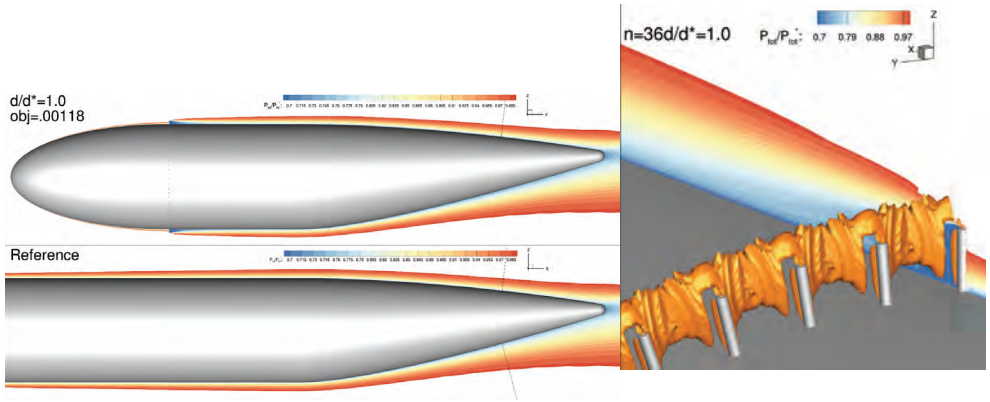
Test Condition Parameters
Mach 0.5 – 0.82
Angle of Attack +/- 3 degrees
Tunnel stagnation pressure
Propulsor RPM (throttle)

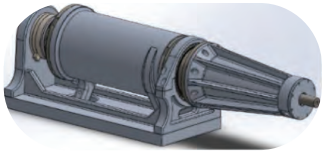
Test Overview

- Powered by an electric motor drive system
- Truncated fuselage requires boundary layer thickeners aft of model nose

Duty type	S1				
Cooling method	Stator: water / Rotor: air				
Inverter	Voltage: 425V max. / Voltage protection: not required				
Circuit connection		Y			
Speed	1000/min	25			
Frequency	Hz	833			
Torque	Nm	152.8			
Power	kW	400			
Voltage	V	424			
Current	A	593			

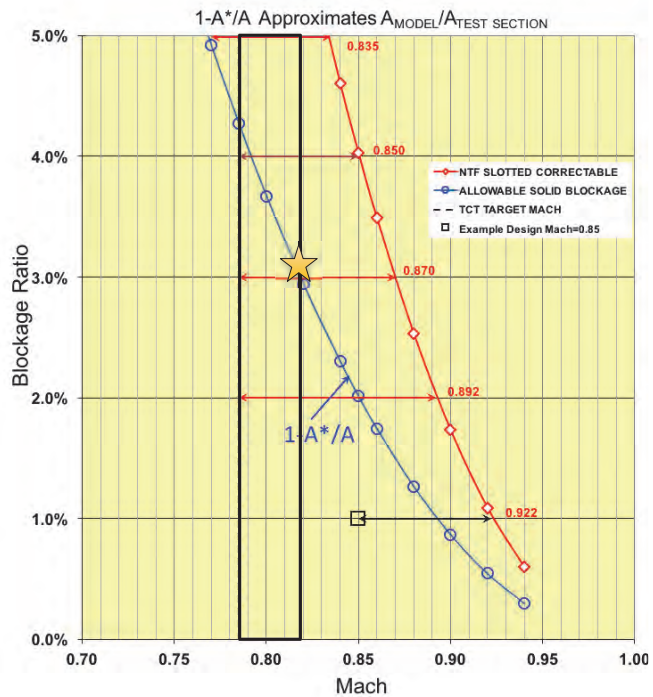






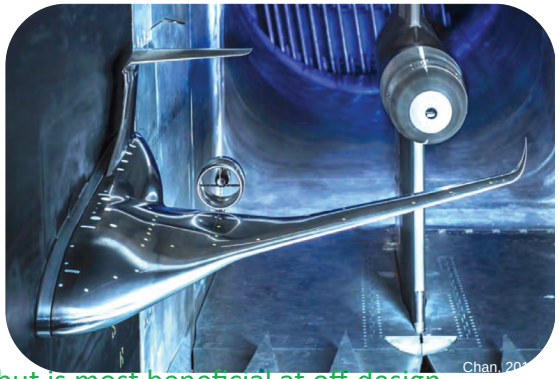
(Some) Model Design Challenges – Model Sizing

- Conflicting requirements
  - Improved airframe measurements with decreased model size
  - Improved fan measurements and performance with increased fan diameter
  - Ames 11' blockage recommendations for airframe performance test: 0.5% -- 1.0%
  - Model stability in the tunnel

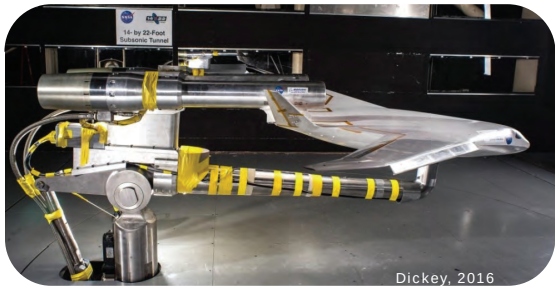


(Some) Model Design Challenges – Propulsor System

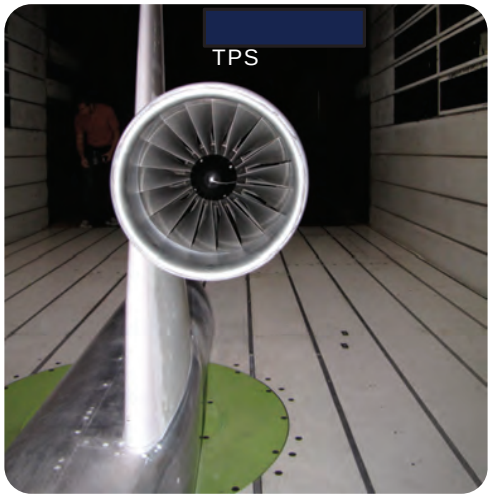
- Flow-through nacelle with mass-flow plugs
  - + Simplifies model design and requires no moving parts
  - + Captured streamlines and mass-flow controlled by the nozzle exit area
  - + Ideal for testing at or near design conditions
  - + Appropriately simulates flow conditions upstream of the propulsor
  - – Although simple, insufficient for quantifying the BLI effect and fan effects on airframe



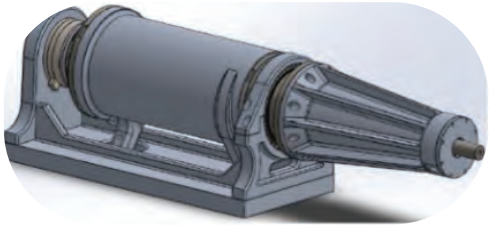
- Ejector propulsion simulator
  - + Complex system that simulates inlet conditions with no moving parts, but is most beneficial at off-design conditions (takeoff/landing)
  - + No moving parts so no turbomachinery facility safety requirements
  - – Does not simulate propulsor exit conditions and large size in measurement region of interest (propulsor jet) proves prohibitive for BLI quantification
  - – Potential fan propagation effects upstream not captured
  - – Requires high pressure air to cross the balance



(Some) Model Design Challenges – Propulsor System



- Turbine powered simulator (TPS)
  - + Can be designed to simulate propulsor inlet or exhaust conditions
  - + Works well for a variety of test conditions
  - + Enables PAI testing with an actual fan
  - + Can properly capture fan upstream propagation characteristics
  - – Requires high pressure air to cross balance
  - – Injects mass flow into exhaust
  - – Cannot match both inlet and exhaust conditions
  - – Extremely costly and has low reliability
- Electric motor drive system
  - + Simulates inlet and exhaust conditions correctly (no injected mass)
  - + Enables quantification of BLI effect and fan upstream propagation effects
  - + High reliability and relatively low cost
  - + Enables testing of a fan with tight control of RPM and torque
  - – Requires high current and large cables to cross balance with potential EMI effects
  - – Never been used in a large, high-speed test



Robust Design for Embedded Engine Systems

NASA Advanced Air Transport Technology Project

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

NASA Propulsion-Airframe Integration Technical Interchange Meeting

NASA-Glenn Research Center, Cleveland, OH

May 30 - 31, 2018

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Acknowledgements

Results discussed in this presentation represent almost 10 year of dedicated research effort funded by NASA (focal point-David Arend) for the design execution at UTRC (3 principal investigators- Razvan Florea, Greg Tillman and Bill Cousins). A large number of researchers, designers and experimentalists contributed to the success of this program. The support of these contributors along with the senior managements at UTRC and NASA is gratefully acknowledged.

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

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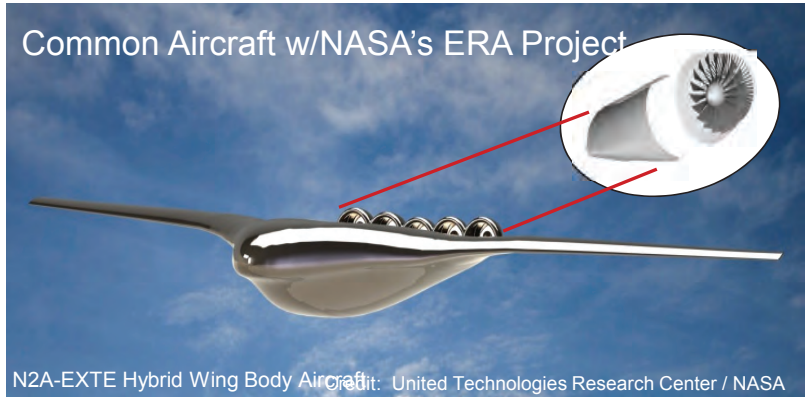
BLI Propulsor Technology Genesis and Applications



Technology Potentially Applicable To

Future BLI Aircraft

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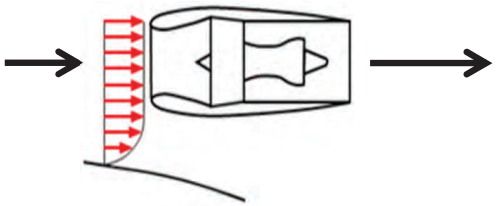
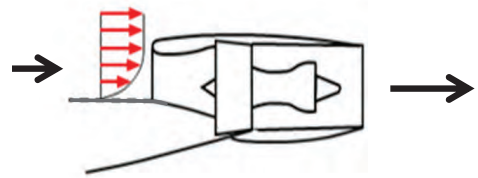
Propulsion Benefits of Boundary Layer Ingestion

$U_{in,conv} = U_0$ $\quad U_{j,conv}$



Conventional Propulsion

$\bar{U}_{in,BLI} < U_0$ $\quad U_{j,BLI} < U_{j,conv}$



Boundary Layer Ingesting Propulsion

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

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

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

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:

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

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

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

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

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.

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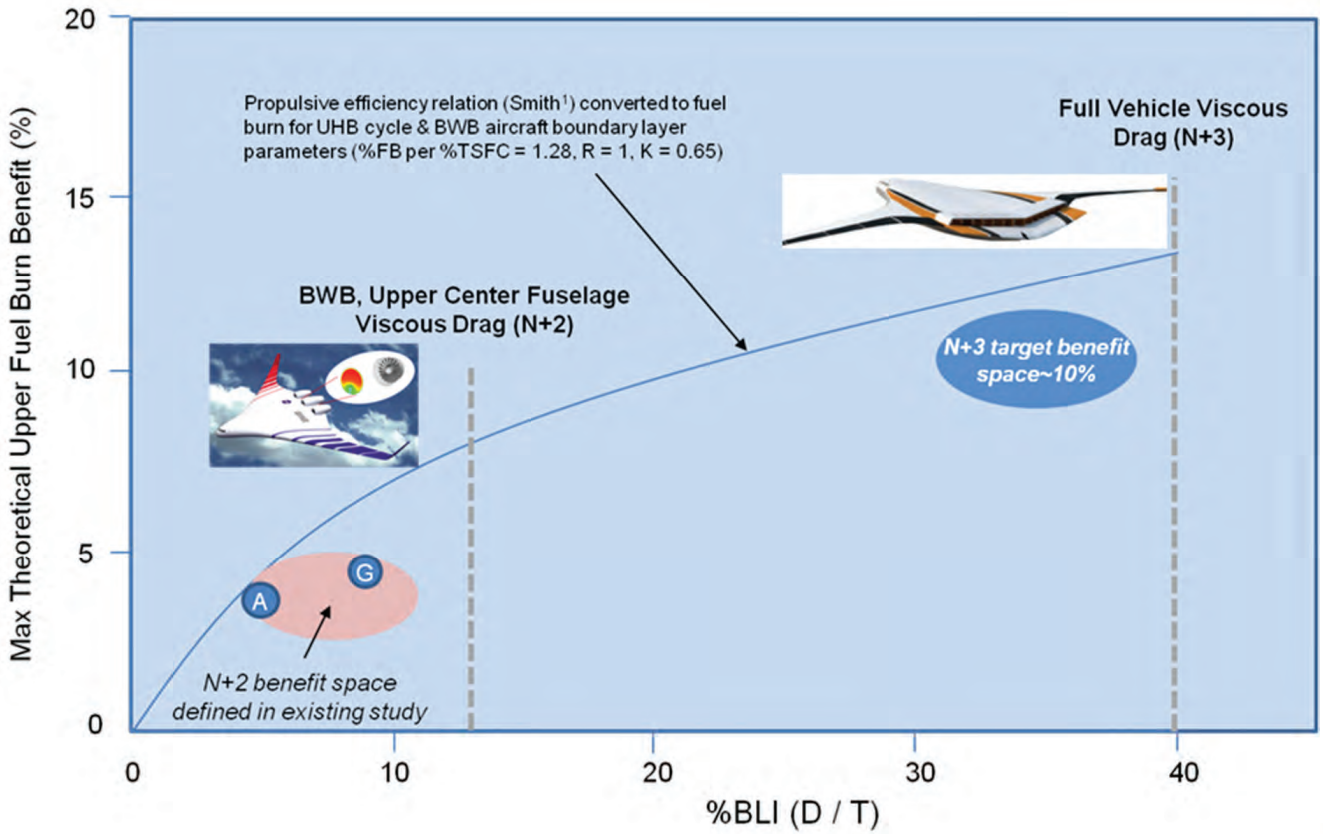
Fuel Burn Benefits Obtained from Boundary Layer Ingestion

N+2 benefit space addressed in present program



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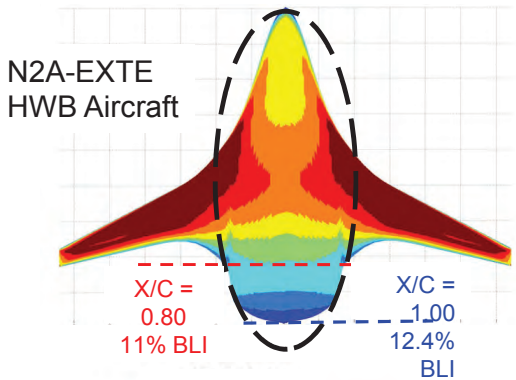
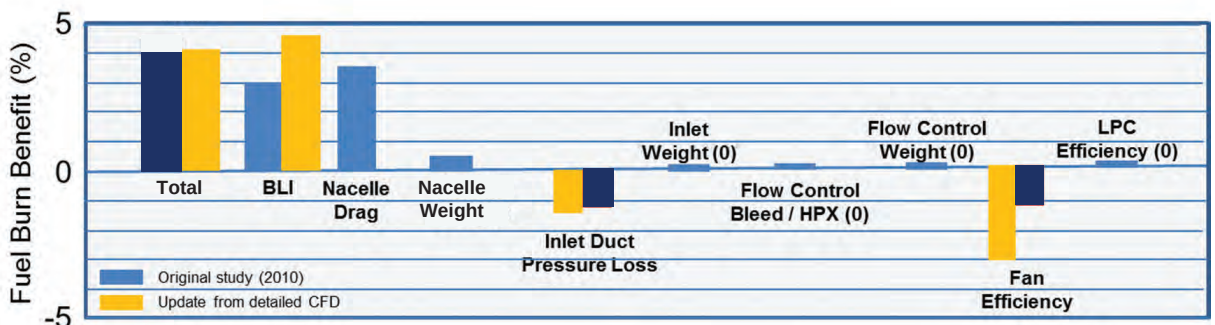
System Studies Defined Technology Needs



- 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)



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.

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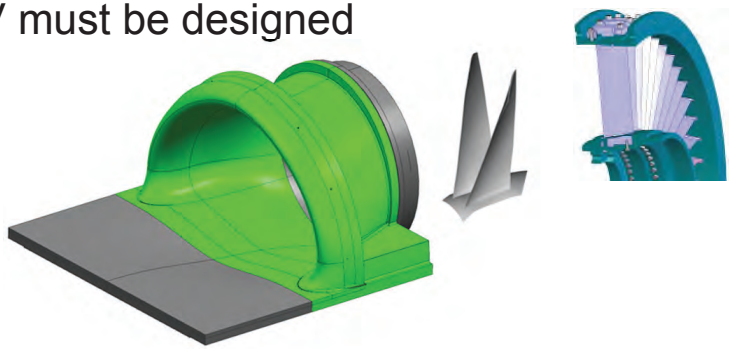
Design Goals

- 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



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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

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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

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Program Evolution

Program evolved as learning & tool capability progressed over time

Program Start

P&W Aero-1 Fan with tip shroud

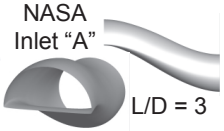
JT15D w/mid-span shroud

NASA tip-turbine fan (TDI 1109)

P&W Aero-1 Fan

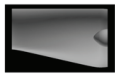
Fan not available

NASA Inlet "A"



L/D = 3

Turbine change required for same operating line



L/D = 1.5

Complete redesign required due to operability limitations

G4 Fan Recommended

L/D = 0.6

G4 fan unshrouded

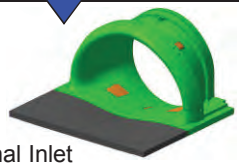
Redesign decision after Research Design Review

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

Recognition that solidity could be increased

Main focus on structural integrity

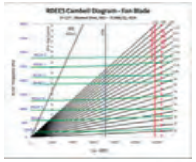
~100 hours of HCF life at ADP



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

Performance drop to meet mechanical constraints

Not done due to program time constraints



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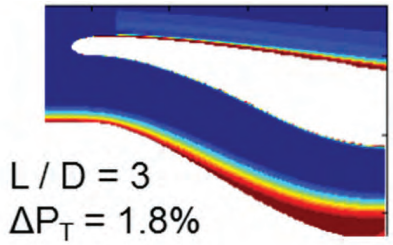
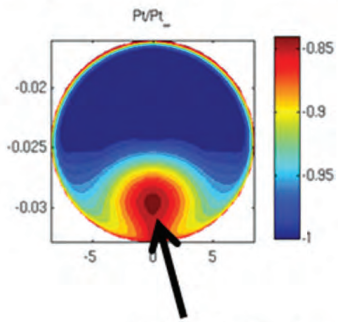
Inlet Design

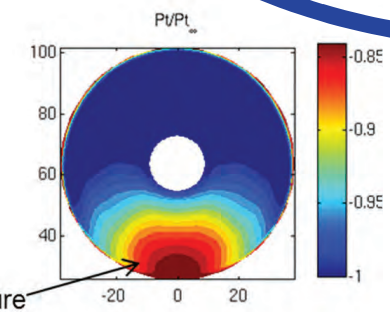
Final design shaped to provide operational distortion pattern



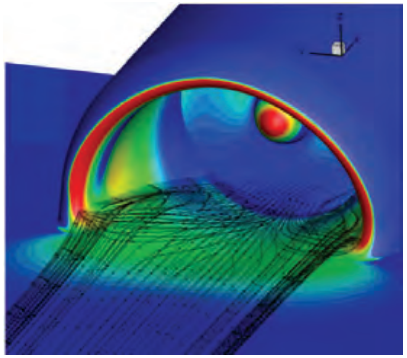
L / D = 3
ΔP_T = 1.8%



Low Pressure
Original Inlet "A"

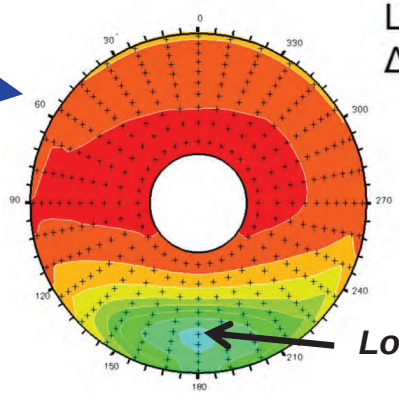


Low Pressure



Designed BLI Inlet

L / D = 0.6
ΔP_T = 0.3%



Low Pressure

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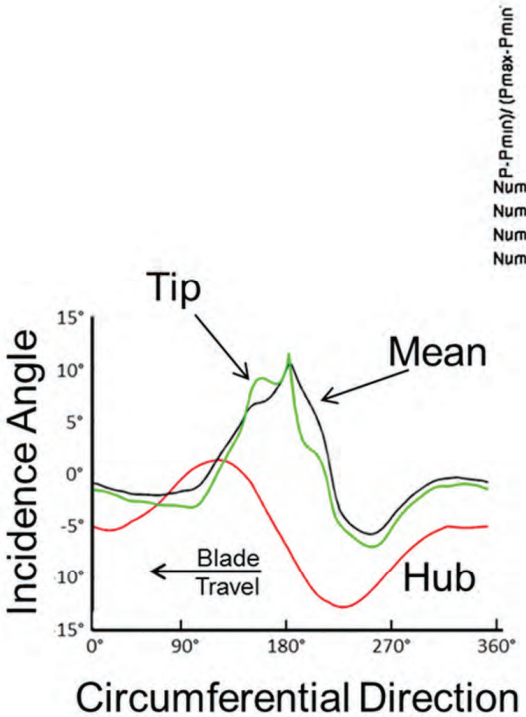
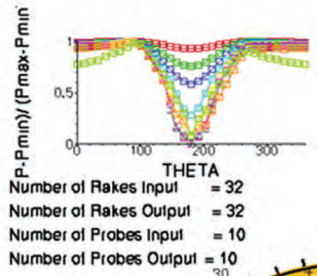
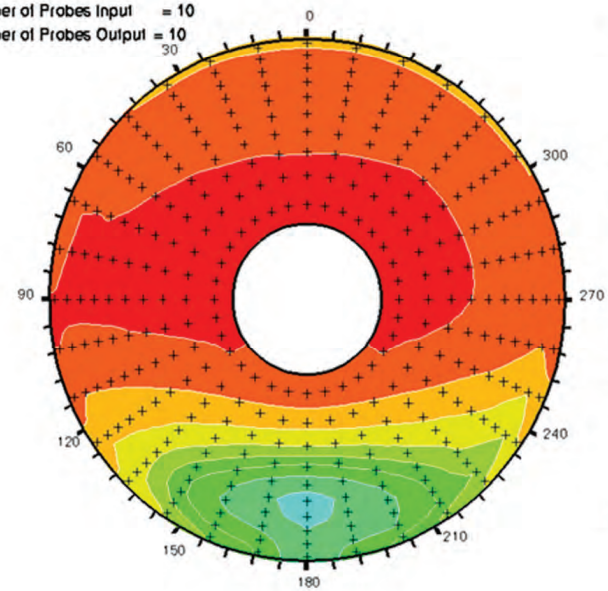
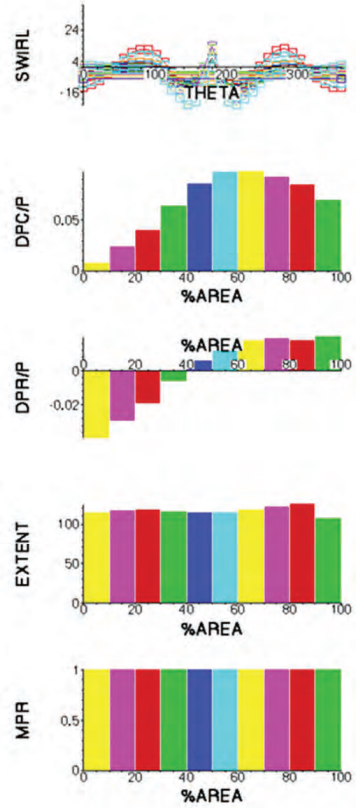
Distortion Intensity and Incidence Swing are Significant

Maximum Values: ΔPc/P ~ 10% ΔPr/P ~ 4% Extent ~ 125°









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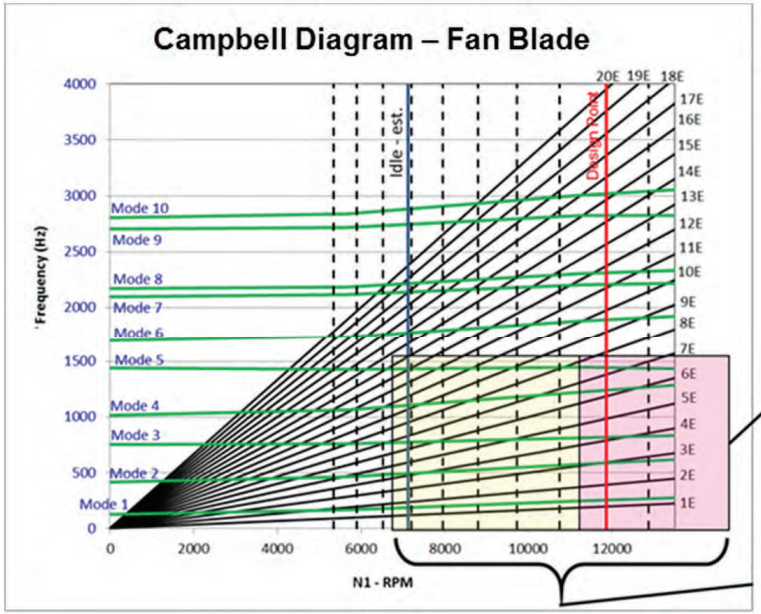
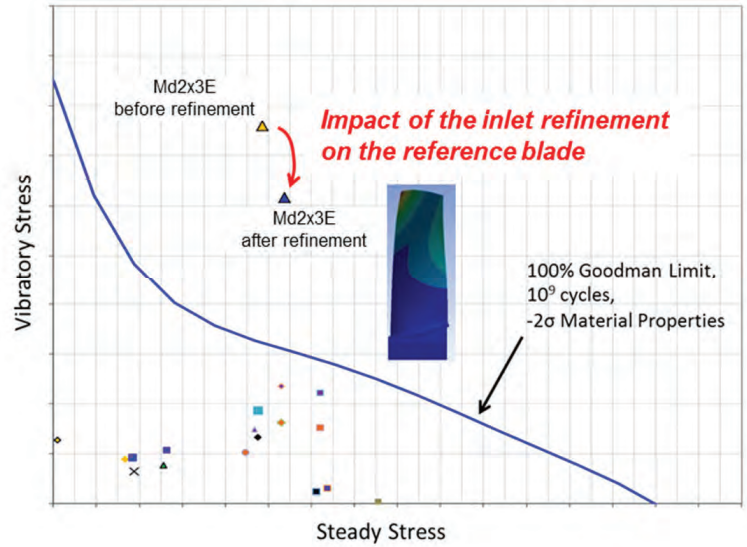
Reference Blade in BLI Environment Not Acceptable

Inlet refinement for distortion shaping had a major influence





Crossings of Greatest Concern
(Includes Md1x1E Off-Resonance)

Crossings of Concern

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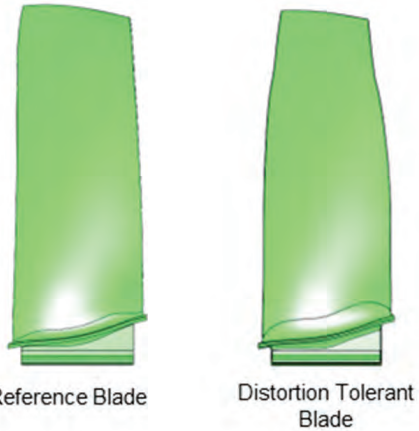
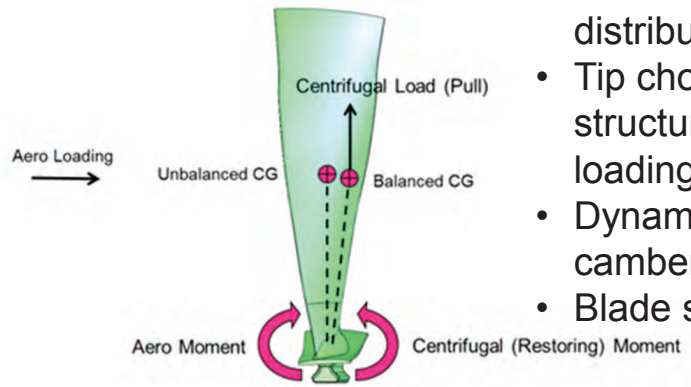
“Standard” Blade Modified to Accommodate Distortion

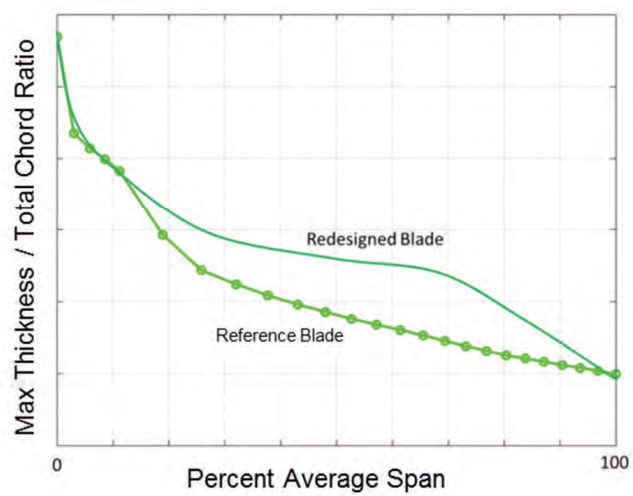
Unique features implemented to develop “distortion tolerant blade”





- 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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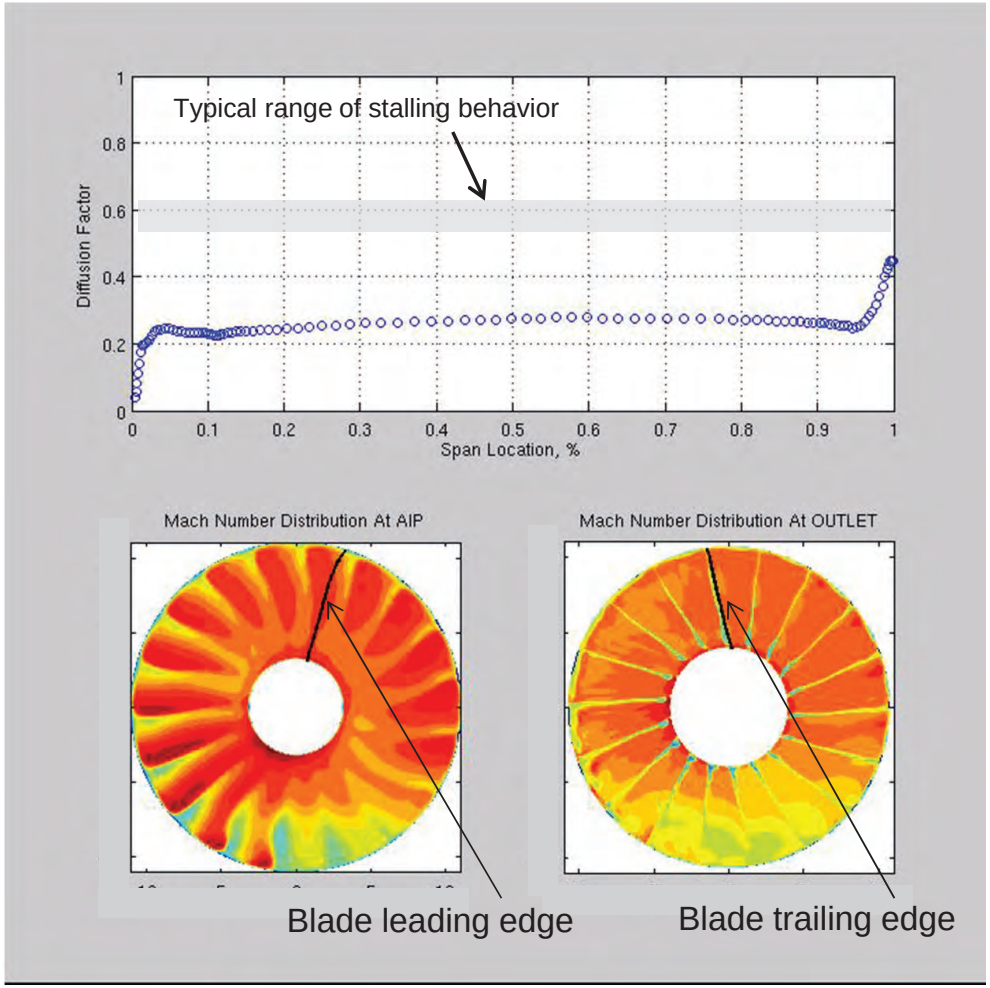
Rapid Loading Changes Require Unique Dynamic Design

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

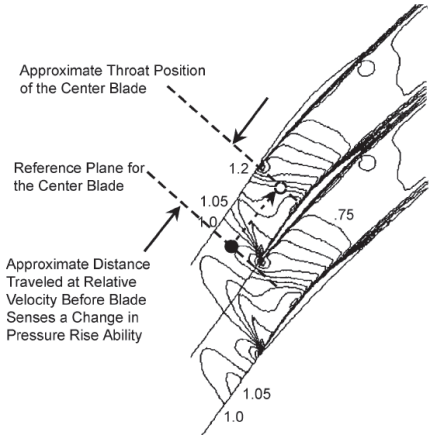
$$k = \beta \omega / v$$

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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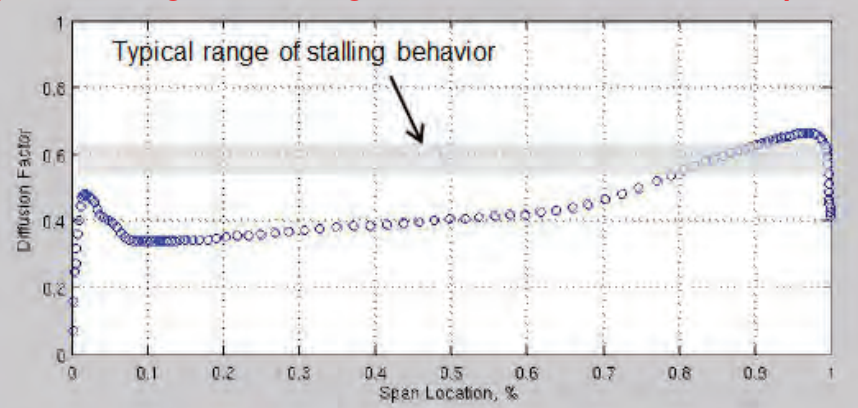
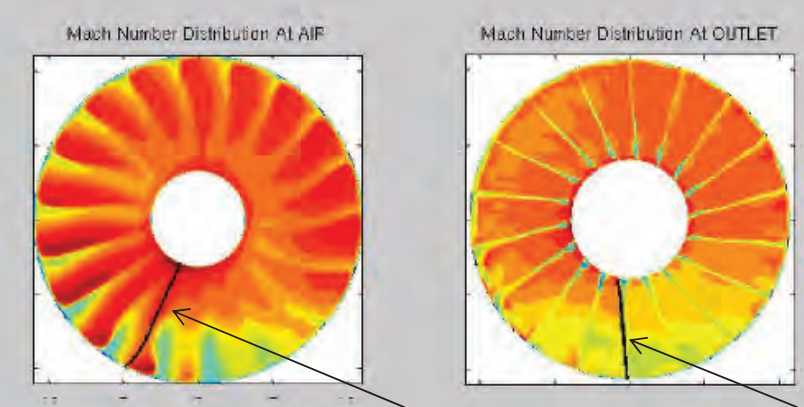
Rapid Loading Changes Require Unique Dynamic Design

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





Blade leading edge

Blade trailing edge

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

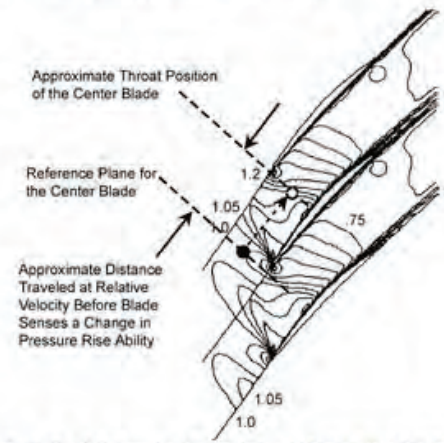
$$k = \beta \omega / v$$

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.



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Rapid Loading Changes Require Unique Dynamic Design

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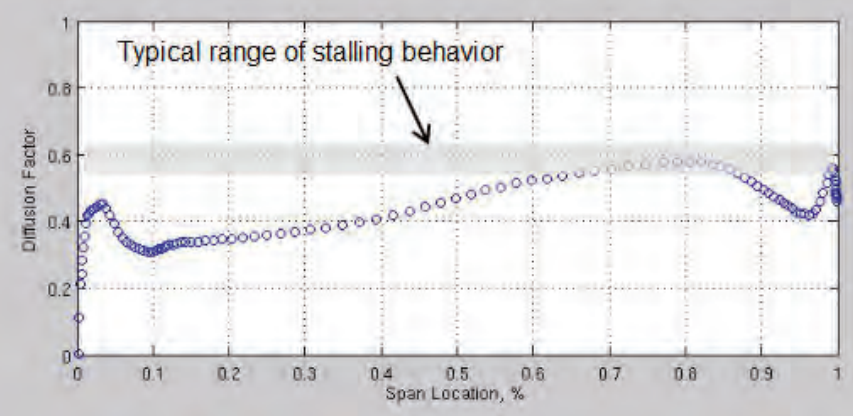
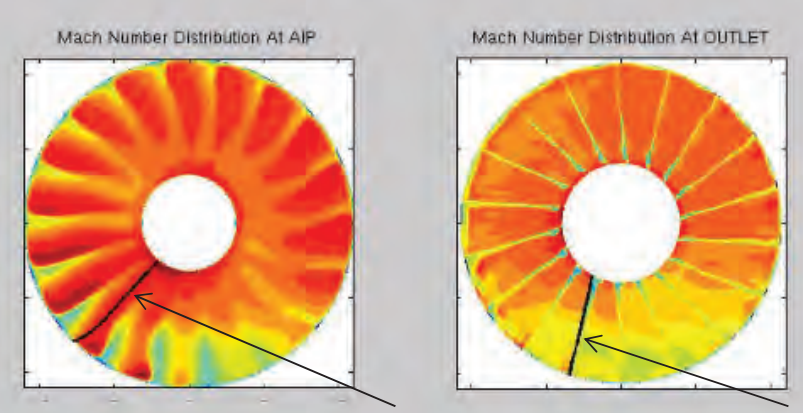
Duplicate of Page 15 showing excursion of D-factor w/blade position





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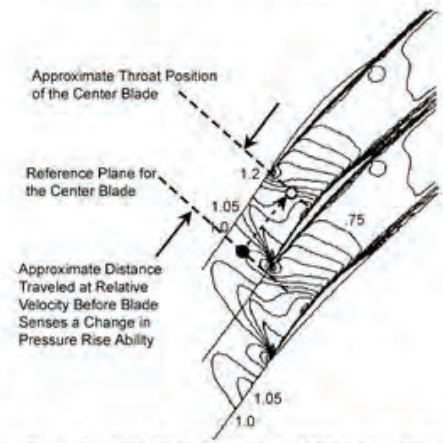

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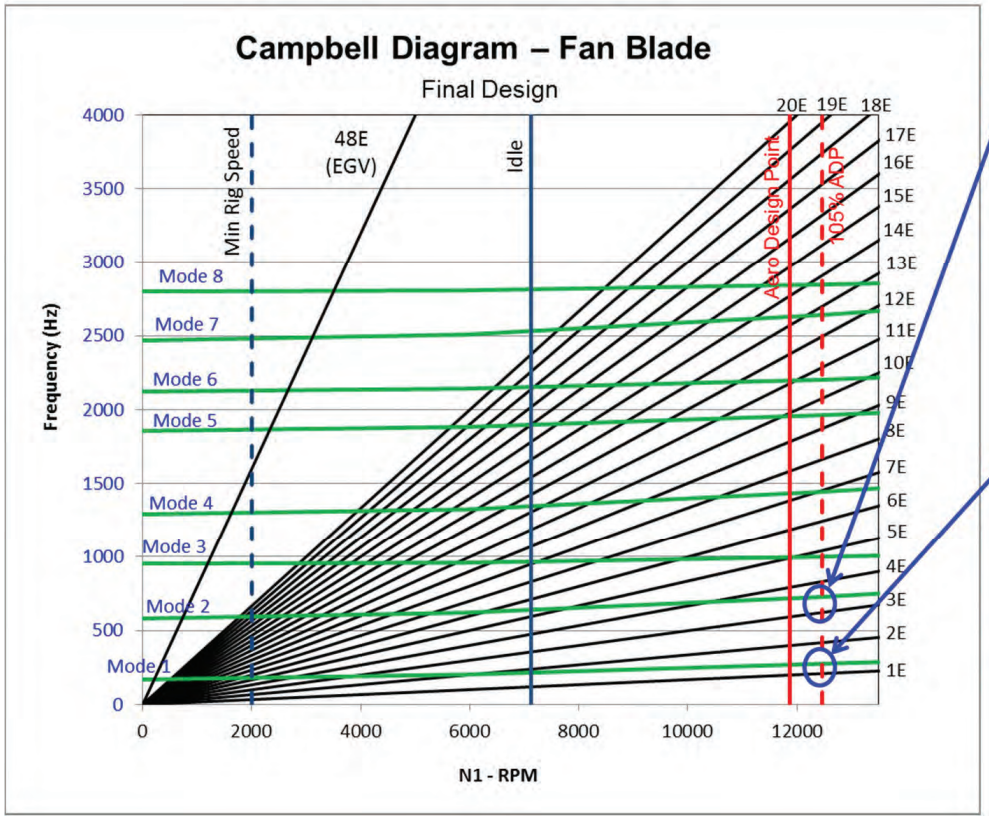
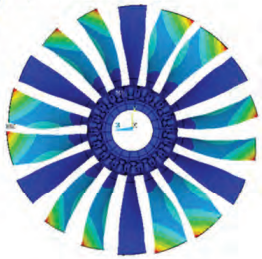
Resulting Blade/Inlet Integrated Design with Dynamics

Mechanical design criteria achieved and dynamic operation satisfied



Md2x3E
(+12.3% FM)



Md1x1E
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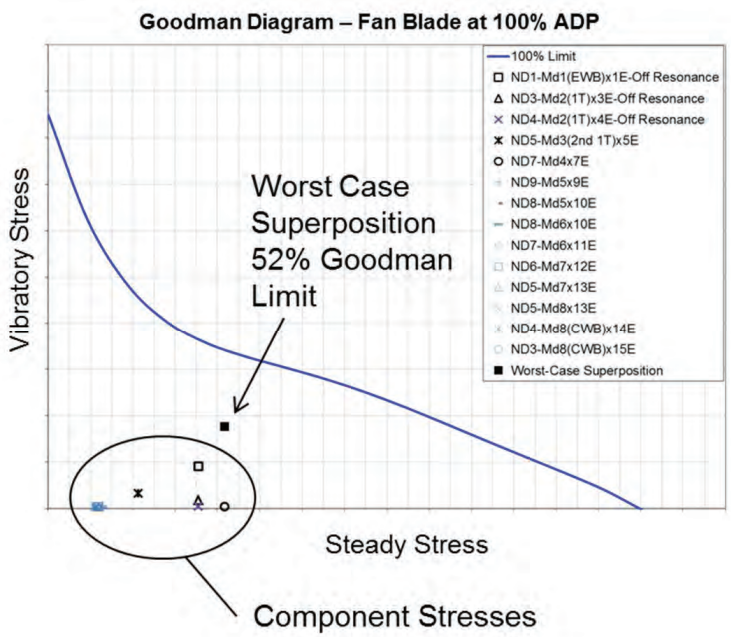
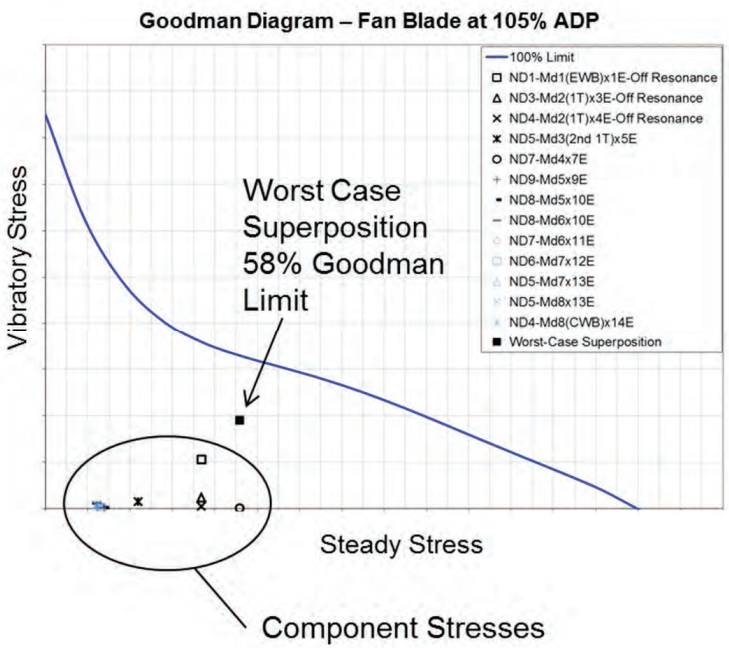
Stress Level Criteria Met with Integrated Design





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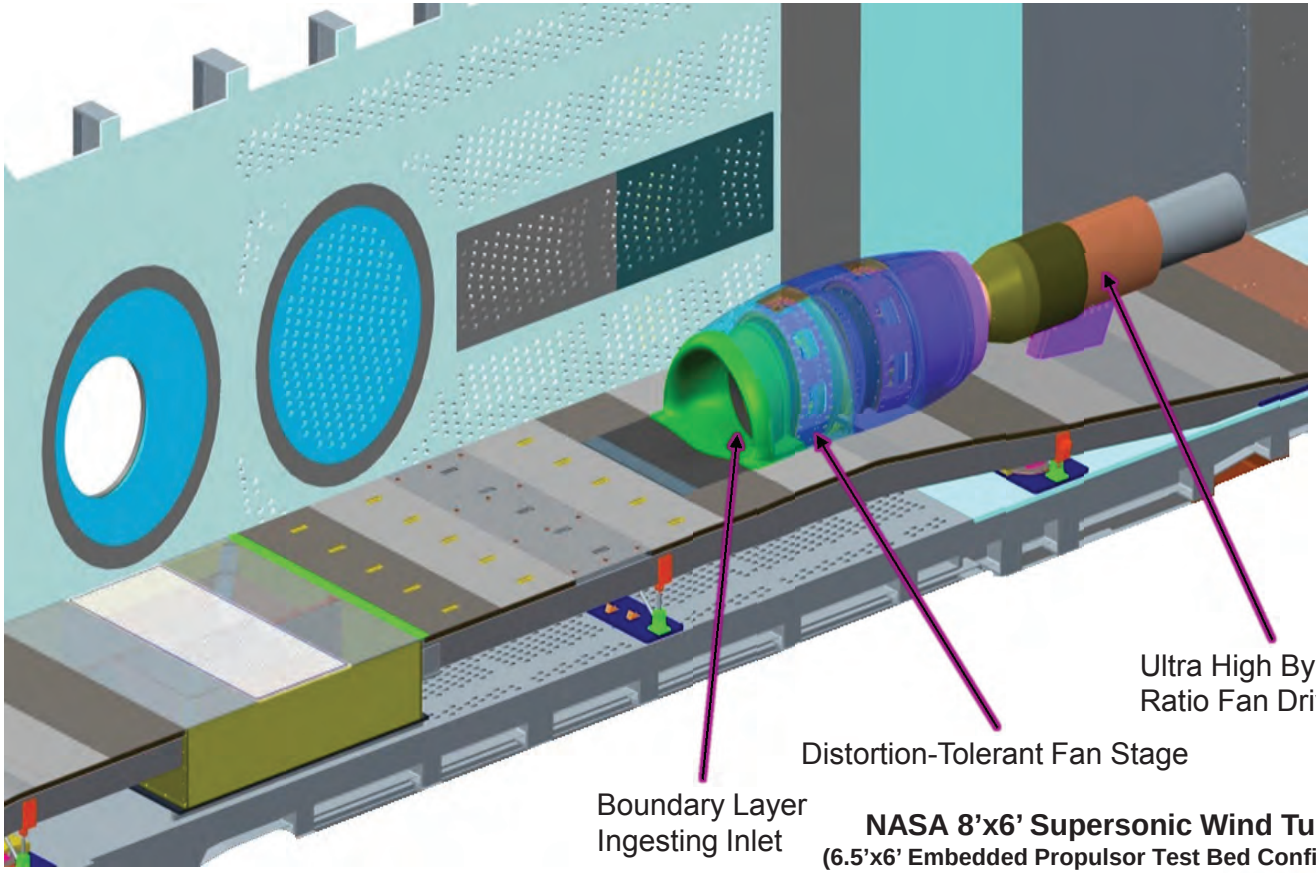
Boundary Layer Ingesting Inlet/Distortion Tolerant Fan Test Article



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

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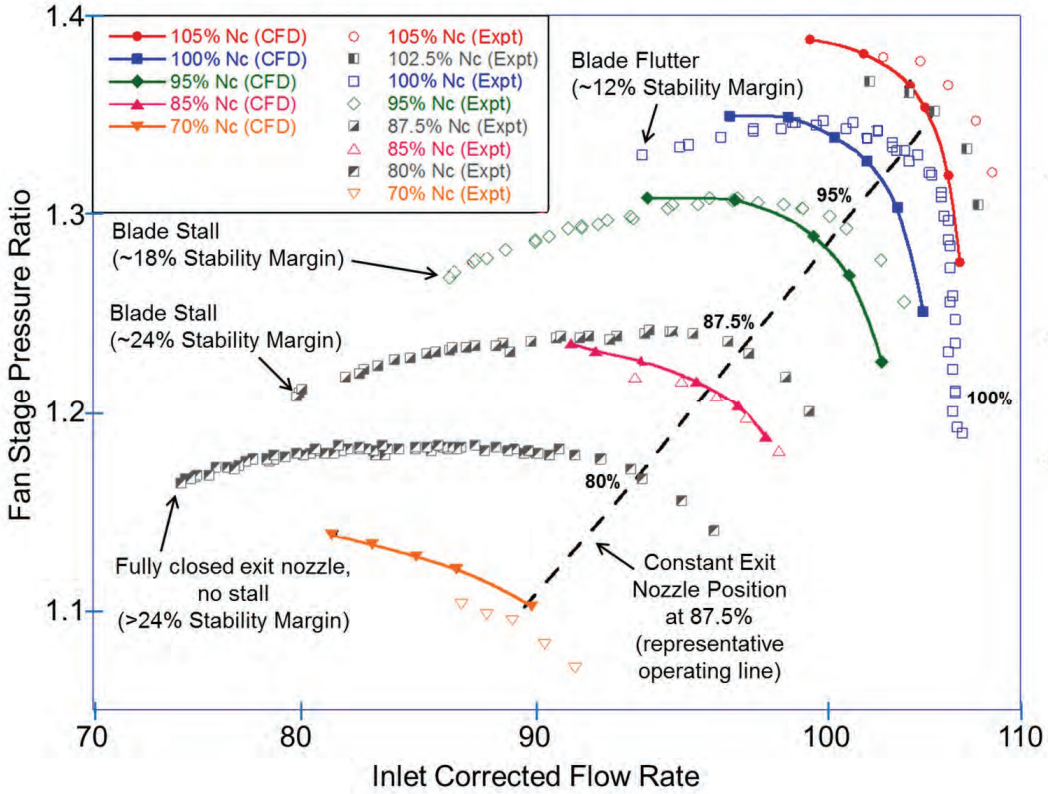
Distortion-Tolerant Fan Stage Stability Margin



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

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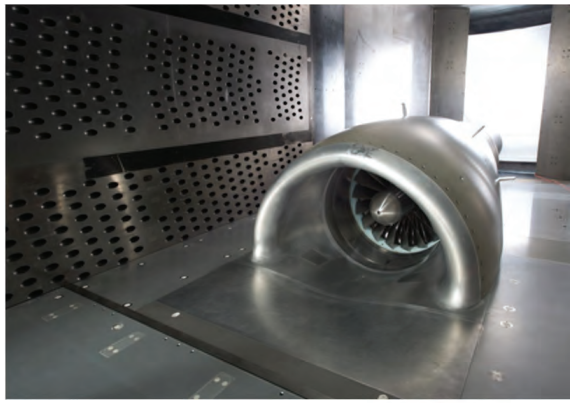
Conclusions

- 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.



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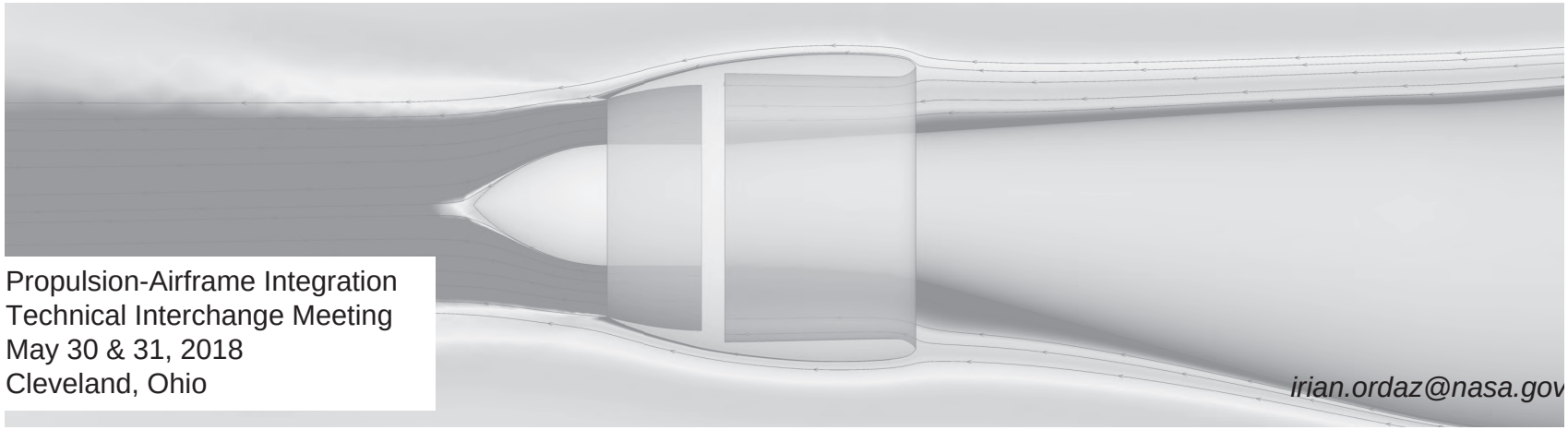
NASA/CP—2018-219955

Aero-Propulsion Analysis and Design Framework

Irian Ordaz

In Support of the Advanced Air Transport Technology Project within the Advanced Air Vehicles Program



Propulsion-Airframe Integration
Technical Interchange Meeting
May 30 & 31, 2018
Cleveland, Ohio

irian.ordaz@nasa.gov

Outline

- Motivation
- Overview of tools and framework
- Conceptual geometry / surface mesh generation
- Surface boundary partitioning
- Volume and boundary layer grid generation
- Post-processing of propulsion system / fan distortion
- Adjoint-based mesh adaptation
- Demonstration and verification of viscous analysis
- Demonstration of aero-propulsive coupling
- Summary
- Weakness and future work
- Acknowledgment

Motivation

WHY

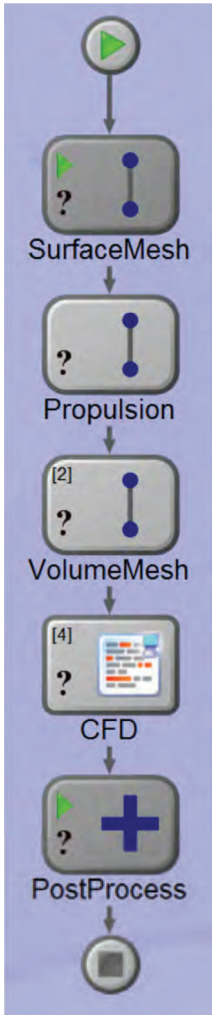
- Growing interest in advanced concepts with highly integrated propulsion systems and highly coupled aero-propulsive effects for improved fuel efficiency
- Technical gap for conceptual design and system level assessment of vehicle
- Application-specific and low-fidelity analysis tools do not adequately capture the physics of these more complex problems

WHAT

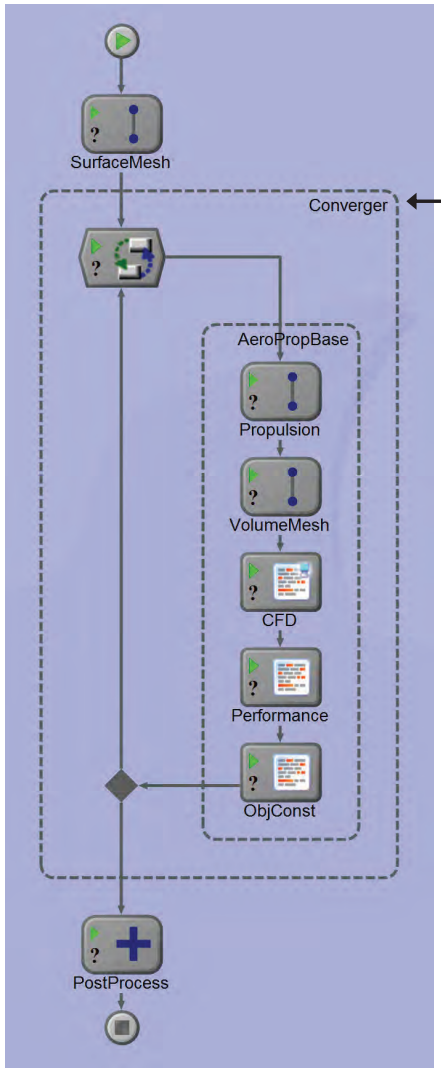
- Develop in-house aero-propulsive analysis and design framework with capabilities that facilitate application during conceptual and preliminary design
- Flexible, scalable, and multi-fidelity higher order analysis
- Reduce time investment to setup the problem by leveraging automation when possible
- Conceptual geometry definition (i.e., minimally OpenVSP)

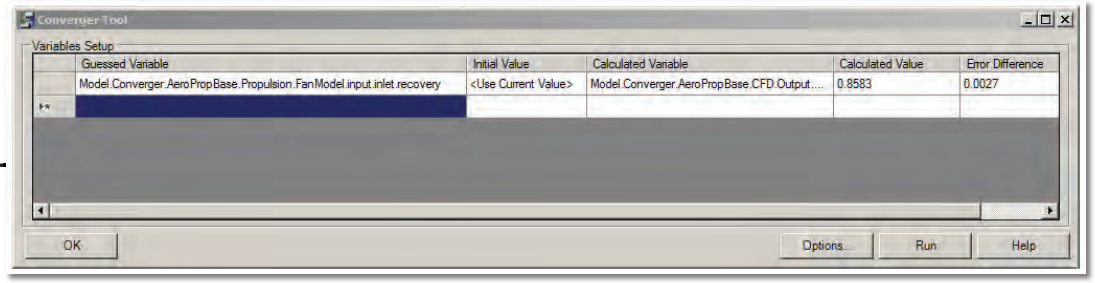
Overview of Tools

- Geometry modeling: **OpenVSP**
- Surface mesh: **OpenVSP**
- Propulsion: **NPSS**
- Volume mesh: **AFLR2** and **AFLR3**
  - Unstructured planar, surface and volume mesh generation software
  - Advancing Front/Local reconnection
- CFD analysis: **FUN3D**
  - Unstructured inviscid, laminar, and turbulent solver
  - Gradient-based mesh adaptation
- Post-Processing: **Excel and Tecplot**



Overview of ModelCenter Framework



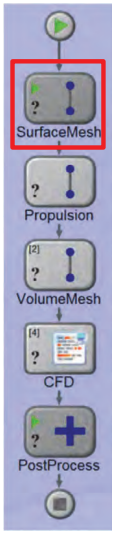


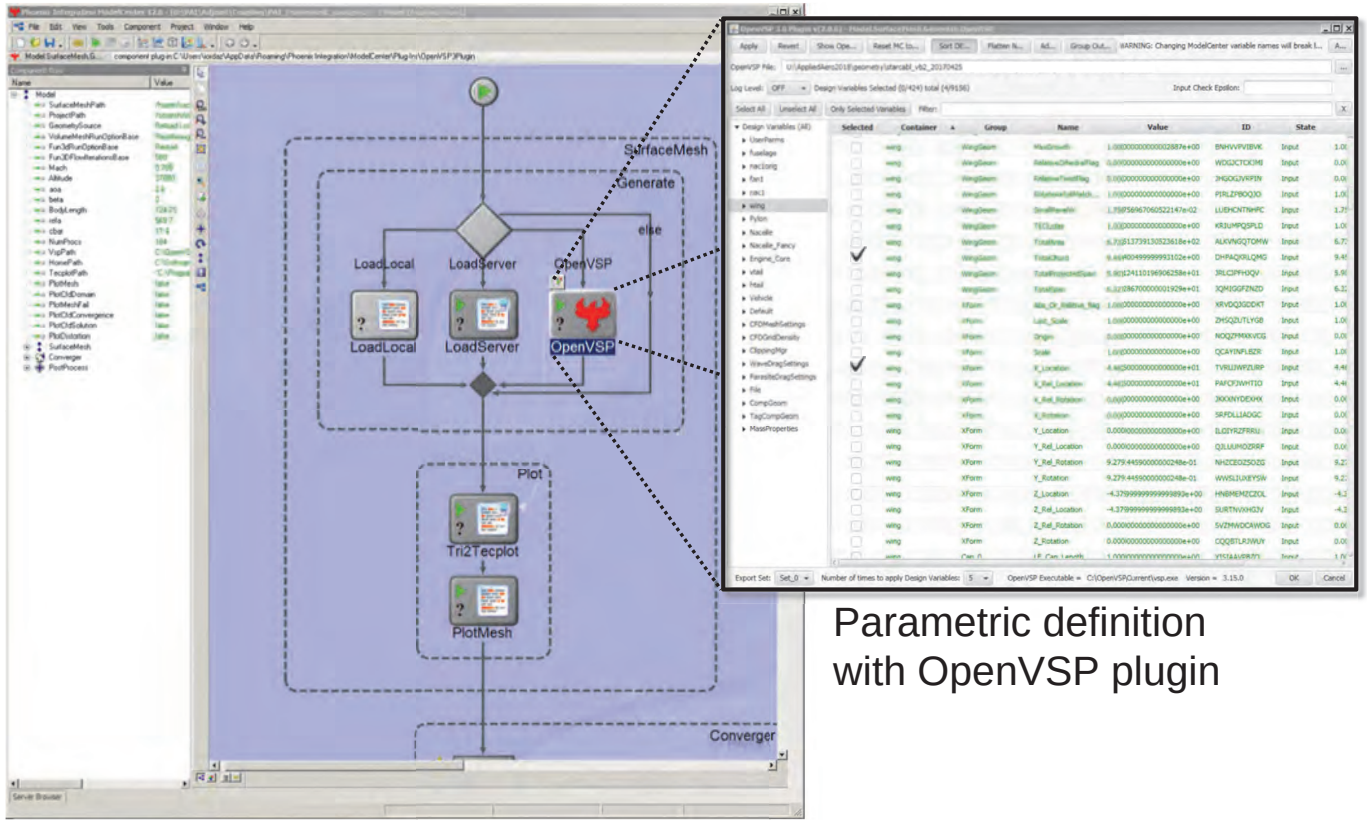
ModelCenter provides tools for

- Convergence
- Parametric studies
- Design of experiments
- *Numerical optimization*
- Data visualization

Conceptual Geometry / Surface Mesh Generation

- Flexible and geometry agnostic
- Parametric deformation within ModelCenter framework with OpenVSP plugin
- OpenVSP ‘CFD mesh’ or other high quality surface mesh
- Must meet requirements for body-fitted unstructured volume mesh





Parametric definition
with OpenVSP plugin

Conceptual Geometry / Surface Mesh Generation

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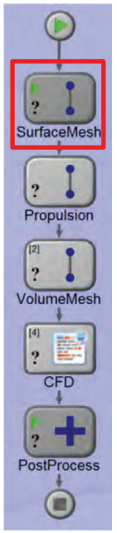
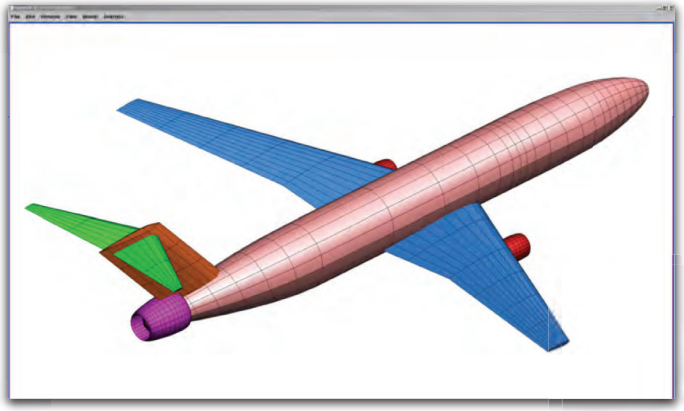
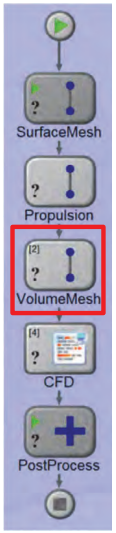


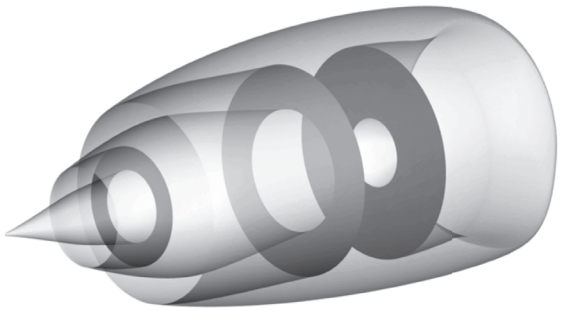


OpenVSP

Surface Boundary Partitioning

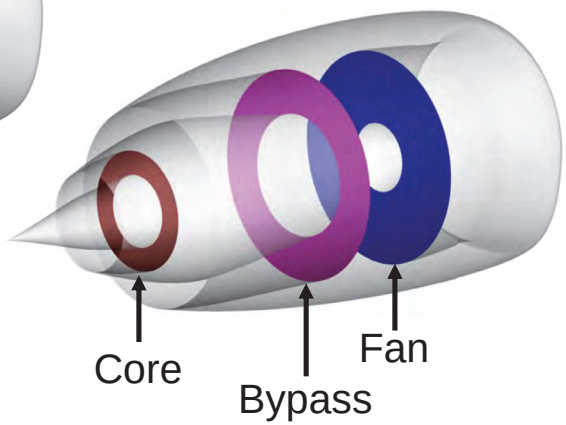
- Automatically partition boundary surface
- Unlimited number of power / non-power boundary conditions
- Ensure proper force book keeping
- Label and group newly partitioned surfaces

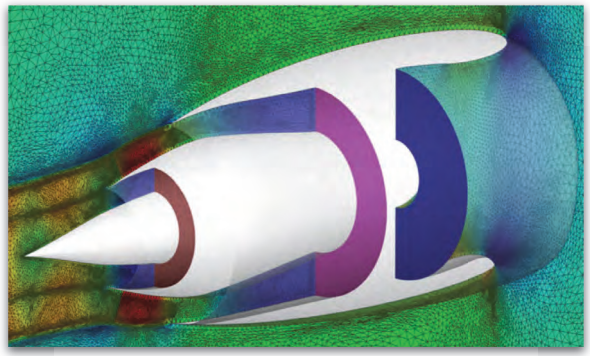




Unpartitioned

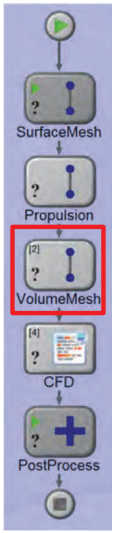
Partitioned

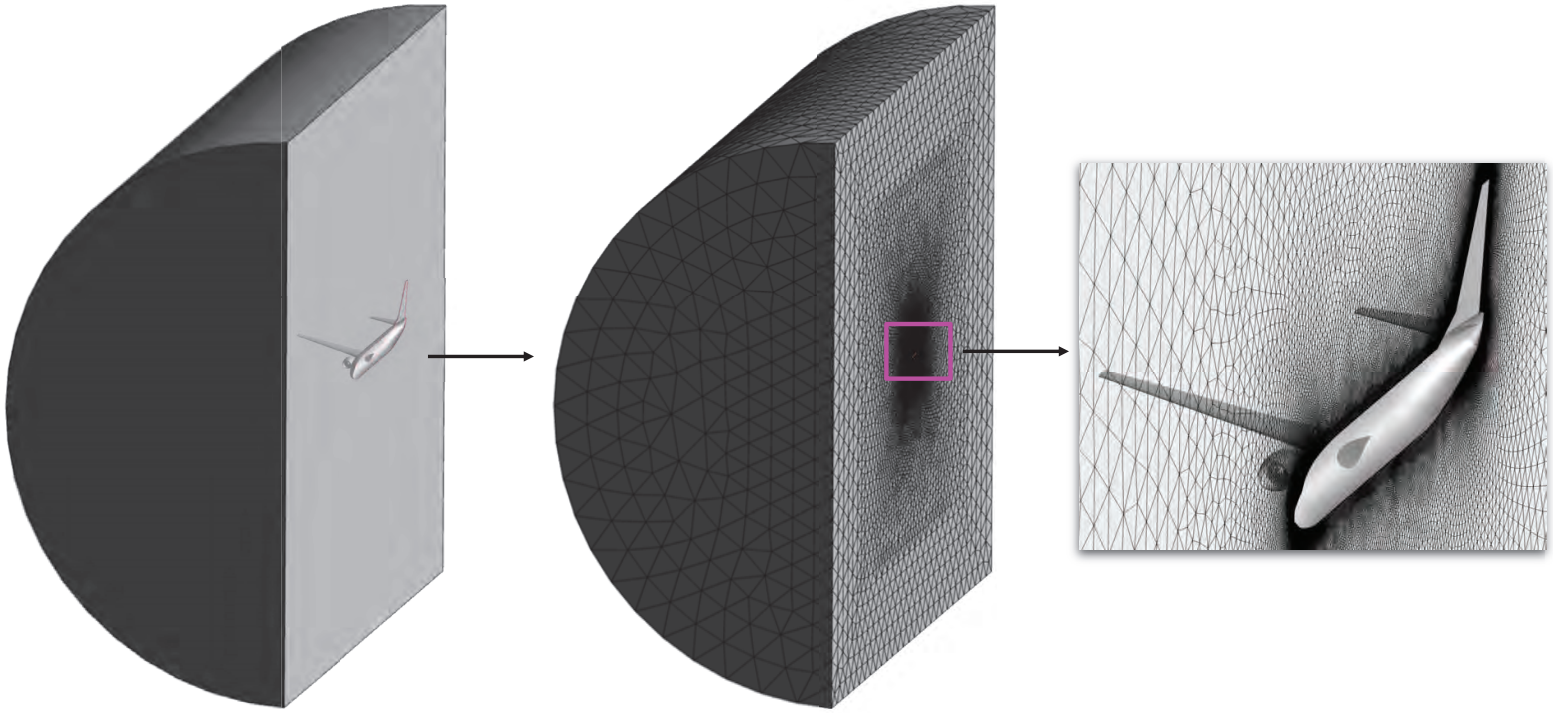




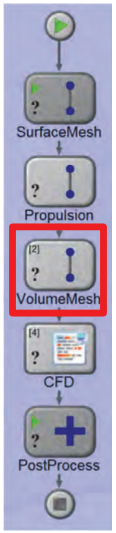
Volume Mesh Generation

- Process automated with in-house tool
- Unstructured and mixed element
- Far-field boundary mesh generated with AFLR2
- Volume mesh generated with AFLR3

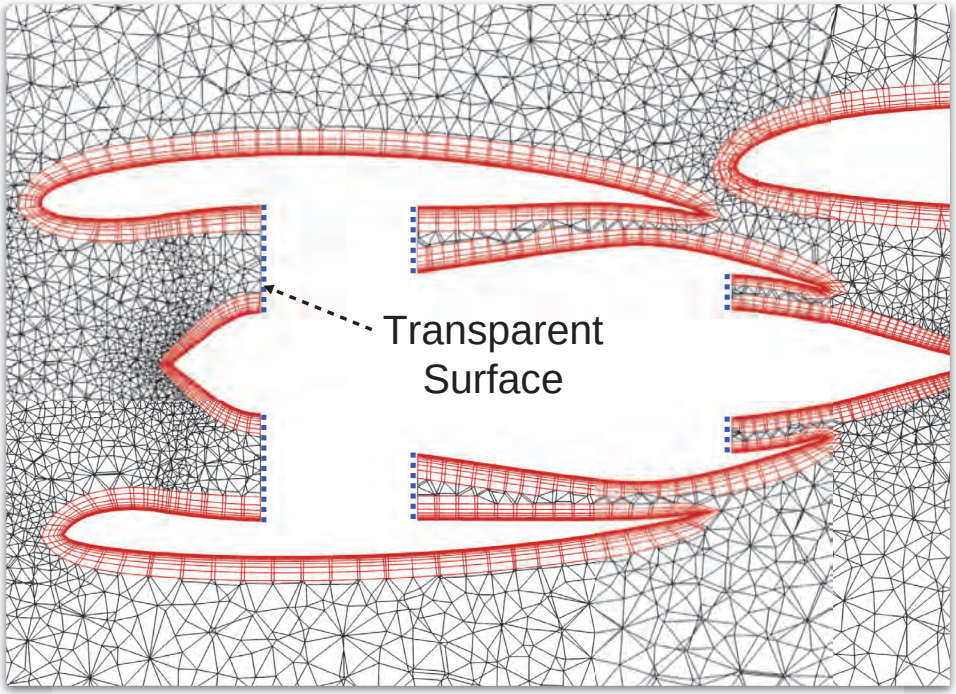




Volume and Boundary Layer Grid



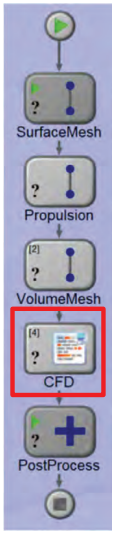
- Grid spacing calculator integrated for fully viscous and wall functions
- Initial grid spacing set explicitly and spacing is allowed to grow geometrically
- Automated management of boundaries
  - Inviscid and viscous
  - Solid and transparent/embedded surfaces



Post-Processing of Aero-Propulsive Analysis Results

Post-Processing of Aero-Propulsion System

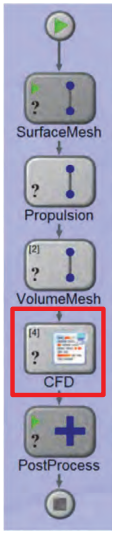
- Automated force and moment book keeping based on *standardized* surface naming convention and input boundary conditions

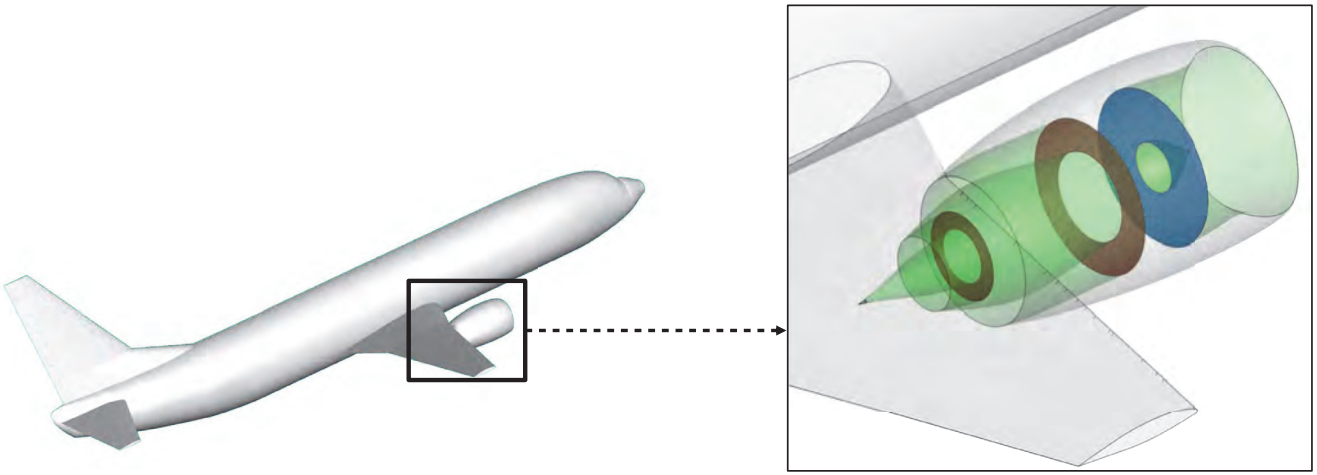


Aerodynamic	Internal Engine Component	Engine Inflow	Engine Outflow
fuse	inlet	fan	core
wing	spike	inflow	outflow
vtail	hub		byp
htail	plug		
hpy	wall		
vpy	noz		
pod			

Post-Processing of Aero-Propulsion System

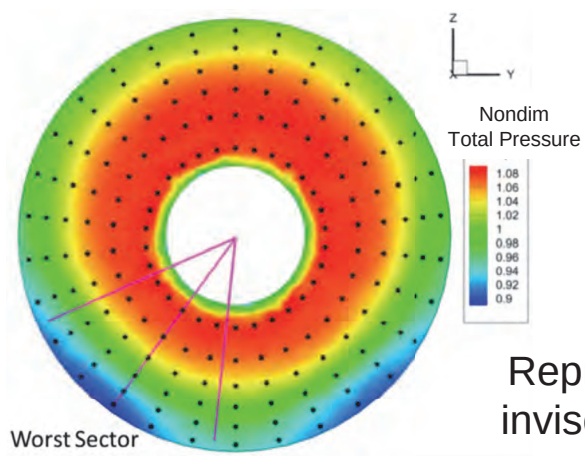
- Automated force and moment book keeping based on *standardized* surface naming convention and input boundary conditions
- Net thrust
- Inlet pressure recovery
- Circumferential distortion (*DC*) and sector with worst distortion
- Area- and mass-averaged FUN3D flow parameters at pre-specified boundary surfaces





Fan Distortion Calculation

- *Based* on the SAE circumferential distortion descriptor (DPCP) defined by the Aerospace Recommended Practice (ARP) 1420 standard*
- *Experimental measurements* from flow samples along concentric rings on the engine aerodynamic interface plane (AIP)
- *FUN3D implementation* based on the average of flow properties for all grid faces which lie on the AIP
  - Discretization of distortion is directly dependent on the underlying mesh
  - ***Ordaz, I., Rallabhandi, S. K., Nielsen, E. J., and Diskin, Boris. "Mitigation of Engine Inlet Distortion through Adjoint-Based Design", 35th AIAA Applied Aerodynamics Conference, AIAA 2017-3410.***

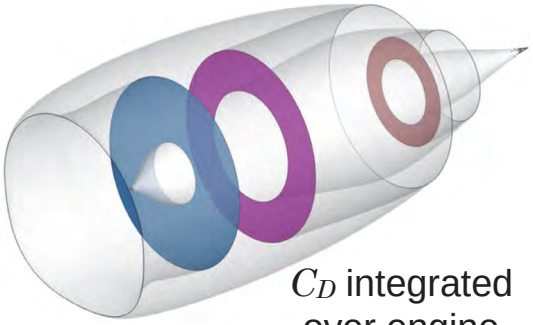


Representative CFM56 fan face in inviscid flow, Mach 0.8, and AoA of 2°

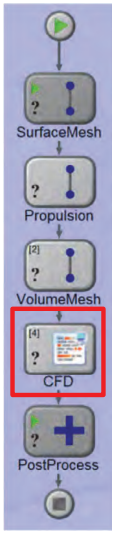
Adjoint-Based Mesh Adaptation

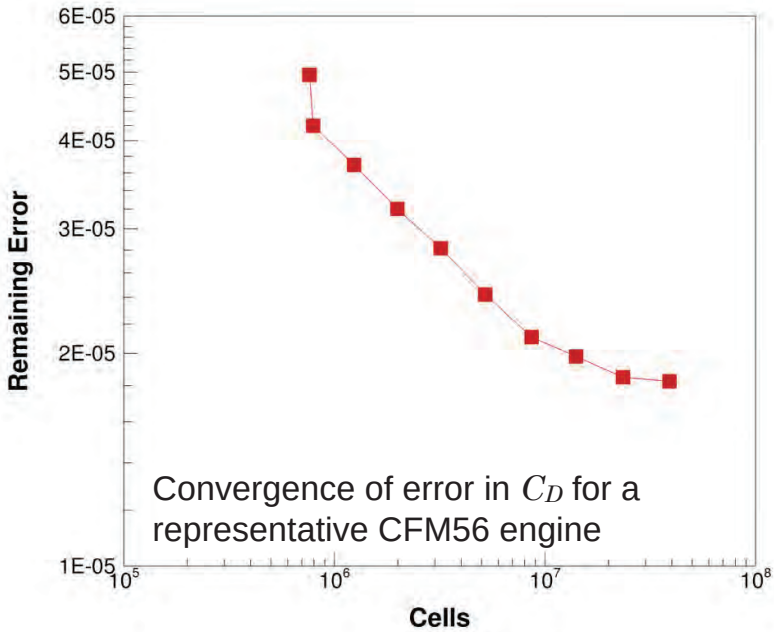
Adjoint-Based Mesh Adaptation (Drag)

- ModelCenter driven with minimum inputs
- Reduce error in C_L, C_D, L/D, DC
- Reduce meshing workload
- Ability to control adaptation mechanics
- NPSS CFM56 engine model
- **Drag decreases by 7% of the non-adapted mesh**

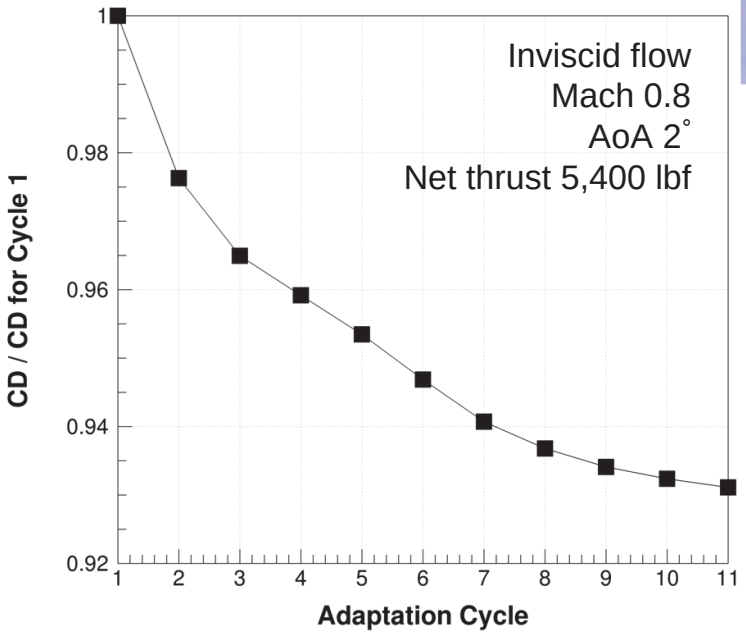


C_D integrated over engine OML excluding BC surfaces

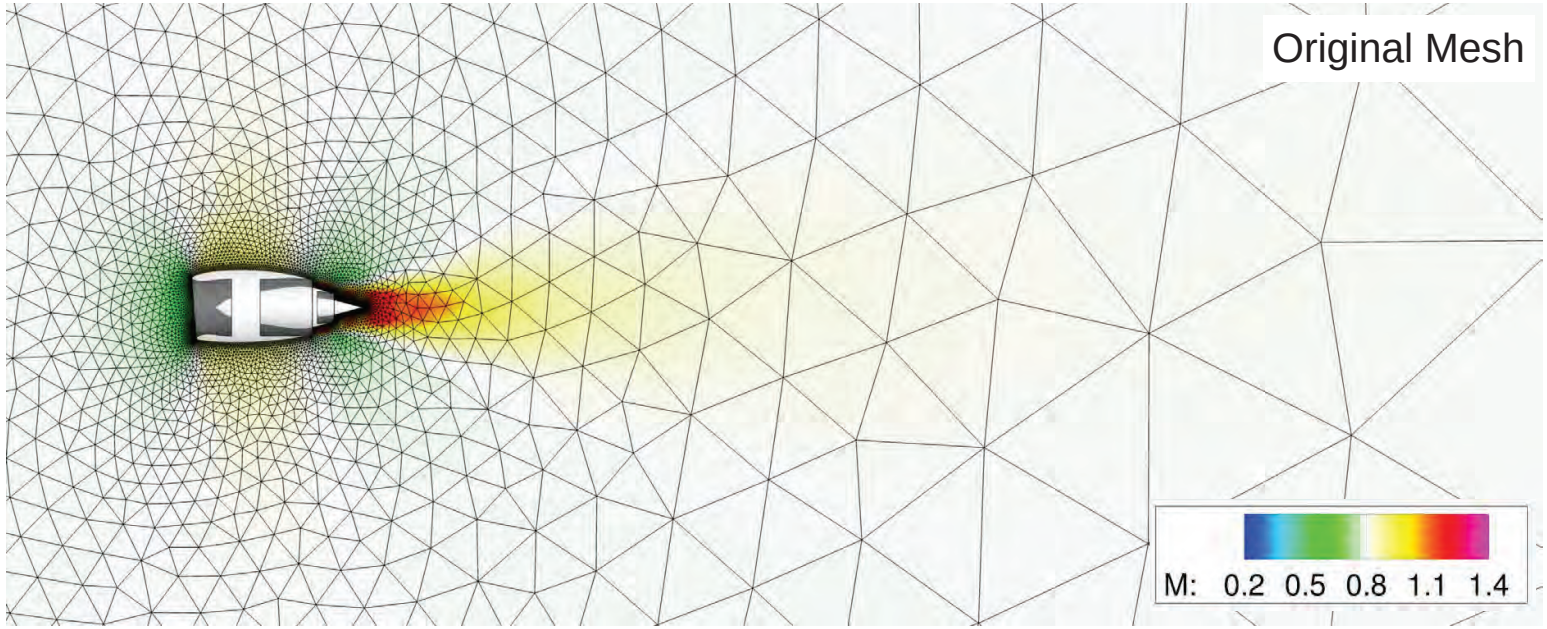


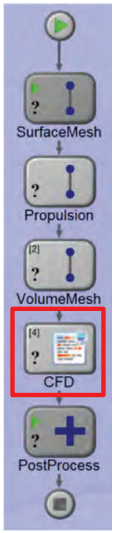


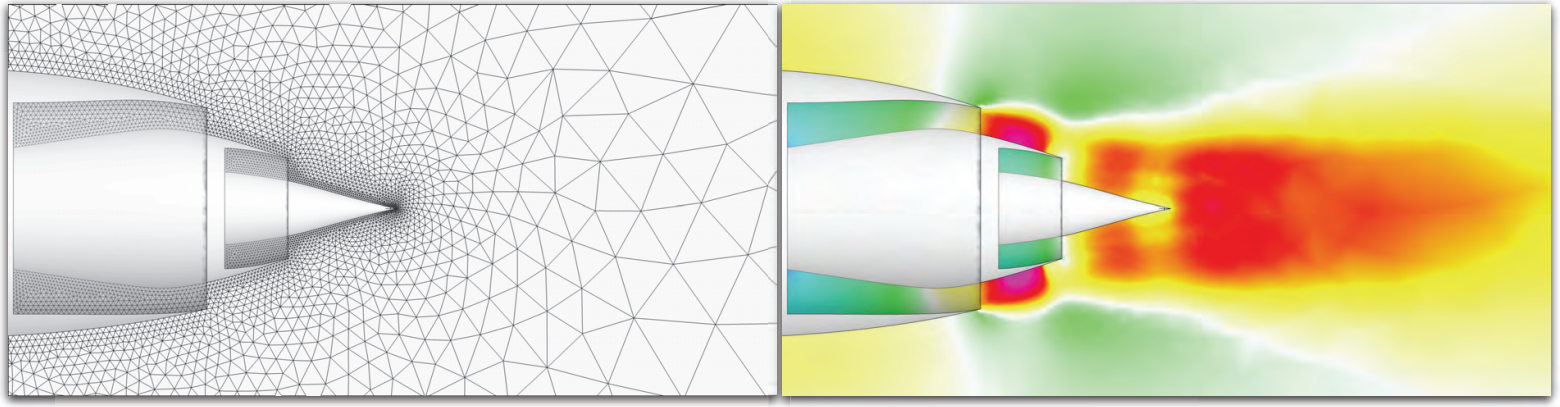
Convergence of error in C_D for a representative CFM56 engine



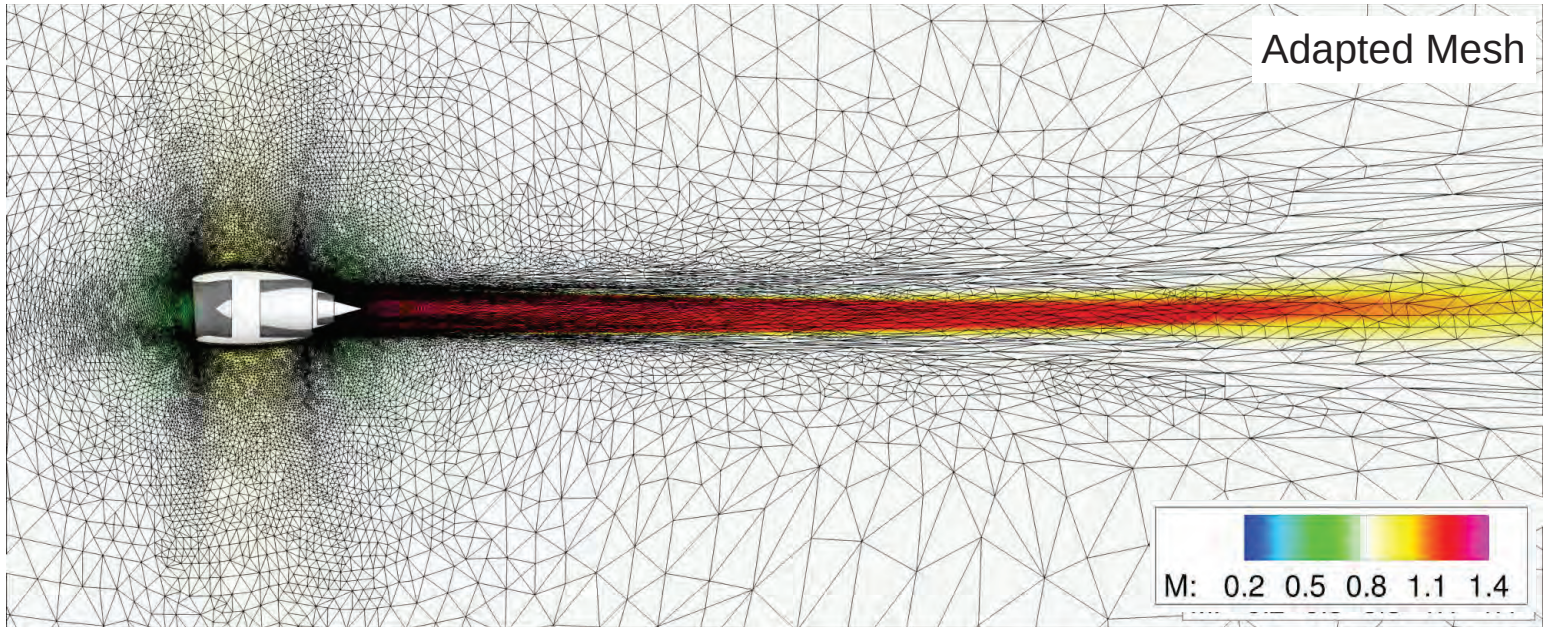
Adjoint-Based Mesh Adaptation (Drag)

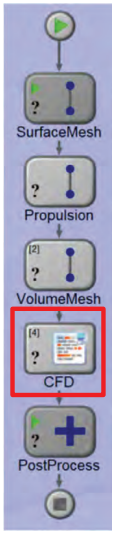


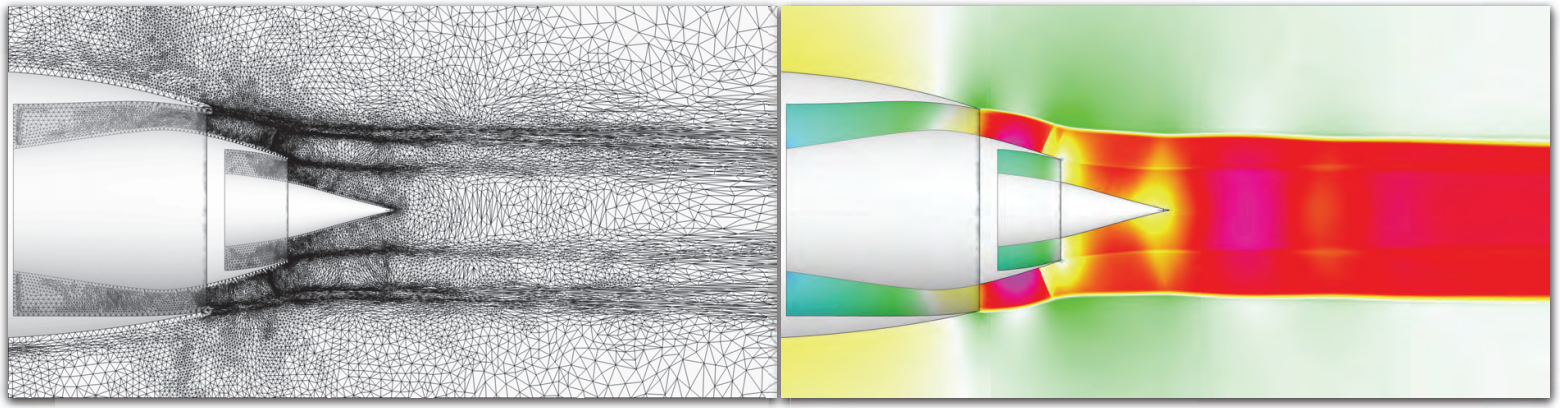




Adjoint-Based Mesh Adaptation (Drag)

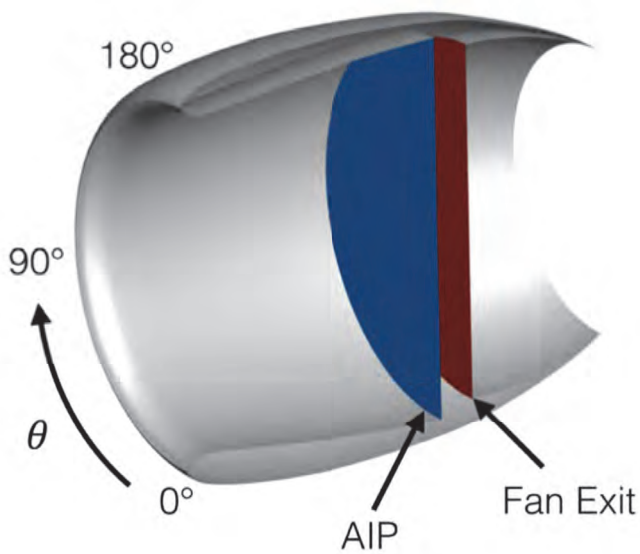


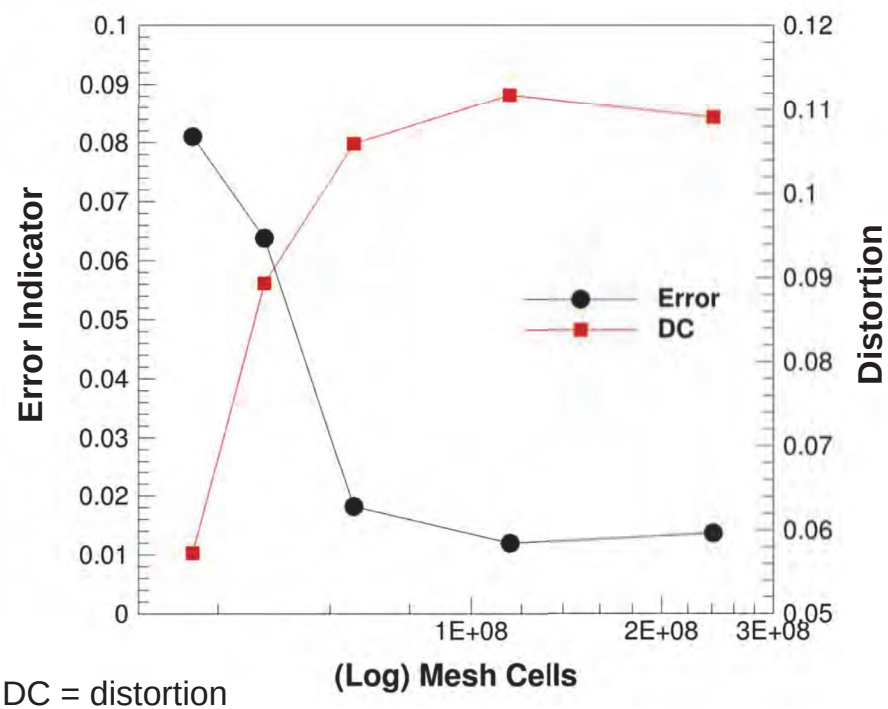




Adjoint-Based Mesh Adaptation (Distortion)

- Fan mass flow of 550 lbm/s
- Initial mesh size is 36.5 million tetrahedral cells
- 5 adaptation cycles with maximum element anisotropy restriction of 10
- Reduce the error in fan distortion calculation associated with mesh discretization
- **Distortion approximately double that of the non-adapted mesh**

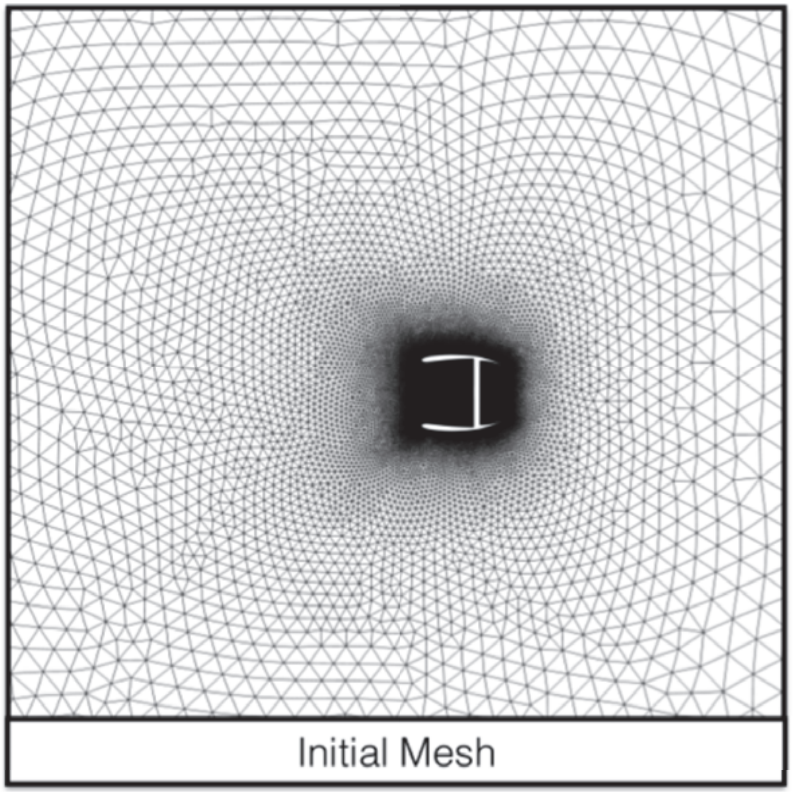




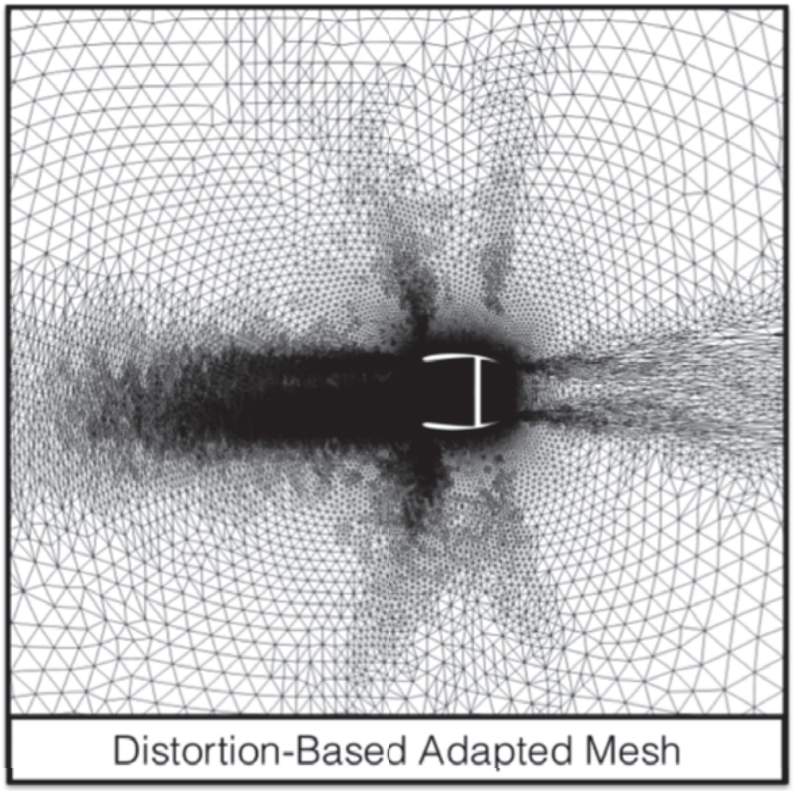
DC = distortion

Adjoint-Based Mesh Adaptation (Distortion)

36.5 million tetrahedral cells



241 million tetrahedral cells

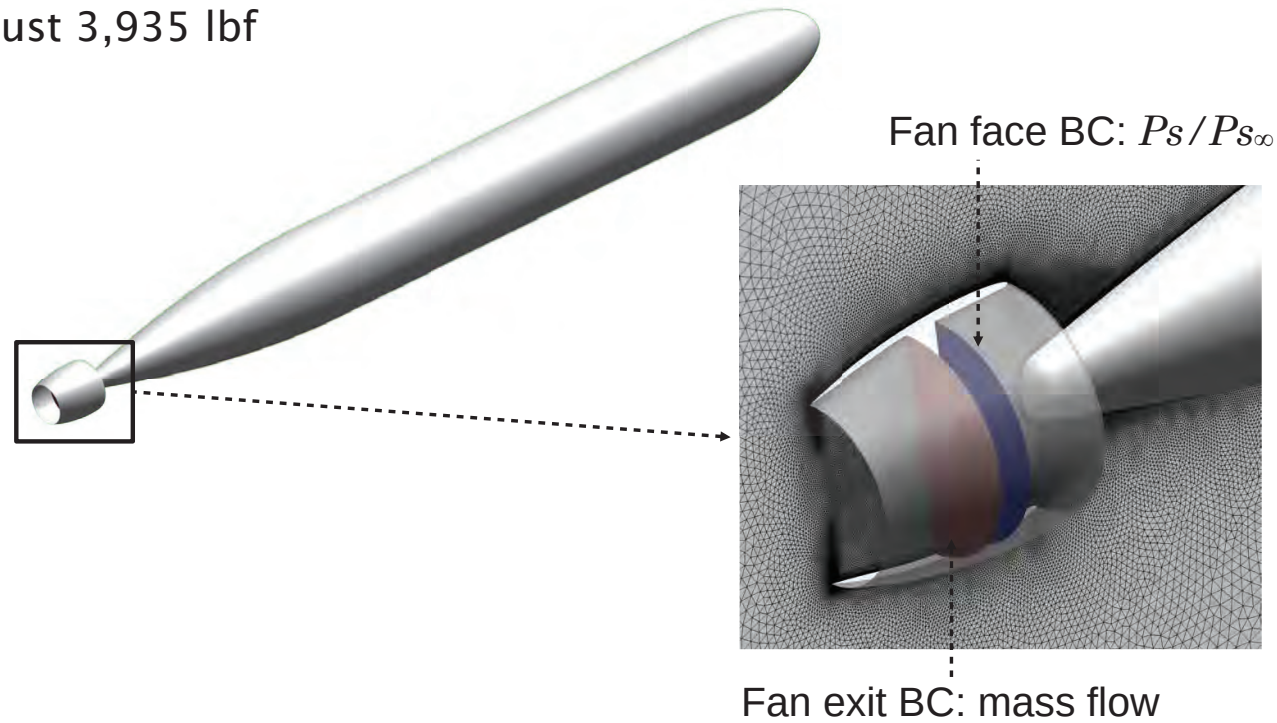


Verification of Automated FUN3D RANS Analysis Process

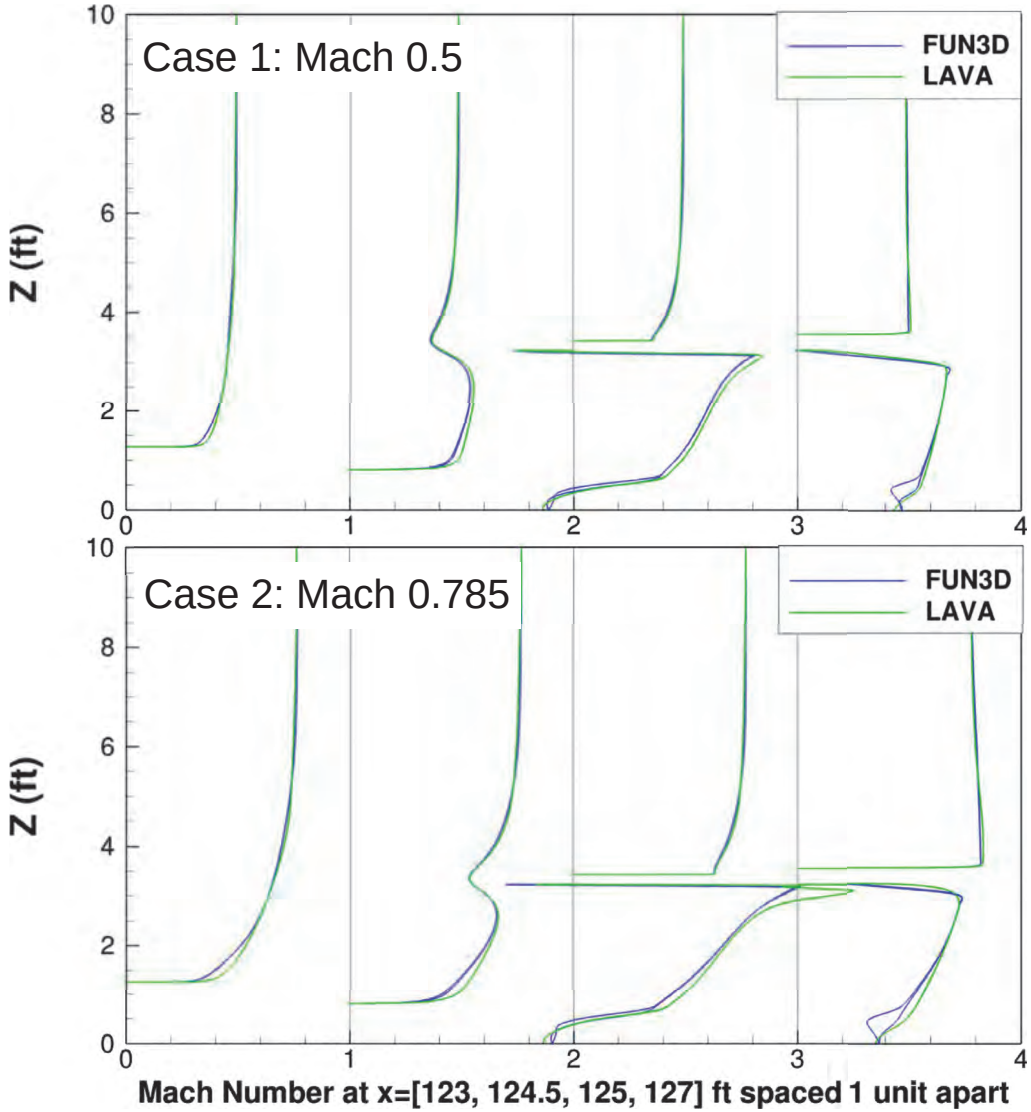
IBLI Tail-Cone Thruster BL Verification

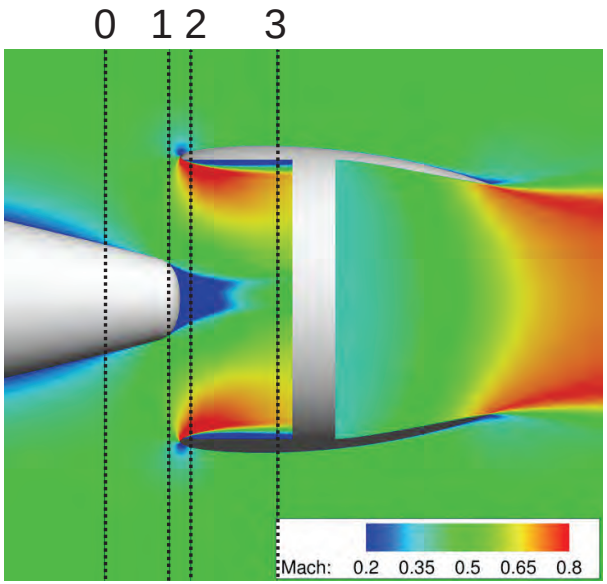
- Altitude 36,000 ft and AoA 0°
- **Case 1:** Mach 0.5, Re/L 1.13 million, mass flow 375 lbm/s, net thrust 5,778 lbf
- **Case 2:** Mach 0.785, Re/L 1.78 million, mass flow 400 lbm/s, net thrust 3,935 lbf

- Fully viscous to wall
- Initial grid spacing located at y^+=0.5
- Prescribed mesh (no adaptation)



IBLI Tail-Cone Thruster BL Verification





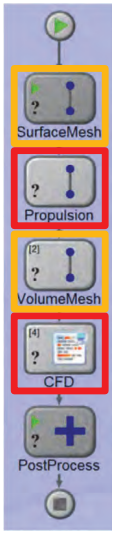
Mach contours for Mach 0.5 case

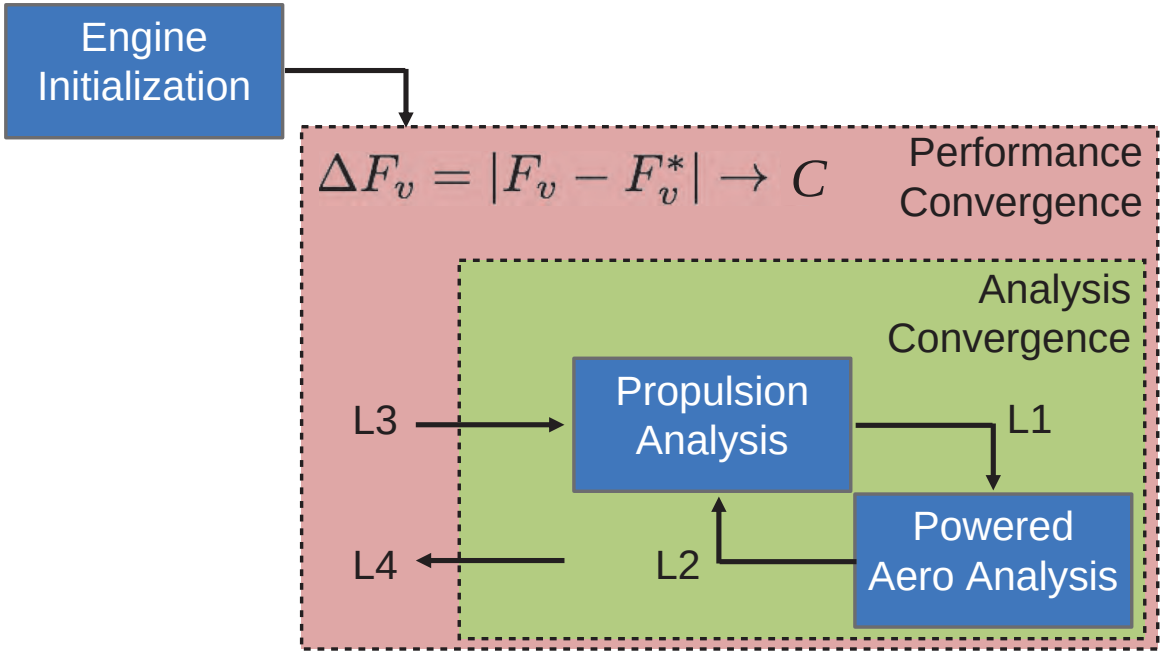
LAVA analysis was conducted at NASA Ames in response to TCT verification effort

Approach for Aero-Propulsive Analysis and Performance Coupling

Aero-Propulsive Analysis/Performance Coupling

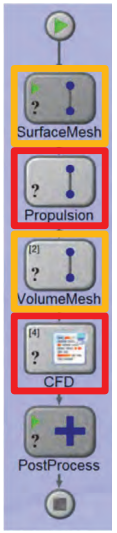
- Analysis convergence vs performance convergence
- Iterative convergence of *analyses through* feedback of *inlet pressure recovery*
- Iterative convergence of *vehicle performance* through *engine throttling or scaling*
- Engine models calculate flow parameters at specified boundary condition

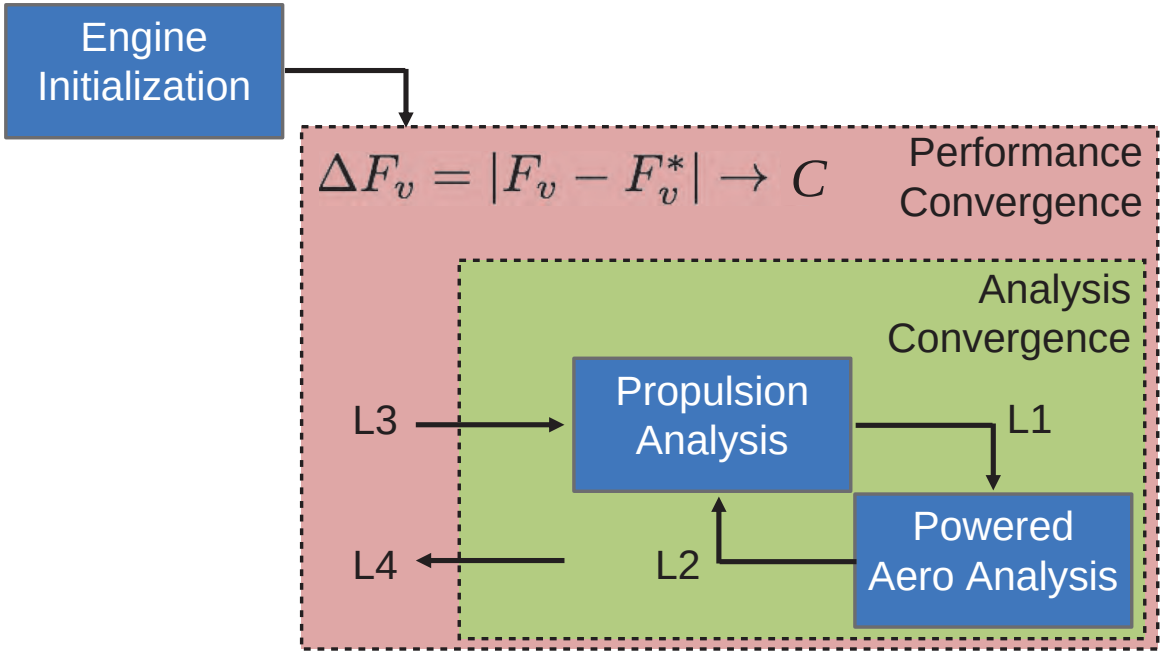




Aero-Propulsive Analysis Coupling

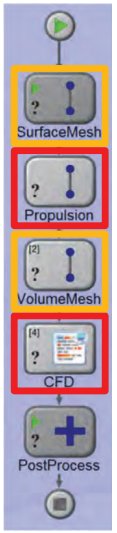
- L1: *A. Inflows - Ratio of static pressure at fan face w.r.t. free-stream static pressure*
  B. Outflows - Mass flow or ratios or total pressure and temperatures w.r.t. static free-stream pressure and temperature at nozzle plenum
- L2: Inlet pressure recovery (ratio of total pressure at fan face w.r.t. free-stream static pressure) calculated from CFD analysis

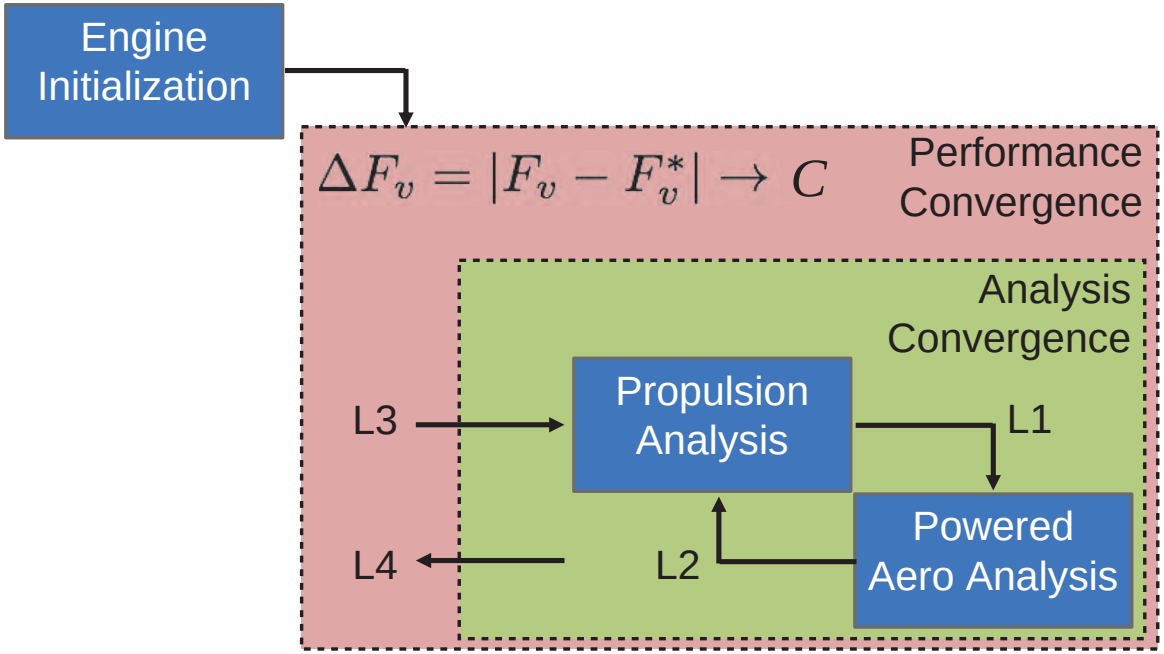




Aero-Propulsive Performance Coupling

- L3: Engine thrust setting or engine scale
- L4: Vehicle net forces and moments

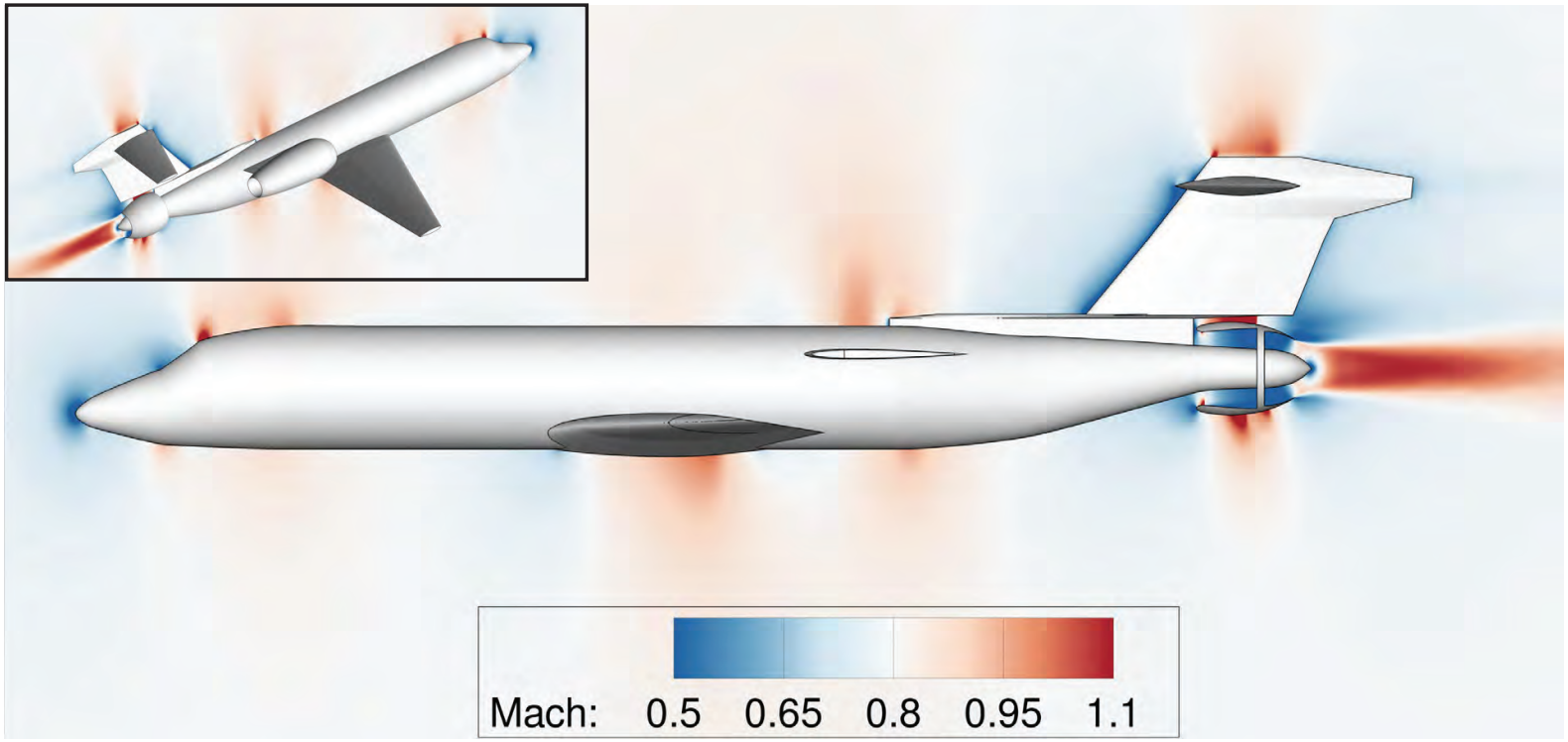




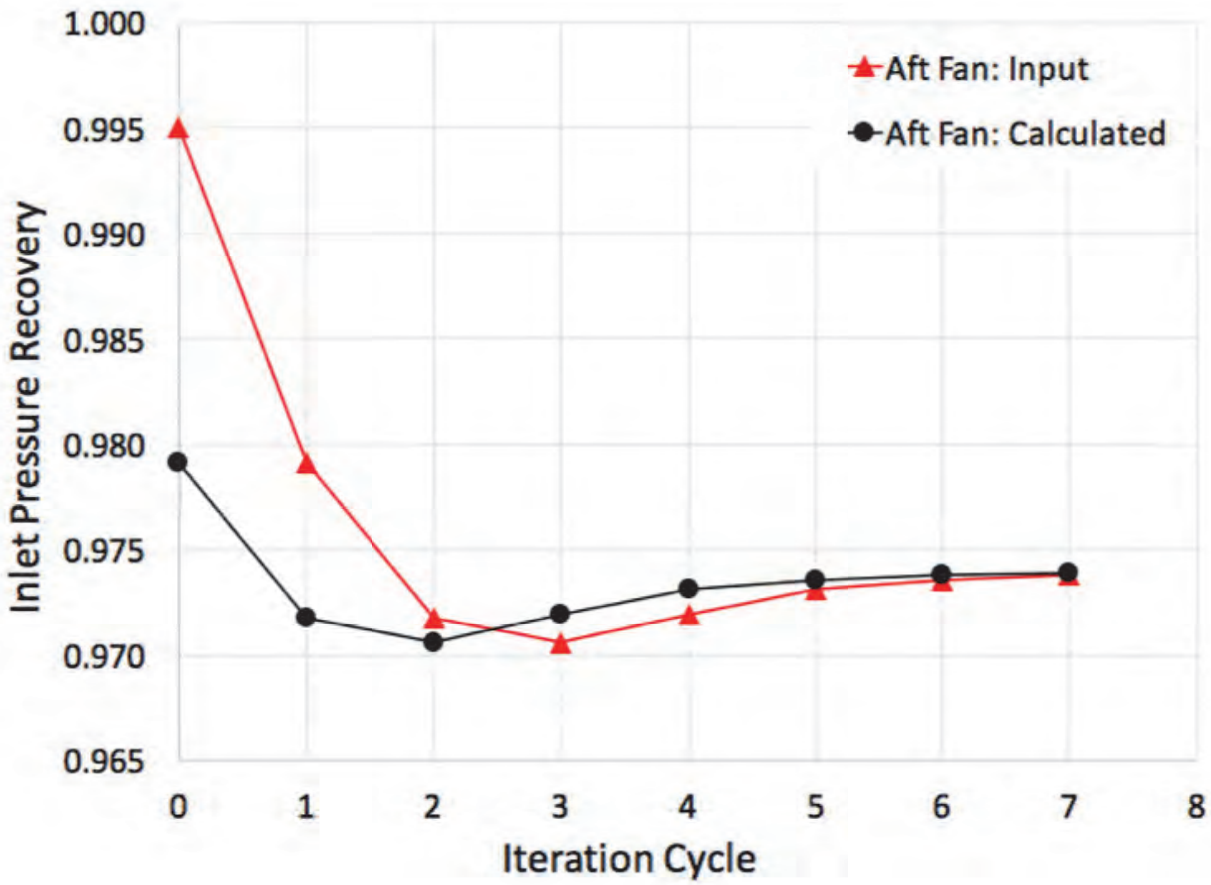
Analysis and Performance Convergence of Business Jet (MTA450) with Aft Fan

Aero-Propulsive Analysis Convergence

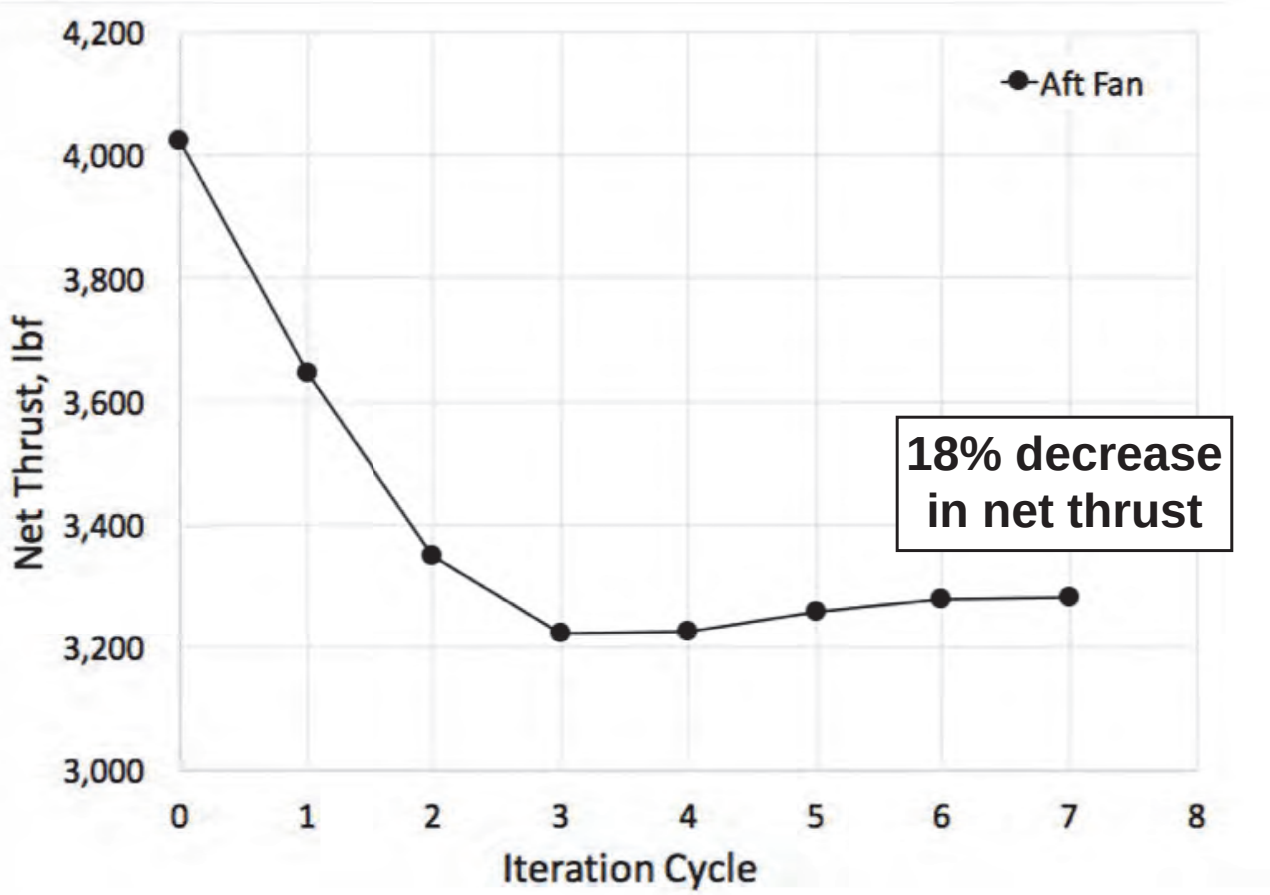
- MTA450 initially developed for CAS and loosely based on Gulfstream G450
- Powered main engines representative of Rolls Royce Tay-651 engine
- Mach 0.8, altitude 21,500 ft, AoA 2°, and aft fan mass flow of 400 lbm/s
- Inviscid (Euler) FUN3D analysis



Aero-Propulsive Analysis Convergence

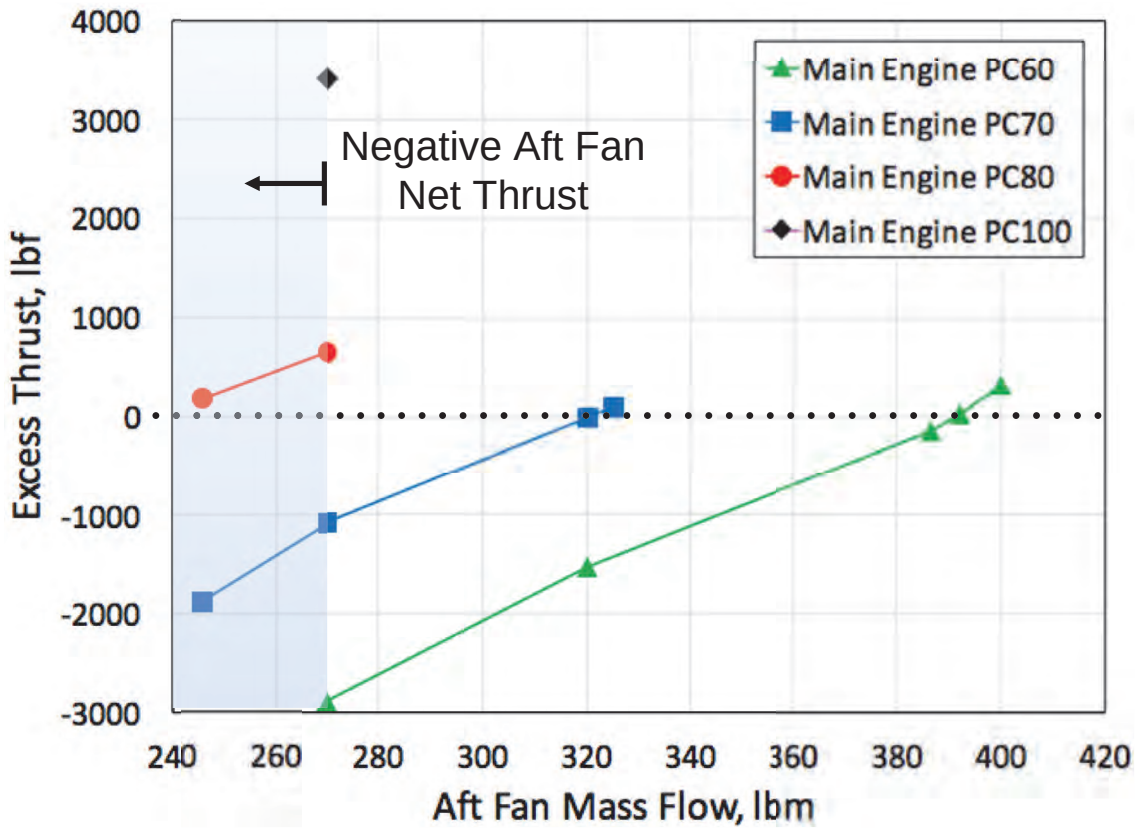


Aero-Propulsive Analysis Convergence



Aero-Propulsive Performance Convergence

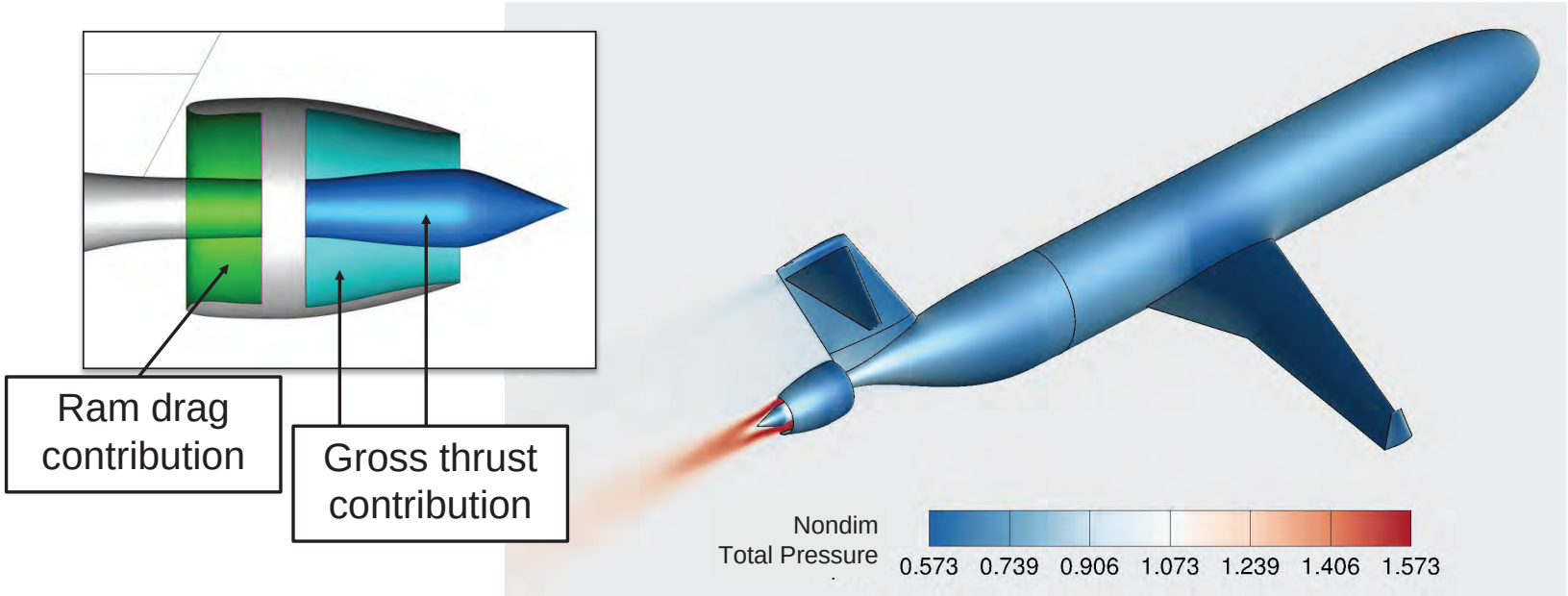
- Steady level flight condition at Mach 0.8, altitude 21,500 ft, and AoA 2°
- Main engine power (PC) and aft fan mass flow varied to achieve zero excess thrust
- Analysis convergence of aft fan is also performed at each performance iteration



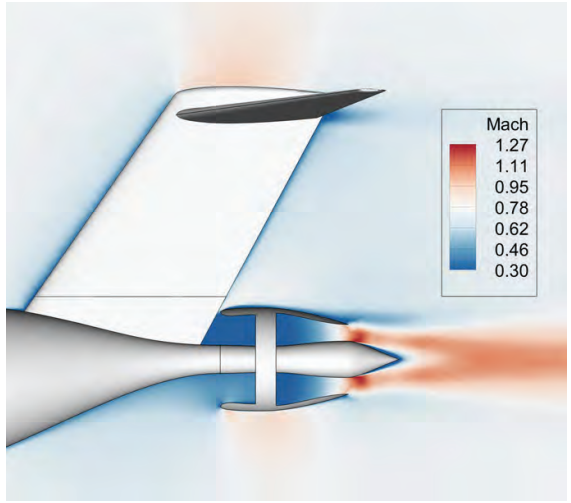
Aero-Propulsive Analysis Convergence of STARC-ABL Configuration

Aero-Propulsive RANS Analysis Convergence

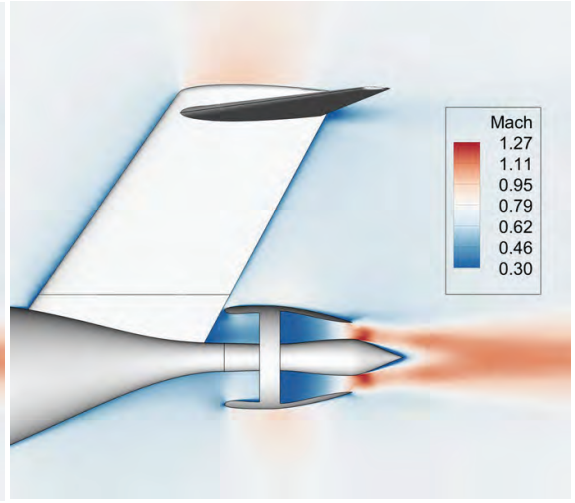
- Geometry is based on STARC-ABL (vb2_20170425) with a modified inlet and nozzle
- Mach 0.785, altitude 37,000 ft, AoA 2.4°, fan power 3,500 hp, mass flow 348 lbm/s
- FUN3D RANS analysis with Re/L 1.7 million
- Nozzle exit area is adjusted to produce approximately 2,000 lbf of net thrust
- Inflow condition (fan face) specifies static pressure ratio w.r.t freestream pressure
- Outflow condition (fan exit) specifies mass flow



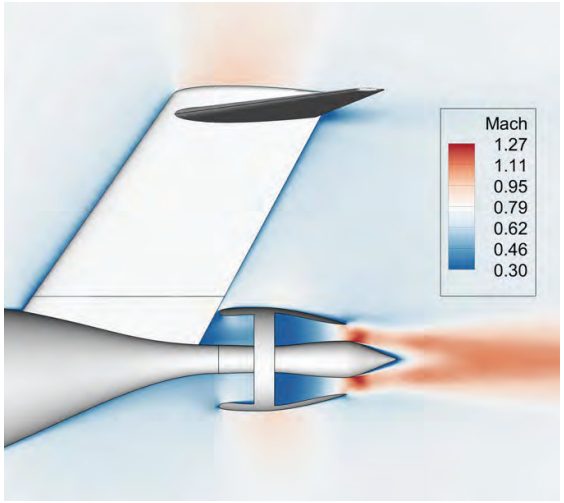
Aero-Propulsive RANS Analysis Convergence



FanSim Input Pr: 1.0
FUN3D Calculated Pr: 0.9163



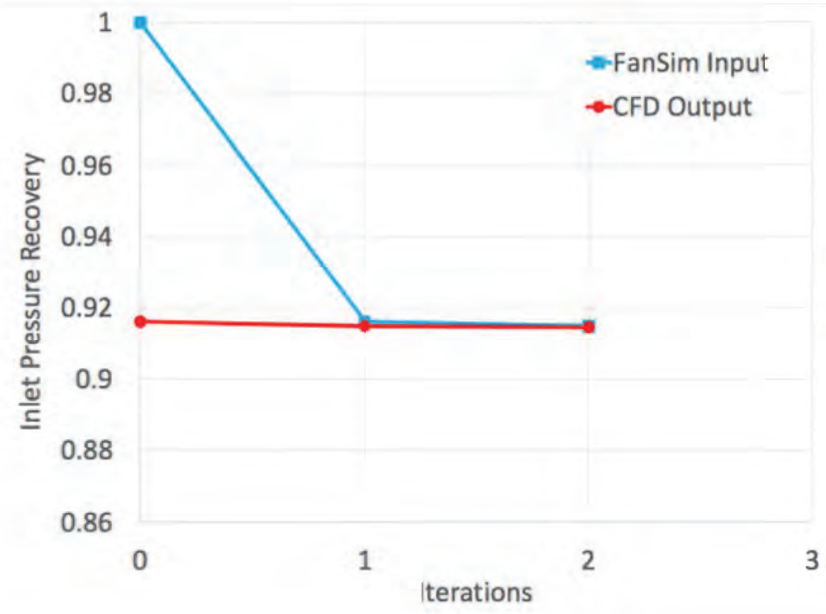
FanSim Input Pr: 0.9163
FUN3D Calculated Pr: 0.9151

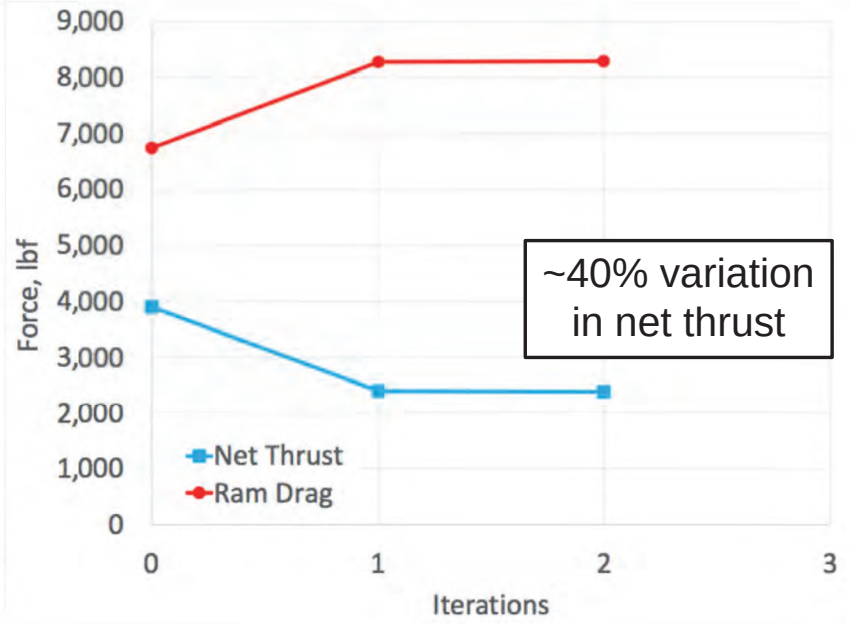


FanSim Input Pr: 0.9151
FUN3D Calculated Pr: 0.9148

- Inlet pressure recovery used as feedback/coupling variable
- Inflow and outflow mass flow discrepancy in FUN3D is less than 2 lbm/s

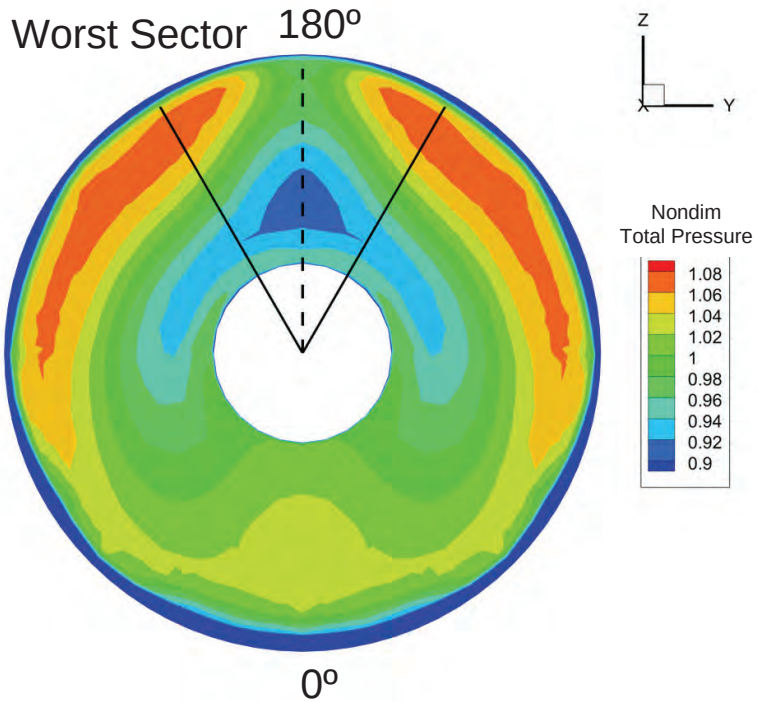
Aero-Propulsive RANS Analysis Convergence

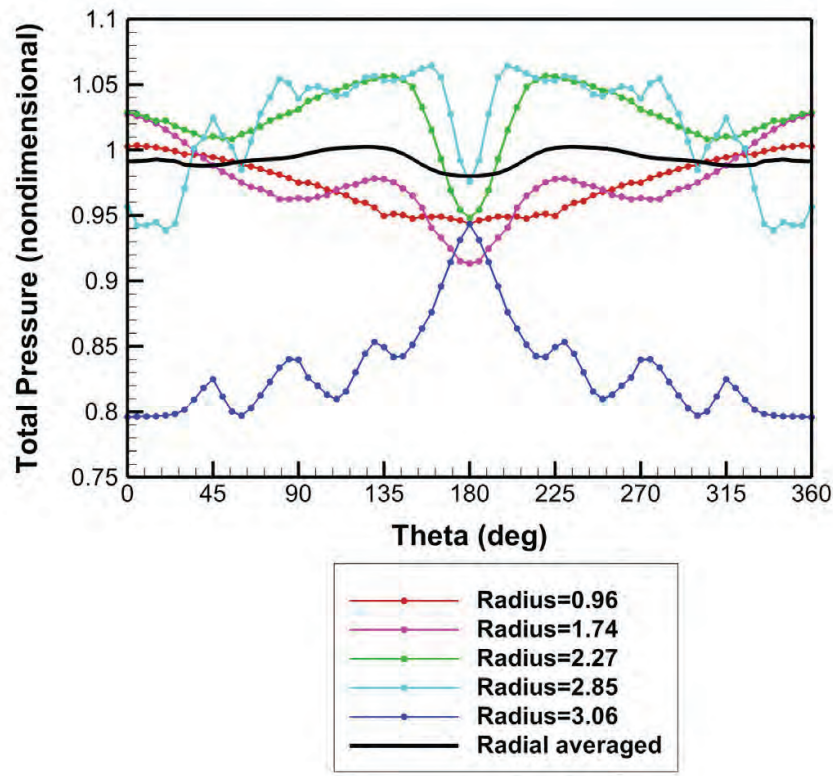




- Solution is well behaved and analysis convergence is achieved in few iterations
- Inlet pressure recovery converges quickly to 0.9148 and net thrust of 2,370 lbf
- Gross thrust is approximately constant at 10,678 lbf
  - *Inflow and outflow conditions are not coupled in FUN3D*
  - *Coupling enforced by the 1D fan model when analysis is converged*

Fan Distortion Analysis





- Sector angle is 60, number of radii is 50 and number of azimuths is 73
- Distortion (DC60) is 0.0696 and worst sector is 180º located in wake of vertical tail
- Nondimensional total pressure at the fan varies between 0.78 and 1.08

Summary

- ModelCenter framework has been developed to allow higher order analysis and design of aircraft concepts that exhibit high aerodynamic and propulsion coupling.
  - ***Reduce workload*** *required by the designer during the setup of CFD meshing and analysis through the use of automation when possible*
  - ***Rapid evaluation*** *of a greater number of concepts which is critical during conceptual design*
  - ***Leverage the iteration and optimization methods*** *in ModelCenter to achieve convergence between the aerodynamics and propulsion system*

- Inviscid (Euler) and viscous (RANS) analysis of aircraft concepts with any number of powered engines

- Adjoint-based mesh adaptation used to reduce error in C_L, C_D, L/D, and DC

- Calculation of propulsion performance from the CFD solution
  - *Net thrust*
  - *Engine mass flow*
  - *Mass- and area-weighted averages of flow parameters at all engine boundary conditions, fan face distortion, and inlet pressure recovery*

Summary

- Aero-propulsion problem decomposed into an analysis and a performance iteration
  - ***Analysis iteration*** *performed to converge the interaction between the aerodynamics and propulsion system using inlet pressure recovery as the feedback variable*
  - ***Performance convergence*** *achieved by scaling and/or throttling the propulsor to achieve a desired net vehicle force*
  - *Convergence process successfully demonstrated for a representative business jet (MTA450) and STARC-ABL concepts with integrated BLI fans*

Weaknesses and Future Work

- Design optimization with coupled aero-propulsion analysis using finite difference to calculate design gradient is not practical
- Propulsion design sensitivities needed for more efficient adjoint-based design
- Improve grid quality of the surface mesh by complementing OpenVSP with Pointwise as an alternative surface mesh generator
  - Anisotropic meshing in Pointwise allows better representation of the geometry with fewer number of surface triangles
  - OpenVSP will still be used as the geometry modeler to output an IGES/STEP file

Acknowledgment

- **Karl A. Geiselhart** at NASA LaRC for numerous discussions and recommendations related to propulsion modeling, for providing a fan propulsion model and the business jet configuration with an integrated aft fan that was used as a case study.

- **Jeffrey J. Berton** at NASA GRC for providing a parametric NPSS model of a representative GE CFM56 engine which was integrated into the framework to exercise the aero-propulsive analysis with adjoint-based mesh adaptation. This NPSS model was adapted from the CFM56-7B27 turbofan model developed by Georgia Institute of Technology for the FAA's Environmental Design Space (EDS) initiative (references provided below).
  - *Mavris, D.: "Environmental Design Space (EDS) Overview," Presentation to the Transportation Research Board, Papers and Briefings on the Development Program for the Aviation Environmental Tool Suite, Workshop no. 4, Dec. 6-8, 2006, URL: http://www.faa.gov/about/office_org/headquarters_offices/apl/research/models/history/media/05_DM_Overview-EDS_2006-11-28_FINAL.pdf [accessed February, 2014].*
  - *Kirby, M.R.; Mavris, D.N.: "The Environmental Design Space," 26. Congress of International Council of the Aeronautical Sciences (ICAS), Anchorage, Alaska, Sep. 14-19, 2008, ICAS 2008-4.7.3.*

- **Christopher M. Heath** (NASA GRC), **Alaa Elmiligui** (NASA LaRC), **Richard L. Campbell** (NASA LaRC), **Michael A. Park** (NASA LaRC), and **Jan-Renee Carlson** (NASA LaRC) for their guidance involving mesh adaptation, propulsive modeling, BL grid sizing, and other topics related to FUN3D.

Questions

CARL Computational Results and Challenges

30 May 2018

Dr. Darius D. Sanders
Compressor Aero Research Lab
Turbine Engine Division
Air Force Research Laboratory

Integrity ★ Service ★ Excellence

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Agenda

- **Introduction**
  - CARL Mission & CFD Challenges
- **StreamVane Distortion Generator**
  - Flowfield Characterization Study
  - Future work using StreamVane as a swirl distortion generator
- **Coupled Distortion Generator-Fan CFD**
  - Harmonic Balance CFD Method Applied to Distortion Prediction
  - Comparisons with unsteady Full Annulus CFD
- **Summary & Conclusions**

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Introduction

- **The Compressor Aero Research Lab (CARL) mission**
  - Enhance the understanding of complex internal flow physics within fans and compressors through analytical, computational, and experimental methods
- **How do we do this?**
  - High-fidelity analysis of design and experimental configurations in support of research goals
  - In-house, 700 core compute cluster
  - DoD Supercomputing Resource Centers (DSRCs)
  - Use of government and COTS CFD software with in-house fan and compressor design tools

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CFD Challenges

- **Minimum Working Domain**
  - Representative inlet and exit boundary conditions required
  - Upstream distortion generator or unsteadiness source required in same computation as the fan
- **Adequate Resolution of Critical Flow Features**
  - Mesh adaptation to fully resolve strength and structure of distortion flow features
- **Increasing Fidelity of Analysis Early in Design**
  - Harmonic Balance for coupled inlet-fan distortion calculations
  - Adding aeromechanic predictive capability, e.g., forced response prediction based on harmonic balance flow and mode shapes

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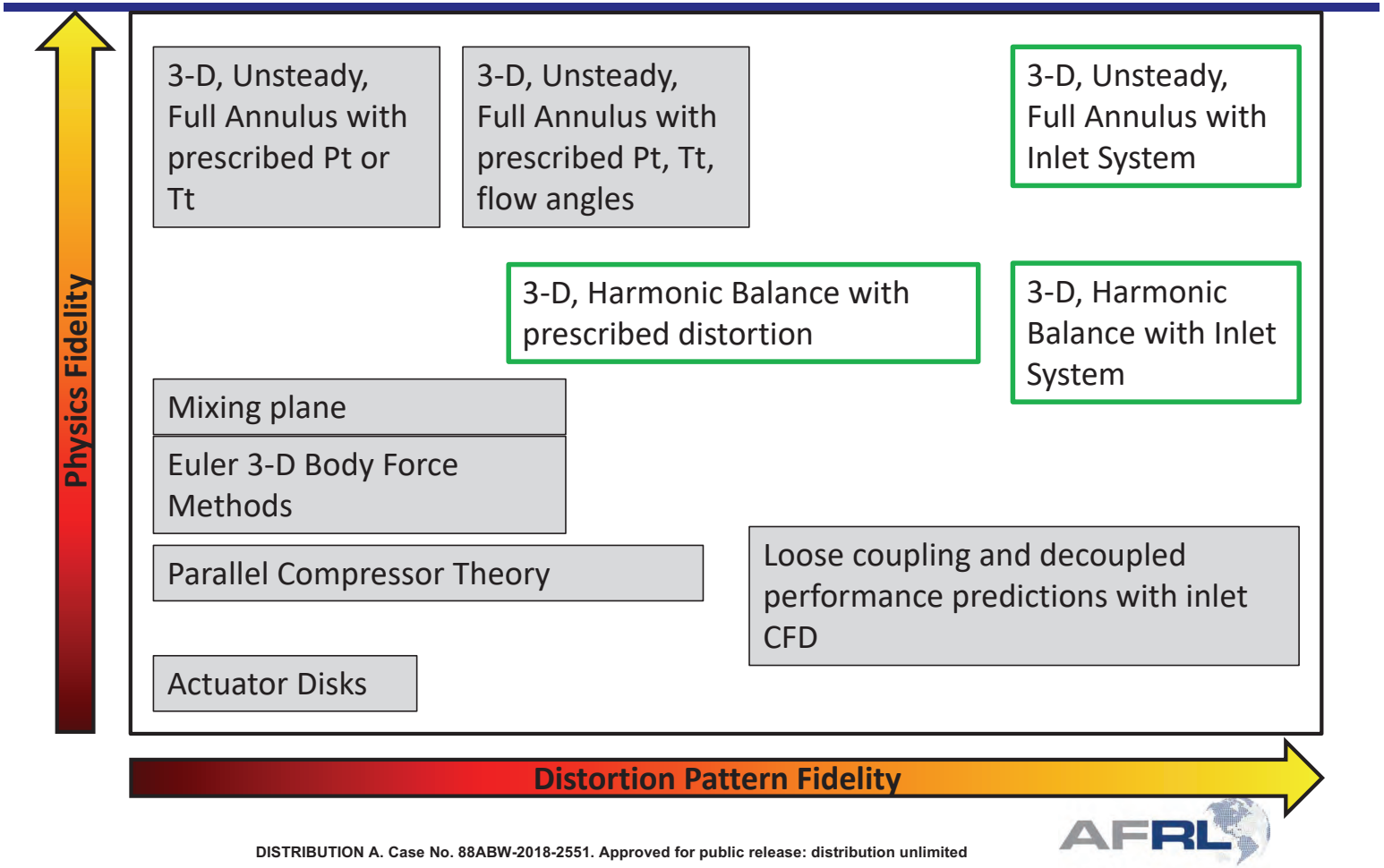
Physics Fidelity vs. Distortion Pattern Fidelity



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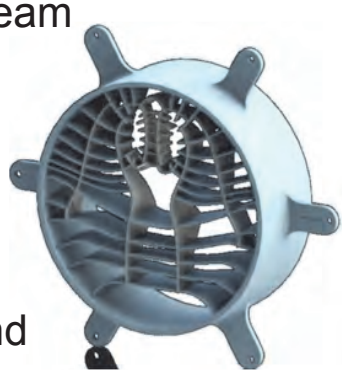
StreamVane™ Distortion Generator

- **Steady-state swirl distortion generator for user-defined flowfield invented by Virginia Tech**
  - User-defined vector field at specified distance downstream
  - Bulk and localized, complex flow features possible
  - 3D printed turning vanes placed to guide flow



StreamVane™

- **Computational Contributions**
  - Development of rapid, repeatable meshing, solution, and adaptation methodology
  - Computation of flowfield to compare with VT and AFRL experiment
  - Assessment of distance, scaling, Mach, and Reynolds number effects
  - Surface pressure prediction for finite element analysis

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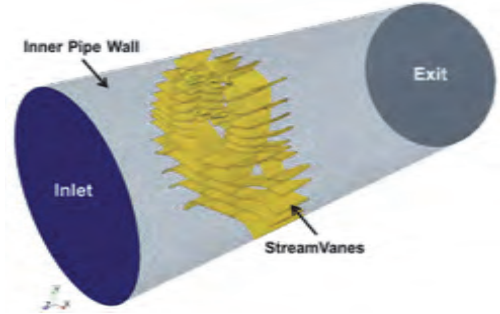
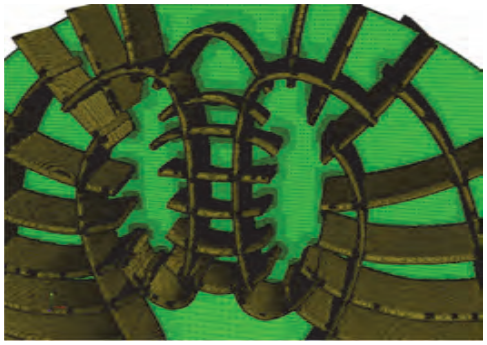
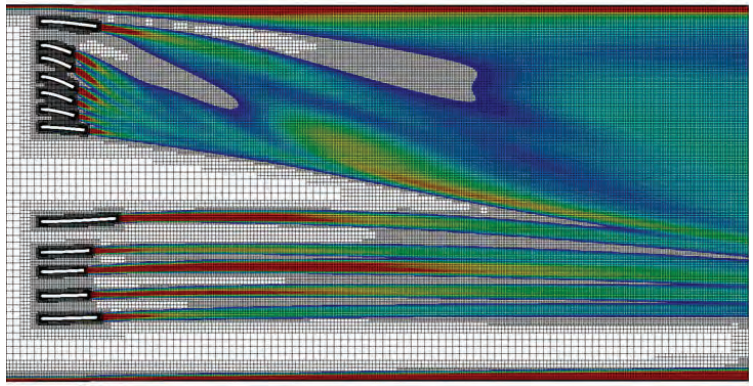
CFD Numerical Method

❑CFD completed using Star-CCM+

- BC's applied 1D upstream, and 2D downstream of StreamVane
- Used an unstructured trimmer mesh with wake region refinement
- Applied steady RANS using Menter's k-ω (SST) model







❑Complex StreamVane geometry required a large cell count

- 48.8M hexahedral cells (y+ range of 0.1-7)
- Used mesh refinement to resolve wake region

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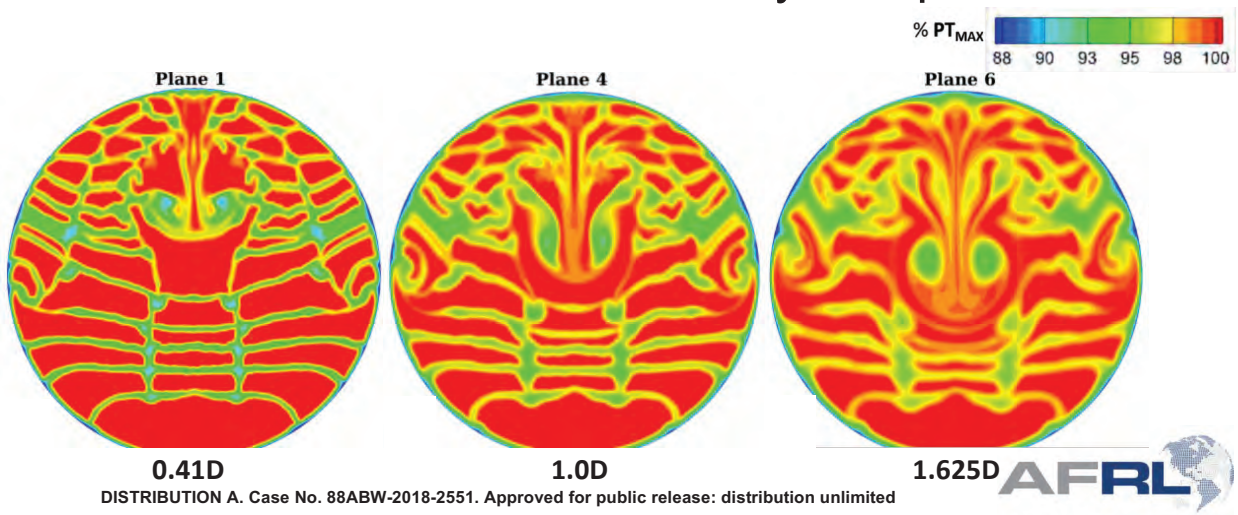
Exit Total Pressure Axial Extent

- **CFD Numerical Prediction Survey**
  - 0.41D spacing illustrates losses originating from the vanes
  - Contours show qualitatively the amount of diffusion that occurs as the wakes propagates downstream
  - Significant amount more diffusion in the experimental survey
- Local mesh refinement produced coherent wake structures that would have otherwise numerically dissipated



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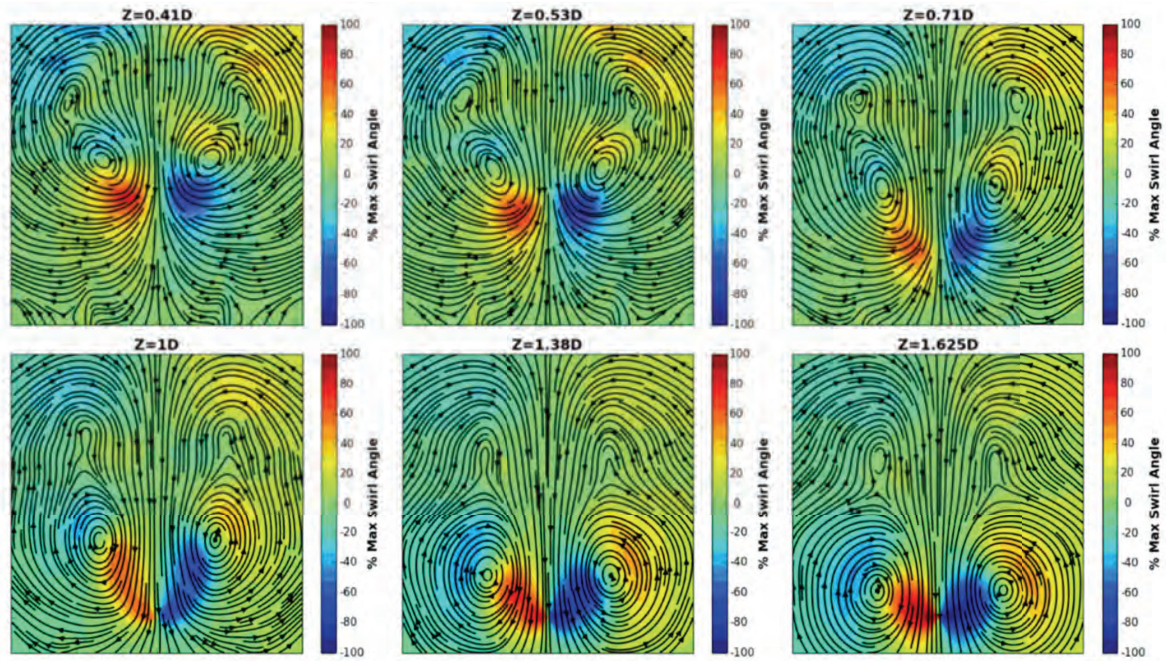
Secondary Flow Axial Extent

❑ Star-CCM+ CFD Survey

- Same six planes surveyed with CFD as with VT PIV
- The swirling flow is considered disorganized until 1D axial position



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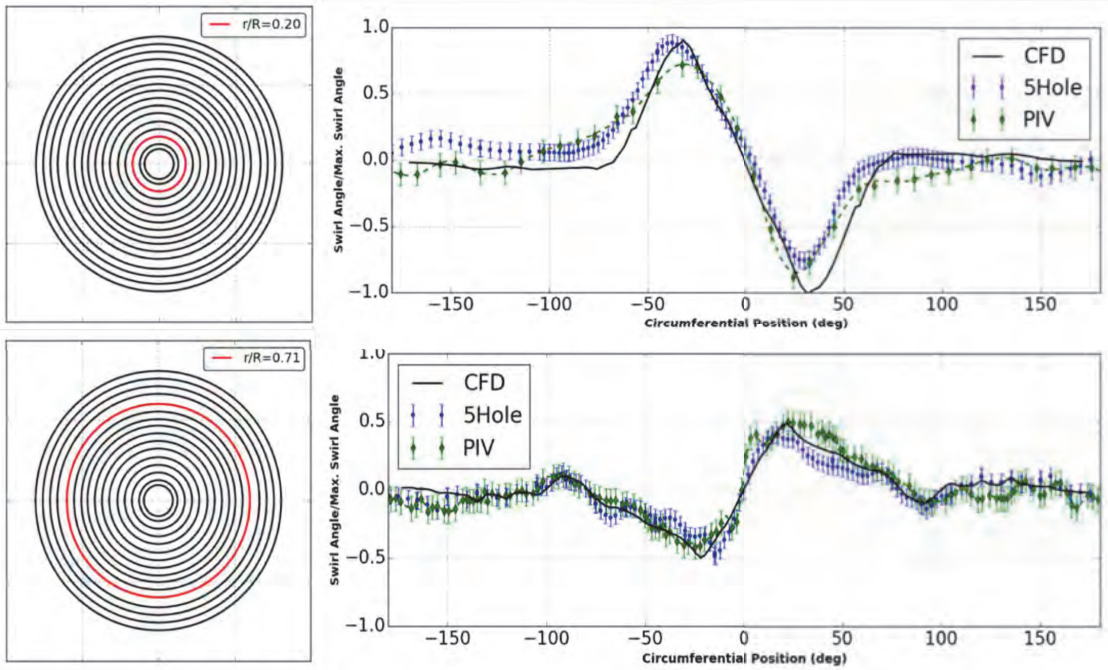
Case Comparison of the Circumferential Distribution of Swirl

- CFD produced a symmetric swirl distribution at peak swirl locations
- 5-Hole probe and PIV case showed asymmetry



- Improved agreement at outer radii, more variability in position at inner radii

➢ Case comparison shows the Mach No and scaling effects were not substantial in effectively characterizing the StreamVane flowfield

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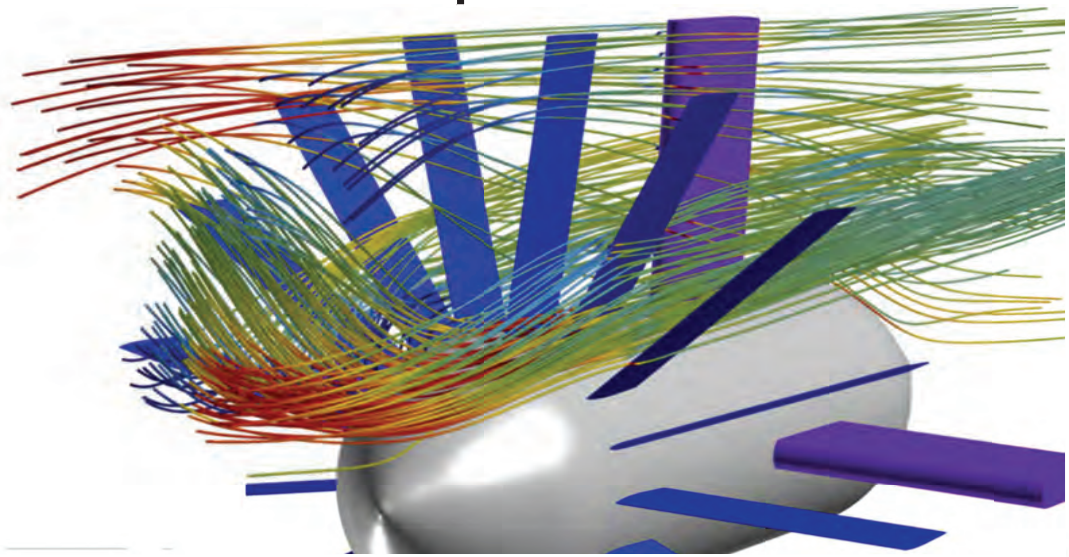
StreamVane™ with Centerbody

- **Flowfield evaluated with Centerbody and with IGVs**
  - Understand redistribution of swirling flows due to central blockage
  - Obtain better prediction of flowfield upstream of fan
- **Full Annulus Fan CFD with StreamVane™ Boundary Condition for comparison to current fan tests**



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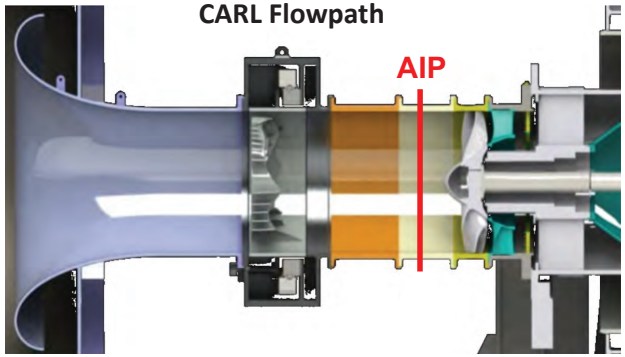
StreamVane™ Results

- **StreamVane™ swirl generator**
  - Highly detailed swirl patterns can be predicted and generated
  - Future StreamVane designs will consider migration of flow features to assure the desired flowfield at the AIP
- **Defining the distance between an AIP and StreamVane**
  - StreamVane™ produces a minimal pressure distortion at one duct diameter as the design intent
  - Radial and circumferential movement of the flowfield quantified for introduction in front of fan stage

➢ **StreamVane technology improve the ability to design future distortion-tolerant compression systems**



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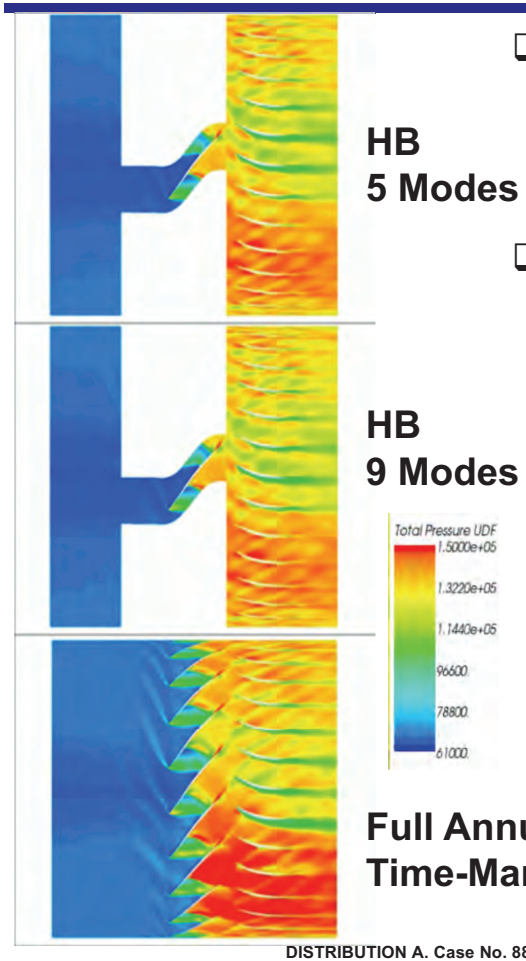
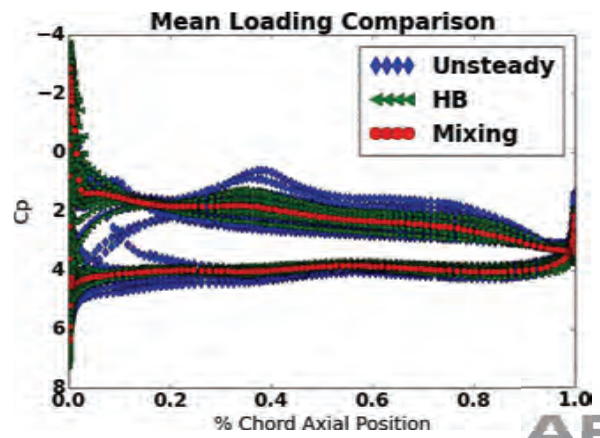
Coupled Distortion Generator-Fan Analysis



- **Comparison of HB & FA CFD methods applied to coupled distortion-generator fan application**
  - Inlet conditions set by distortion generators rather than an imposed total pressure BC
- **Harmonic Balance shows qualitatively similar distortion transfer behavior as Full Annulus CFD**
  - Wide variation of pressure on stators implies different mechanical design requirements
  - HB does not capture full range of loading change



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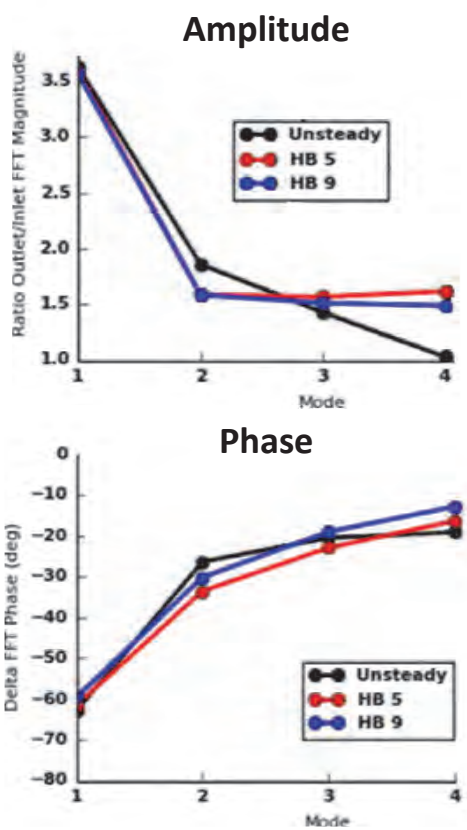
Coupled Distortion Generator-Fan Analysis



- ❑ Harmonic Balance is a tenable method for computing distortion transfer in coupled systems, but misses certain physics
  - Lack of complete reconstruction of flow field features
  - Unsteadiness in upstream volume will only be driven by the rotor passing and its harmonics
- ❑ Full annulus has the highest fidelity but is very resource-intensive for rapid analysis
- ➢ Provides a viable CFD method for flowfield prediction in coupled distortion-generator fan applications

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Summary

❑ Challenges

- Well-defined domain and boundary conditions
- Resolution of critical flow features (temporal and spatial adaptation)
- Increasing fidelity of analysis in early design phase
- Requirements for high-fidelity computations
- Fluid-Structure Interaction for coupled systems

❑ Key Results

- StreamVane flowfield was characterized using experiments generating complex swirl patterns
- StreamVane will be applied upstream of centerbody and fan for further comparison to experiment
- Harmonic balance CFD method successfully demonstrated for use in coupled distortion-generator fan applications

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Conclusions

- Execution of organic R&D effort enables continuous improvement and addressing challenges
- Comprehensive CFD simulation methodology based on extensive experimental validation is essential for consistent, accurate predictions
- High-fidelity CFD methods are required for distortion generators and quantifying aspects of distortion transfer in propulsion systems

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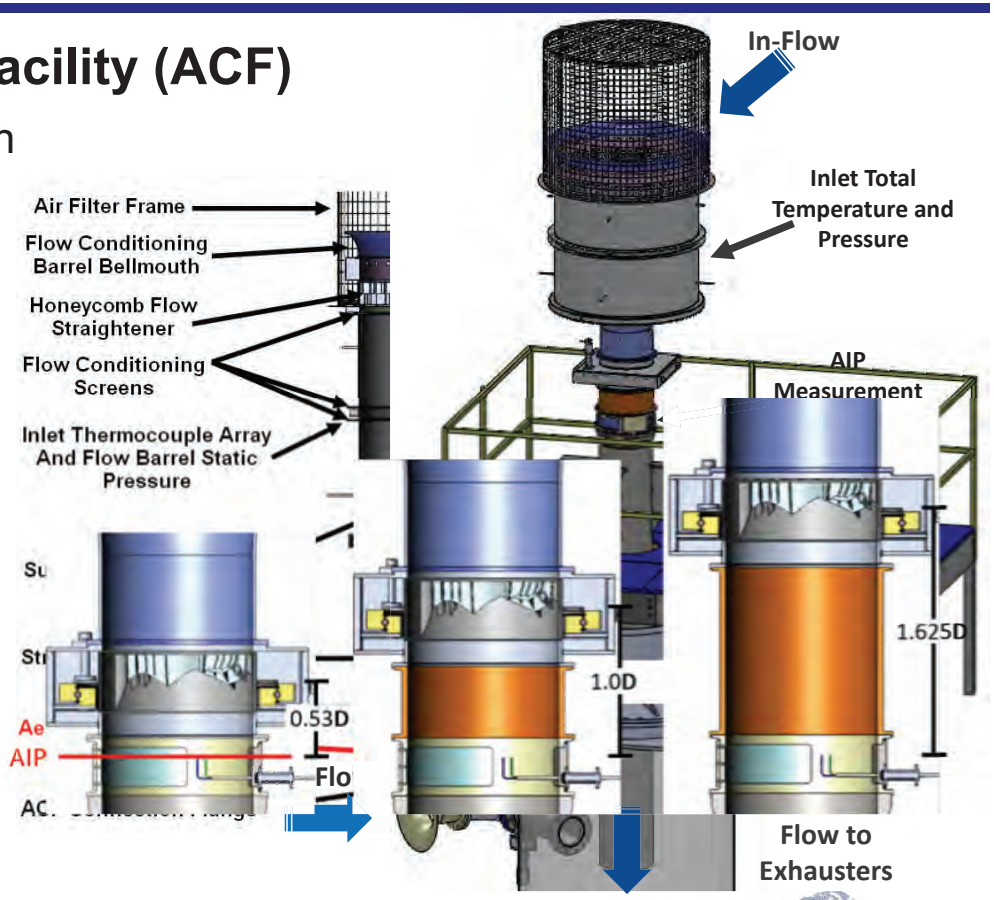
StreamVane™ Experimental Evaluation

❑ Annular Cascade Facility (ACF)

- Vertical test configuration
- 17 inch diameter test section
- Utilizes two gas turbo exhauster to pull up to 70lbm/s
- Closed-loop feedback control of Mach number to within ±0.5%
- 10 duct diameters in length before flowpath change
- Various stages of Flow conditioning
- AIP location is fixed



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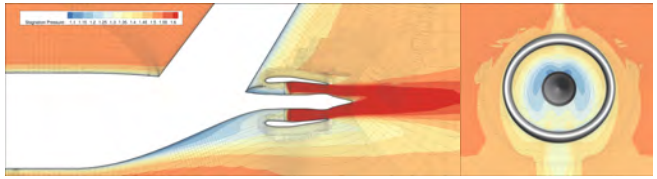

Coupled Aero-Propulsive Design Optimization Of a Boundary Layer Ingestion Propulsor

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NASA Glenn Research Center

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Science and Technology Corporation, Ames Research Center

May 30, 2018

Acknowledgements

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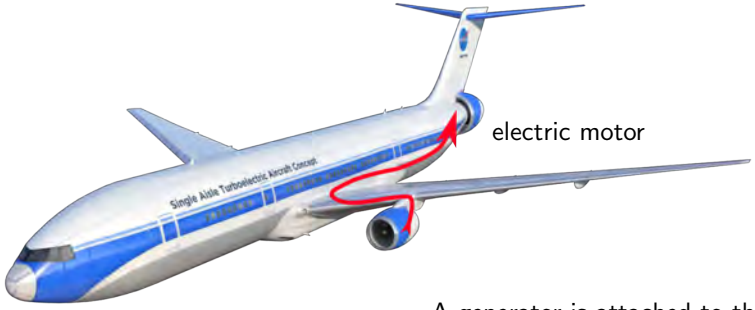
  - Dr. Joaquim R. R. A. Martins and
    Dr. Charles Mader (Univeristy of Michigan)
  - Dr. Eric Hendricks (NASA Glenn Research Center)
- This work was funded by:
  - Transformational Tools and Technologies (T^3) project
  - Advanced Air Transport Technology (AATT) project

NASA's STARC-ABL adds a turbo-electric BLI tail cone thruster (TCT) to a conventional airframe

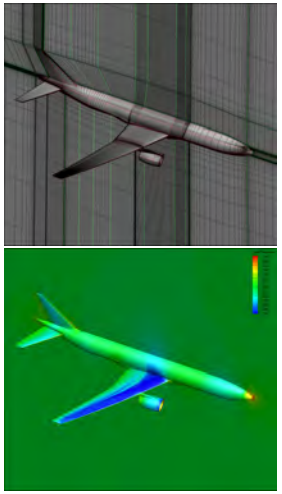


A generator is attached to the low-speed spool on each under-wing engine

We performed studies on the effects of propulsion system sizing on a BLI TCT aircraft configuration using efficient gradient based optimization of fully coupled aeropropulsive models.

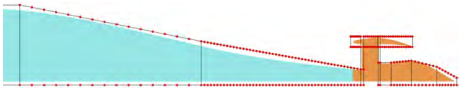
Aerodynamics are modeled in ADflow, a RANS CFD solver with an adjoint developed by the University of Michigan

- Based on the SUmb solver of van der Wiede et al. [AIAA 2006-0421]
- Parallel, finite-volume, cell-centered, multiblock, RK-NK solver for RANS Equations
- Spalart-Allmaras turbulence model
- Adjoint developed using algorithmic differentiation (AD) to evaluate partial derivatives
- Full turbulence adjoint

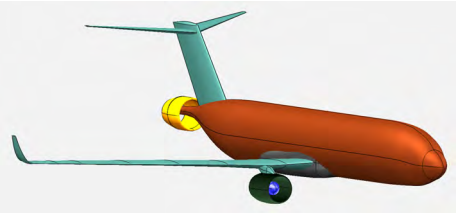


Geometry is handled by two different approaches: Free form deformation or OpenVSP

FFD is used for a simplified 2D axisymmetric model

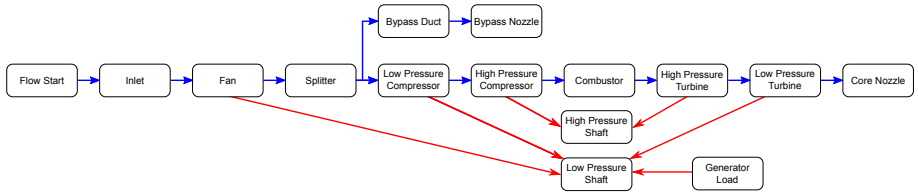


OpenVSP is used for the full 3D configuration



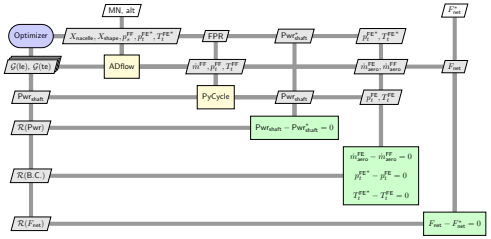
Propulsion model is built with pyCycle, a 1D cycle analysis library with analytic derivatives developed at NASA Glenn

- Uses the same physics as NPSS with CEA thermo package
- Developed with the OpenMDAO software stack
- Partial derivatives computed via hand differentiation, and uses OpenMDAO to compute the total derivatives



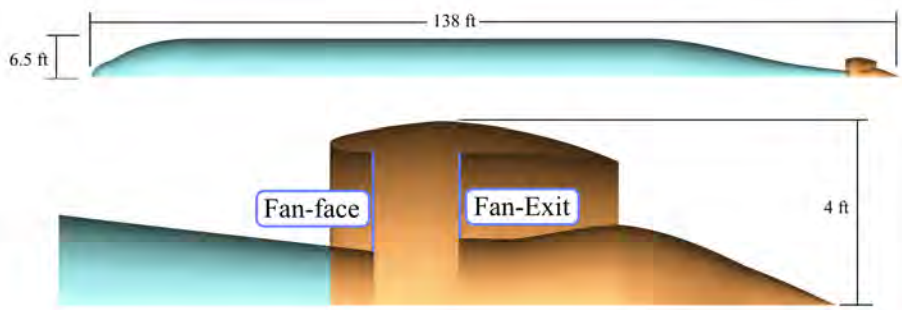
OpenMDAO is used to assemble the coupled model and compute coupled derivatives for optimization

- Open-source framework, specializing in efficient gradient based MDO
- Parallel execution and distributed memory via MPI
- Can compute coupled derivatives for an arbitrarily complex multidisciplinary model with 1000's of components and millions of degrees of freedom



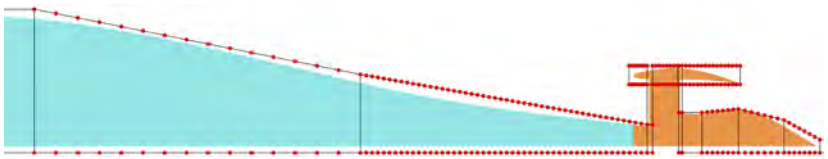
For BLI propulsion systems, aeropropulsive interaction is a primary effect that can only be captured with fully coupled models

To study the basic aeropropulsive interactions, the STARC-ABL configuration is simplified



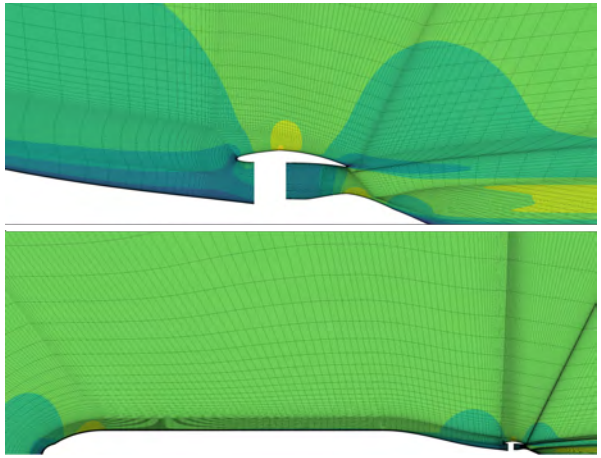
- Loosely based on 737 fuselage dimensions
- Removed wing, tail, and under-wing engines to simplify the analysis

Geometric shape changes are done via free form deformation (FFD)



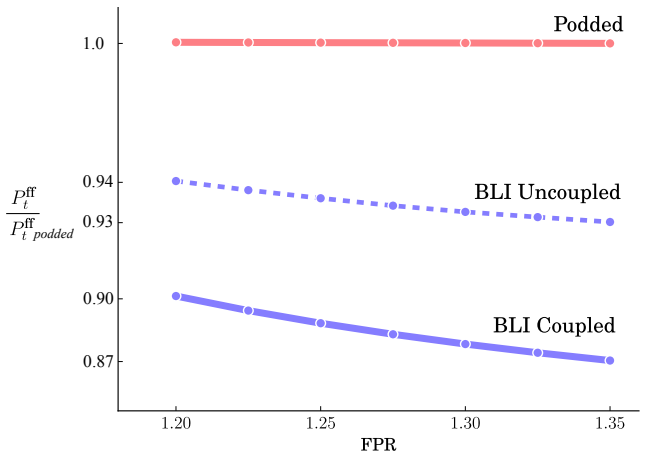
- fine shape changes along the aft fuselage, nacelle, and plug are made via motion of individual control points
- propulsor can be resized by rigidly moving all the nacelle control points together

Very inexpensive aerodynamic model that captures the central aeropropulsive effects



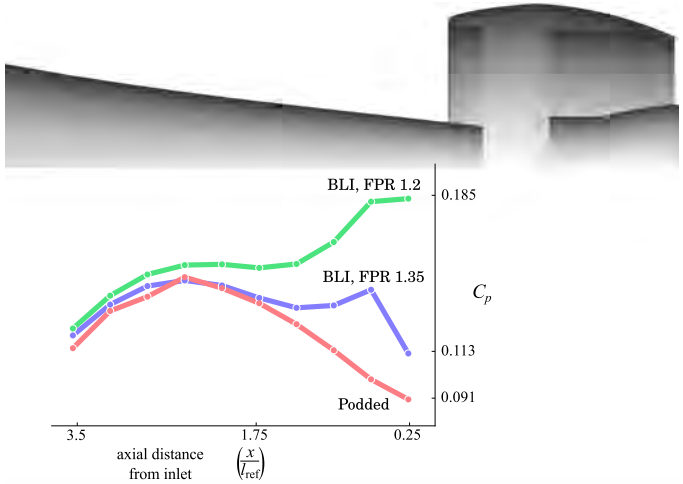
- $\approx$ 170,000 cell mesh
- solution time $\approx$ 2 minutes
- aeropropulsive coupling through powered boundary conditions

Uncoupled analysis over predicts inlet total pressure recovery



Inlet total pressure recovery is a critical propulsion performance parameter

Surface pressure distributions on the aft fuselage are affected by presence of the propulsor



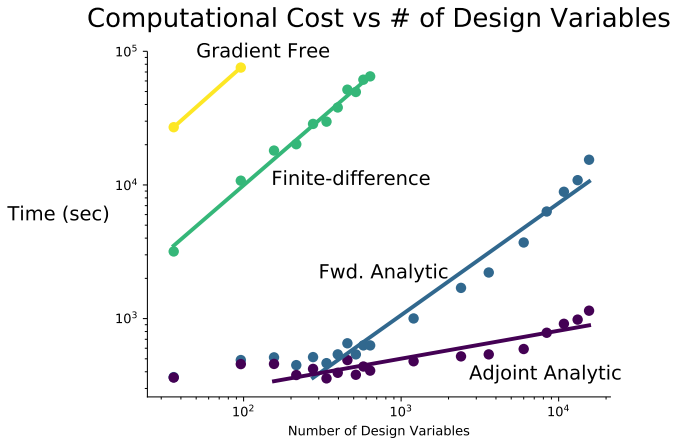
This causes propulsion sizing and throttle dependent C_L, C_D, C_M

Throttle-dependent pitching moment was observed in wind-tunnel testing of the D8 aircraft

"During the tests, the model angle of attack was found to change when the propulsor power was varied, through compliance of the force balance, due to lift-producing changes in the flow around the nacelles and reduced pressure on the top aft fuselage of the BLI configuration."

Alejandra Uranga, Mark Drela, Edward Greitzer, Neil Titchener, Michael Lieu, Nina Siu, Arthur Huang, Gregory M. Gatlin, and Judith Hannon. "Preliminary Experimental Assessment of the Boundary Layer Ingestion Benefit for the D8 Aircraft," 52nd Aerospace Sciences Meeting, AIAA SciTech Forum, (AIAA 2014–0906)

Aeropropulsive coupling creates a large and complex design space. Gradient based optimization is the most efficient tool to navigate that design space, enabling the use of a fully coupled model for design.



Multiple design optimizations for different BLI propulsor sizes showed that the overall propulsion system sizing depends heavily on power transmission efficiency (η_{trans})

The optimization problem, with 316 design variables and 11 constraints, was run to a specified $C_{F_x}^{\text{net}*}$

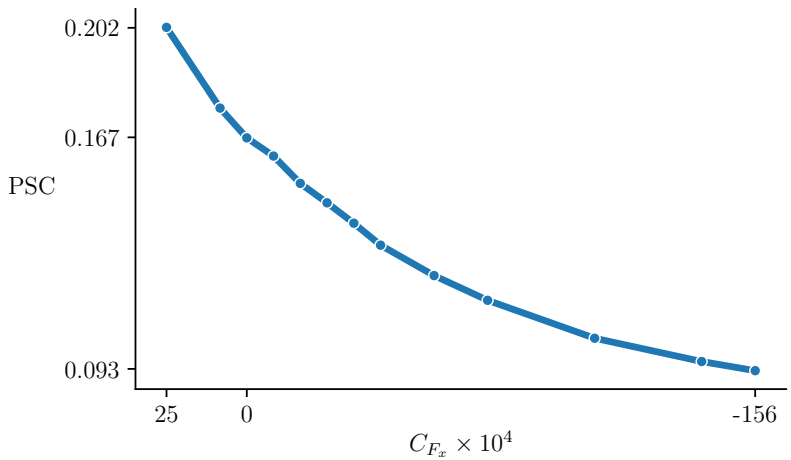
	Variable/Function	Description	Quantity
minimize	$\text{Pwr}_{\text{shaft}}$	Propulsor shaft power	
with respect to	FPR	Fan pressure ratio	1
	X_{nacelle}	Global nacelle shape variables	3
	X_{shape}	Nacelle and fuselage local shape variables	308
	p_s^{FF}	Static pressure at the fan face	1
	$\text{Pwr}_{\text{shaft}}^*$	Propulsor shaft power target	1
	p_t^{FE*}	Total pressure target at the fan exit	1
	T_t^{FE*}	Total temperature target at the fan exit	1
		Total	316
subject to	$C_{F_x}^{\text{net}} = C_{F_x}^{\text{net}*}$	Specified net force on full body	1
	$\mathcal{R}_{\dot{m}} = 0$	Mass Residual	1
	$\mathcal{R}_{\text{Pwr}} = 0$	Propulsor shaft power residual	1
	$\mathcal{R}_{p_t^{FE}} = 0$	Total pressure residual	1
	$\mathcal{R}_{T_t^{FE}} = 0$	Total temperature residual	1
	$.9 < \mathcal{G}(le) < 2$	Leading Edge Thickness	3
	$.9 < \mathcal{G}(te) < 2$	Trailing Edge Thickness	3
		Total	11

Optimizations were performed on both podded baseline and BLI configurations

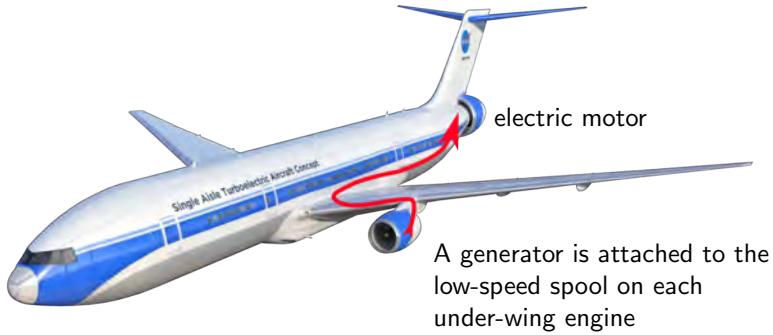
- Optimizations between podded and BLI configurations were compared for the same $C_{F_x}^{\text{net}*}$
- 26 optimizations were run, 13 on each configuration at different values of $C_{F_x}^{\text{net}*}$
- The ratio of shaft powers needed to achieve the same net force on the entire body is used to compute a power saving coefficient

$$\text{PSC} = \frac{\text{Pwr}_{\text{shaft}}^{\text{Pod}} \quad \text{Pwr}_{\text{shaft}}^{\text{BLI}}}{\text{Pwr}_{\text{shaft}}^{\text{Pod}}}.$$

The BLI propulsor uses between
9.3% and 20.2% less power depending on $C_{F_x}^{\text{net}*}$

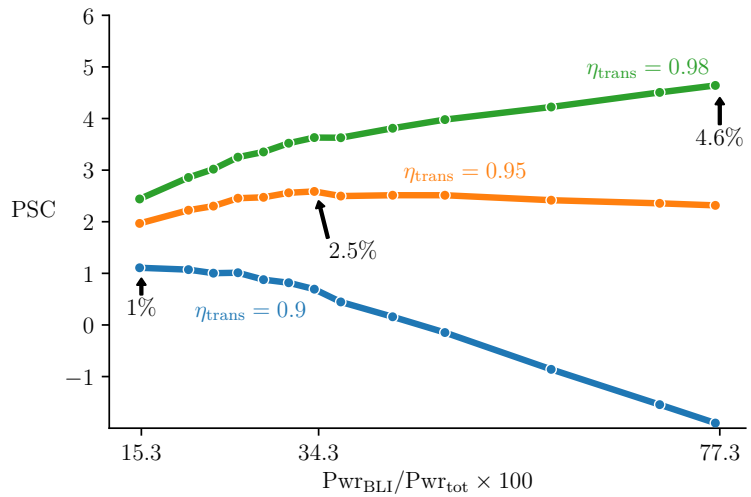


Accounting for η_{trans} allowed us to estimate overall propulsion system performance

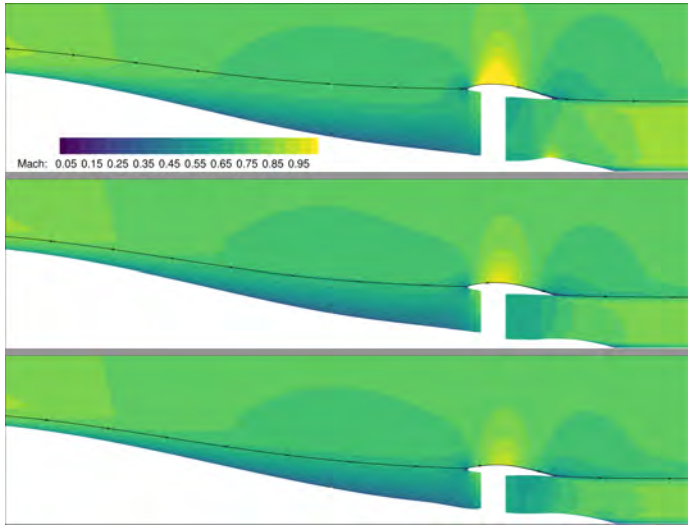


- Traditional power transmission is roughly 90% efficient
- Advanced traditional power transmission could reach 95% efficiency
- Superconducting technology could boost efficiency to 98%

At cruise, STARC-ABL will use between 1% and 4.6% less power than the baseline



The optimal shape changes for different sized propulsors, highlighting the importance of leveraging optimization



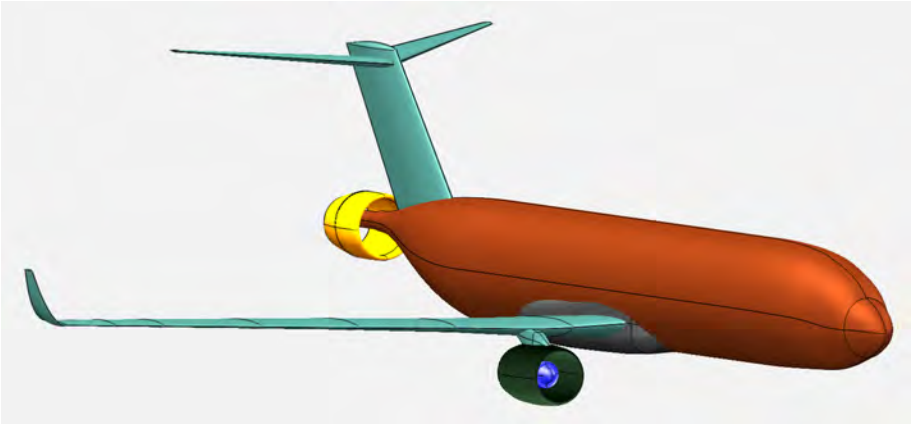
$\eta_{\text{trans}} = .98$

$\eta_{\text{trans}} = .95$

$\eta_{\text{trans}} = .90$

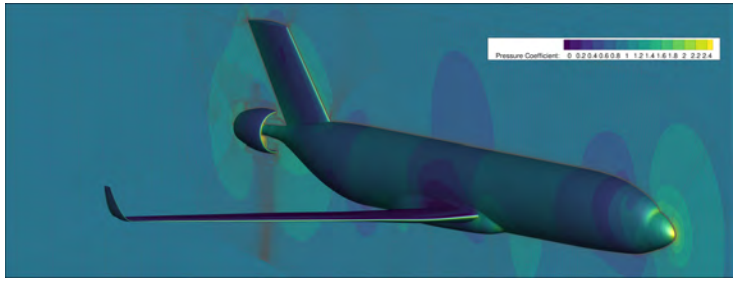
While 2D aerodynamics can model the fundamental aeropropulsive interaction, 3D aerodynamics models are necessary to accurately capture the full aeropropulsive effects

Geometry generation is done via a VSP model, using finite-differences to compute partial derivatives derivatives

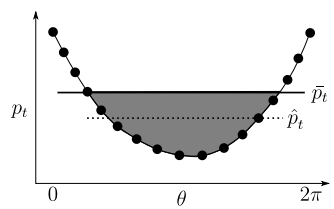


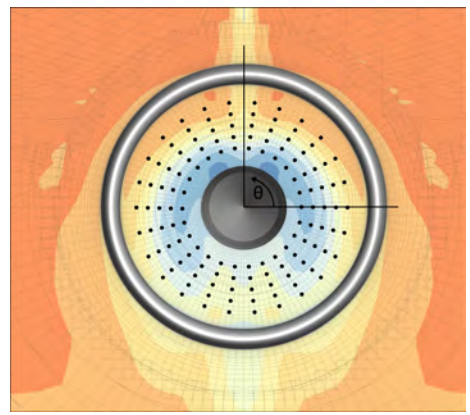
3D aerodyanmic analysis built a 6 million cell overset mesh

- Wing shape was pre-optimized for mimimum drag with 5 point stencil around cruise (MN 0.785, 37000 ft)
- Solutions take $\approx$ 10-15 minutes on 400 cores



Distortion is computed using a smoothed version of the ARP-1420 standard





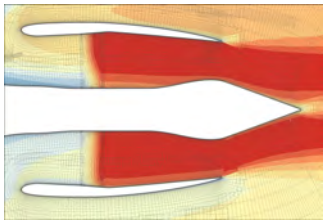
- $\kappa^i = \frac{\hat{p}_t{}^i \quad \bar{p}_t{}^i}{\bar{p}_t{}^i}$
- compute one κ^i for each ring
- $\hat{\kappa} = \mathrm{KS}(\kappa^i)$

Gaetan K. Kenway and Cetin C. Kiris. "Aerodynamic Shape Optimization of the STARC-ABL Concept for Minimal Inlet Distortion", 2018 AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, AIAA SciTech Forum, (AIAA 2018-1912)

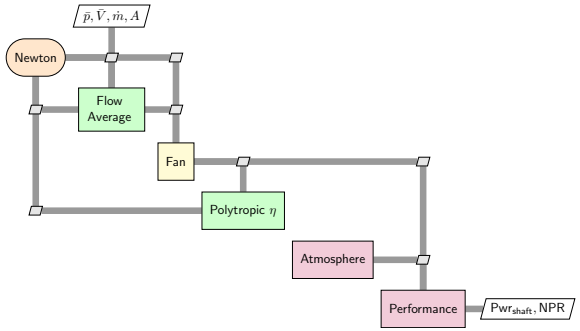
Irian Ordaz, Sriram K. Rallabhandi, Eric J. Nielsen, and Boris Diskin. "Mitigation of Engine Inlet Distortion through Adjoint-Based Design", 35th AIAA Applied Aerodynamics Conference, AIAA AVIATION Forum, (AIAA 2017-3410)

BLI propulsor thrust is modeled in ADflow via a body-force model, and fan efficiency is modeled in pyCycle

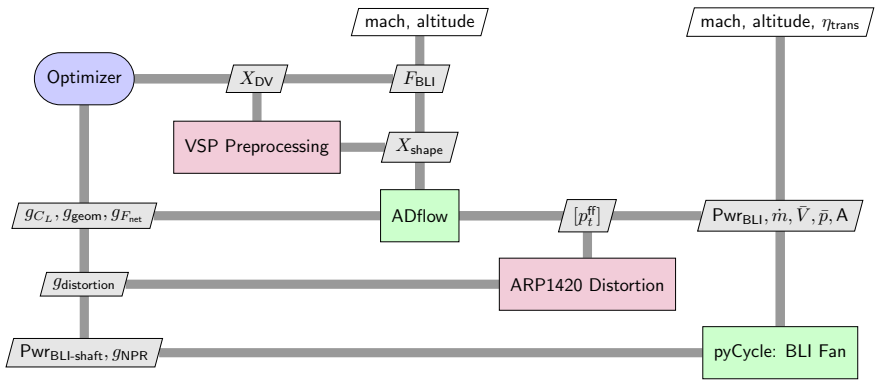
ADflow



pyCycle



The full model is composed of 4 “disciplines”



- VSP preprocessing component provides a more physical parameterization for the geometry
- $[p_t^{\text{ff}}]$ is an array of 150 pressures from the 30x5 computational rake

Finding the minimum shaft power required for a specified F^*_{net} yields the most efficient BLI propulsor for a given size

	Variable/Function	Description	Quantity
minimize	$\text{Pwr}_{\text{BLI-shaft}}$	Shaft power required for the BLI propulsor	
with respect to	F_{BLI}	BLI propulsor body-force applied	1
	X_{shape}	Fuselage and propulsor nacelle shape variables	25
		Total	26
subject to	$C_L = 0.5$	Lift coefficient at cruise	1
	$0.99 < g_{\text{geo}} < 3.0$	Geometric thickness constraints	10
	$\text{NPR} > 1.65$	Nozzle pressure ratio constraint	1
	$F_{\text{net}} = F^*_{\text{net}}$	Required net force on the body	1
		Total	14

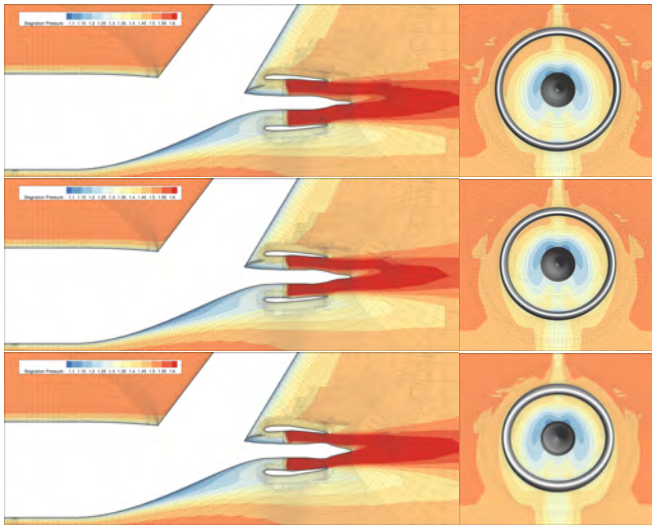
F^*_{net} is a positive quantity representing the total thrust required from the underwing engines for steady cruise

Three values for F^*_{net} were considered:
9000 N, 11000 N, 13000 N

9000 N

11000 N

13000 N



We ran optimizations at the same three F^*_{net} values, with and added distortion constraint

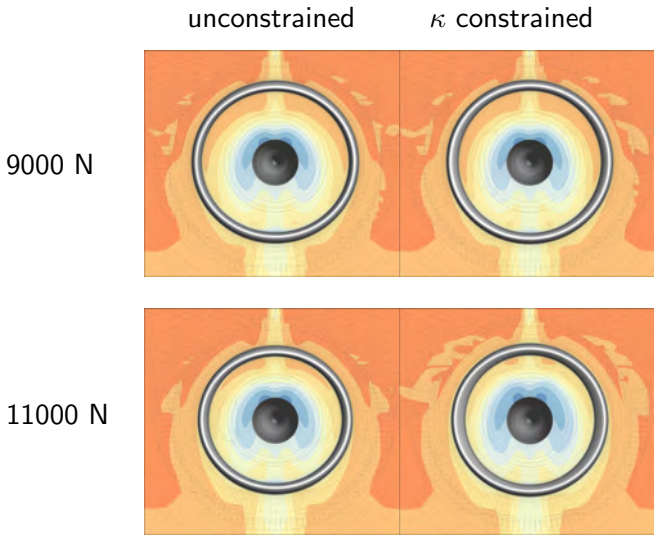
	Variable/Function	Description	Quantity
minimize	$Pwr_{BLI\text{-}shaft}$	Shaft power required for the BLI propulsor	
with respect to	F_{BLI}	BLI propulsor body-force applied	1
	X_{shape}	Fuselage and propulsor nacelle shape variables	25
		Total	26
subject to	$C_L = 0.5$	Lift coefficient at cruise	1
	$0.99 < g_{geo} < 3.0$	Geometric thickness constraints	10
	$NPR > 1.65$	Nozzle pressure ratio constraint	1
	$F_{net} = F^*_{net}$	Required net force on the body	1
	$\hat{\kappa} < .035$	aggregated distortion metric	1
		Total	15

1.5% reduction in distortion can be achieved with $\approx$ 1% increase in shaft power

	unconstrained			κ constrained		
F^*_{net} (N)	FPR	κ ($\hat{\kappa}$)	Pwr_{shaft} (kW)	FPR	κ ($\hat{\kappa}$)	$\%\Delta Pwr_{shaft}$
9000	1.233	0.0440 (0.0447)	3646.5	1.236	0.0300 (.0350)	1.2
11000	1.271	0.0430 (0.0430)	3176.7	1.308	0.0301 (.0350)	0.9
13000	1.286	0.0403 (0.0413)	2623.3		coming soon!	

- κ constraint forces a slight increase in FPR, which causes the increase in of the shaft power
- some shape changes to the inlet and aft-fuselage shape also help make the flow more uniform

The distortion constraint forces a more oval inlet to spread out the low-pressure zone at the fan-face

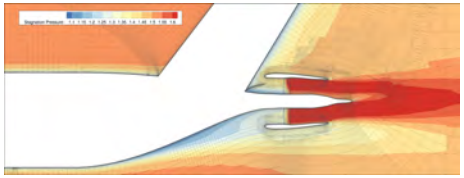


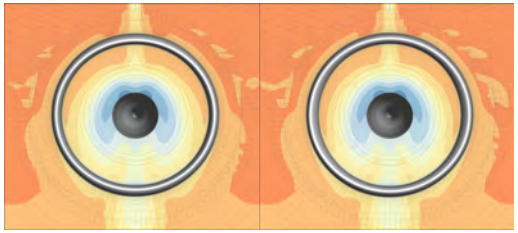
The next step is to add in a detailed under-wing engine model built in pyCycle and optimize the full propulsion systems for different assumed values of η_{trans}

Conclusions

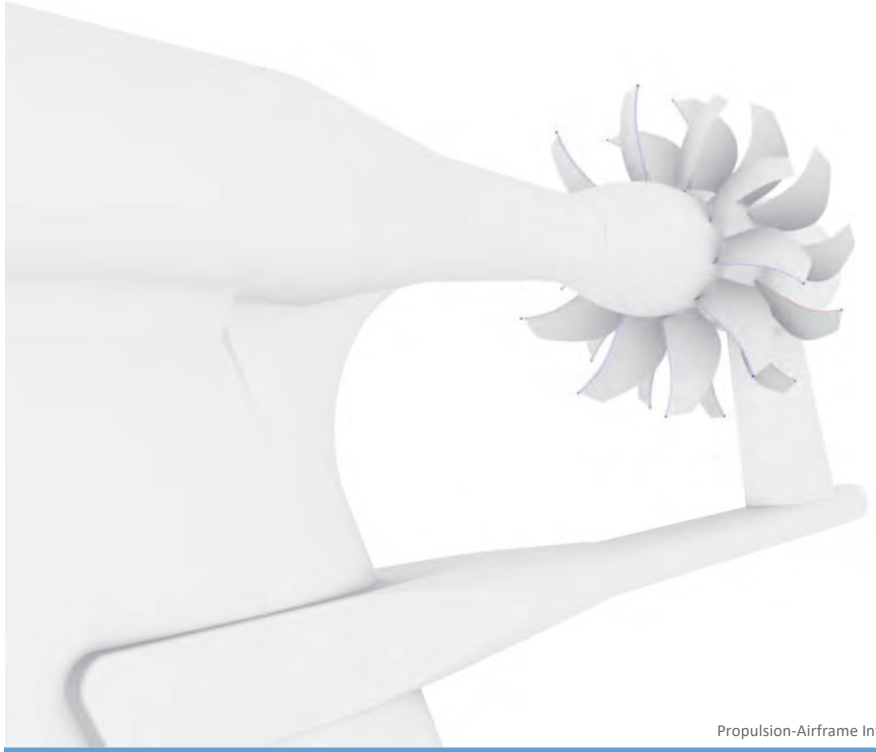
- Fully coupled models are necessary, but require gradient based optimization to efficiently explore the design space
- 2-D aerodynamics are useful to study the aeropropulsive interactions, but 3-D aerodynamics are necessary for realistic performance predictions
- Aeropropulsive coupling has a strong impact on overall propulsion system design for BLI concepts

Questions?





COMPUTATIONAL STRATEGIES TO SUPPORT PROPULSION-AIRFRAME INTEGRATION APPLICATIONS

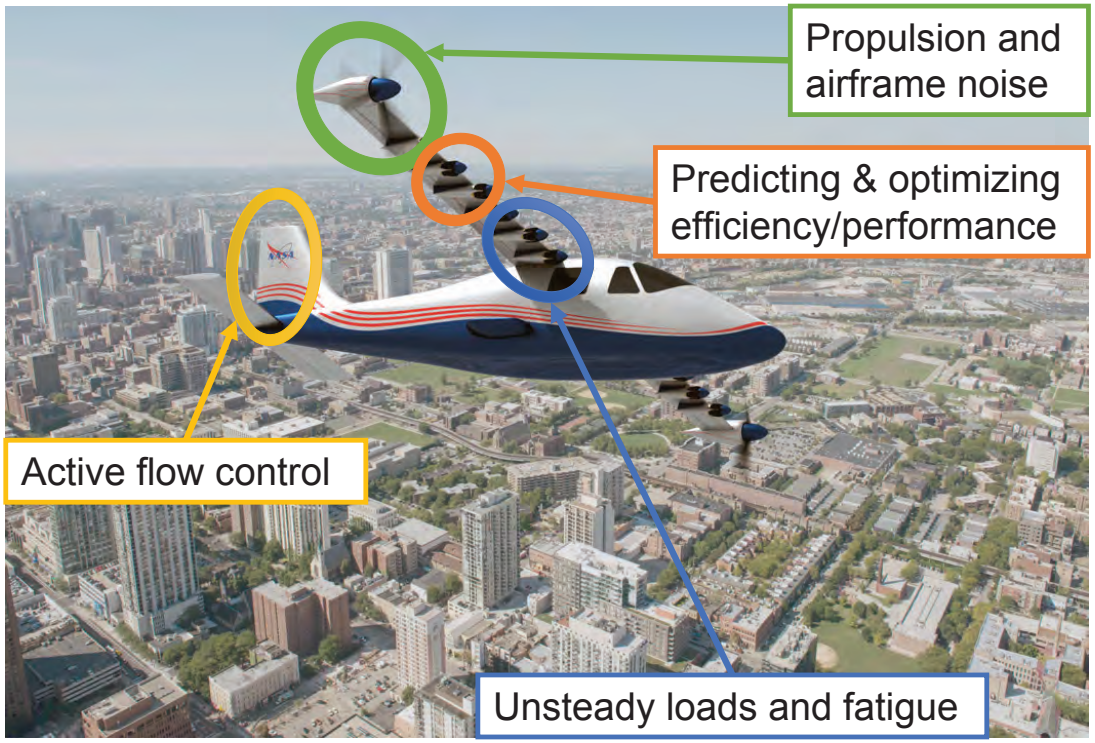


Francois Cadieux
Cetin Kiris

Computational Aerosciences Branch, NASA Ames Research Center

Propulsion-Airframe Integration Technical Interchange Meeting, May 30-31, 2018

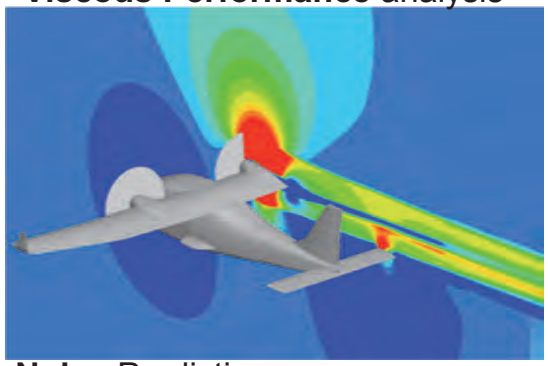
Challenges of PAI



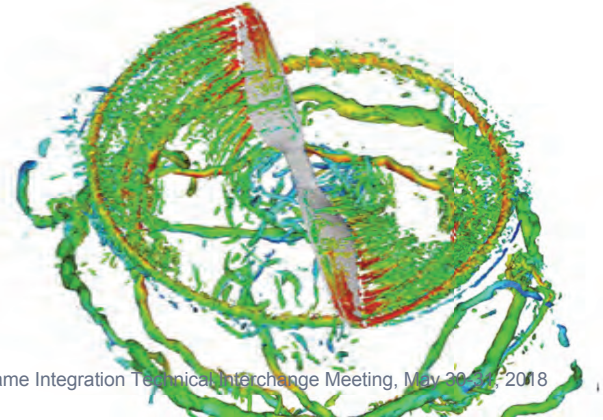
Choosing the Right Strategy

- Fidelity changes with design stage
  - Conceptual/preliminary/detailed design
  - Performance analysis versus noise prediction
- Grid paradigm
  - Grid generation time
  - Boundary layer resolution
- Delivering “on time and on budget”
  - Understand computational req’s of different tools
  - Limit scope of trade studies, design optimizations, and aero-databases

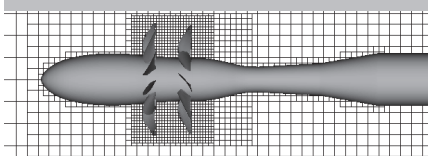
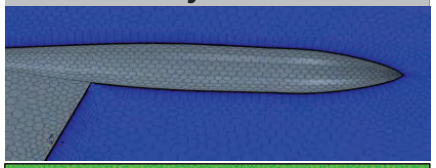
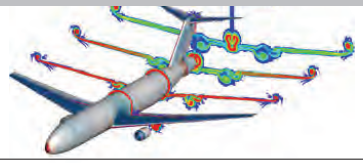
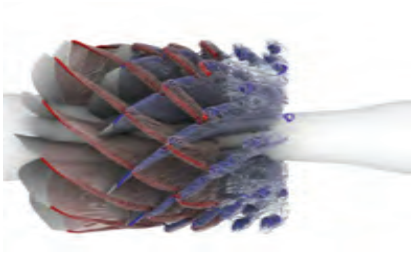
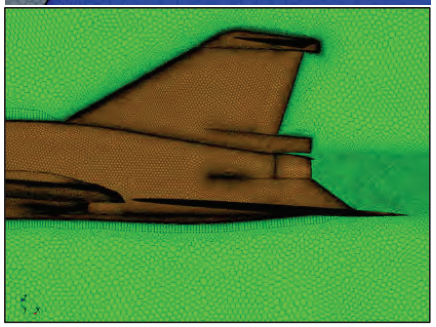
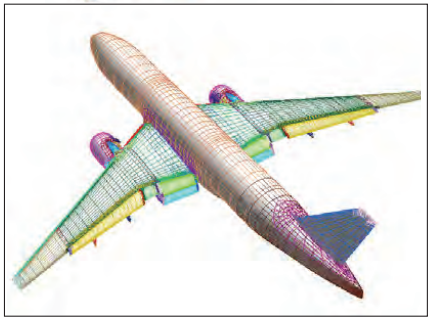
Viscous Performance analysis



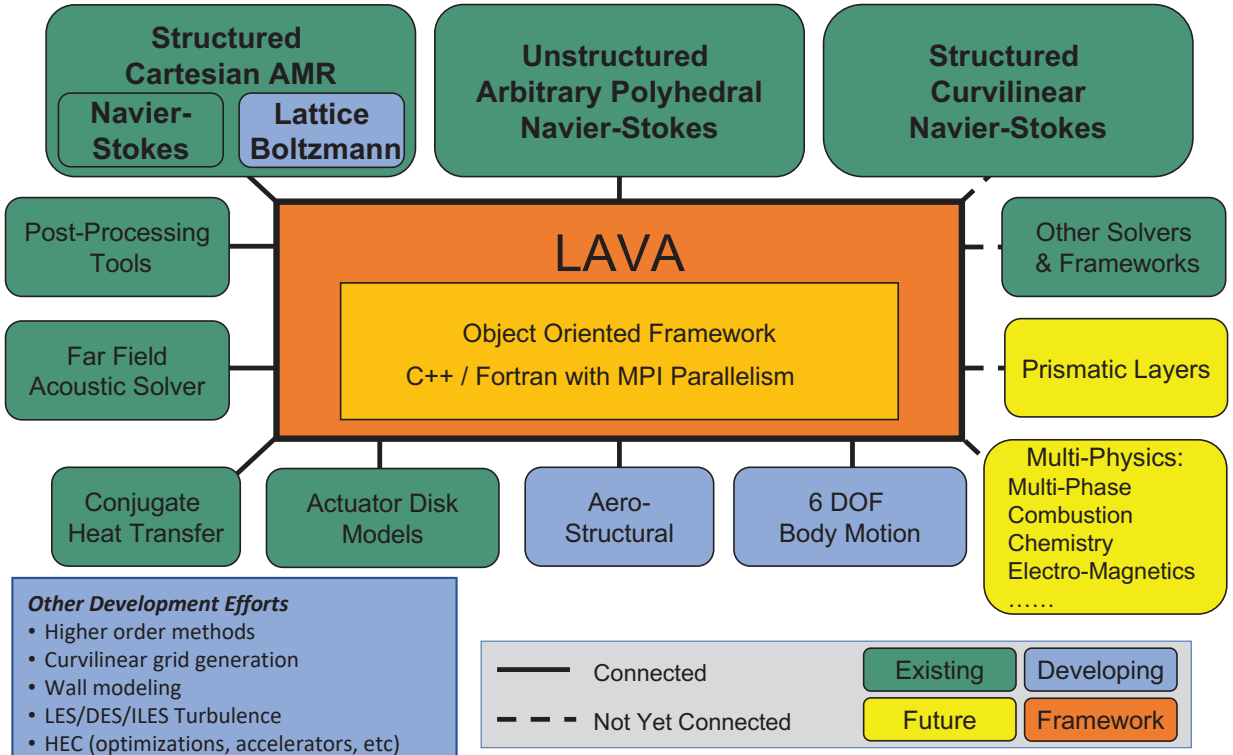
Noise Prediction



Choosing The Best Grid Paradigm

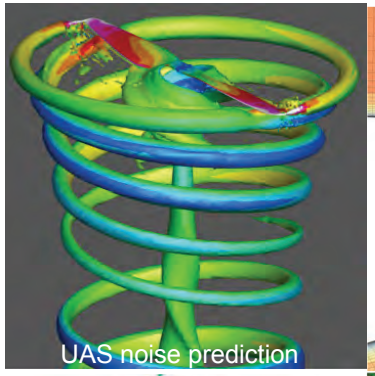
Structured Cartesian	*Unstructured Arbitrary Polyhedral*	*Structured Curvilinear*
		
		
• Automatic grid generation with Adaptive Mesh Refinement • Low computational cost • Reliable higher order methods • Non-body fitted → Resolution of boundary layers inefficient	• Partially automated grid generation • Body fitted grids • Grid quality can be challenging • High computational cost • Higher order methods yet to fully mature	• High quality body fitted grids • Low computational cost • Reliable higher order methods • Grid generation largely manual and time consuming

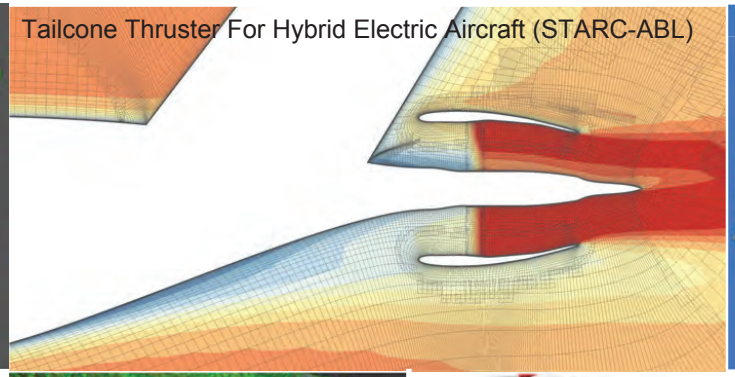
Launch, Ascent, and Vehicle Aerodynamics (LAVA)

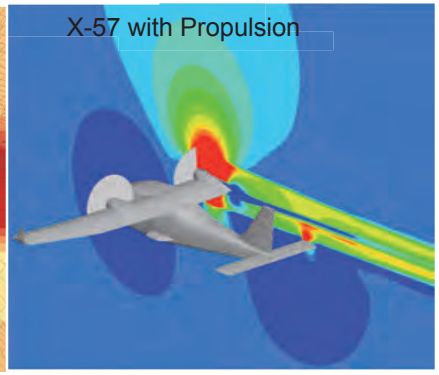


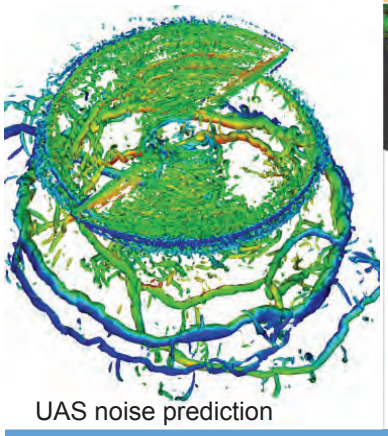
Kiris at al. AST-2016 and AIAA-2014-0070

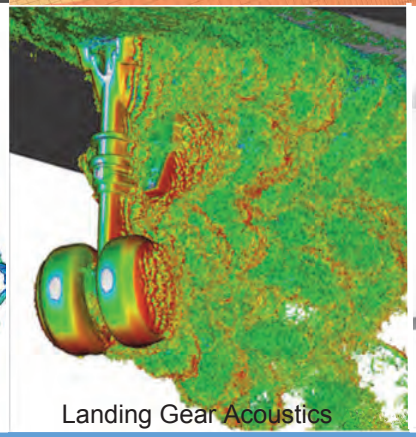
Recent Examples of Performance Analysis, Design Optimization and Noise Prediction with LAVA

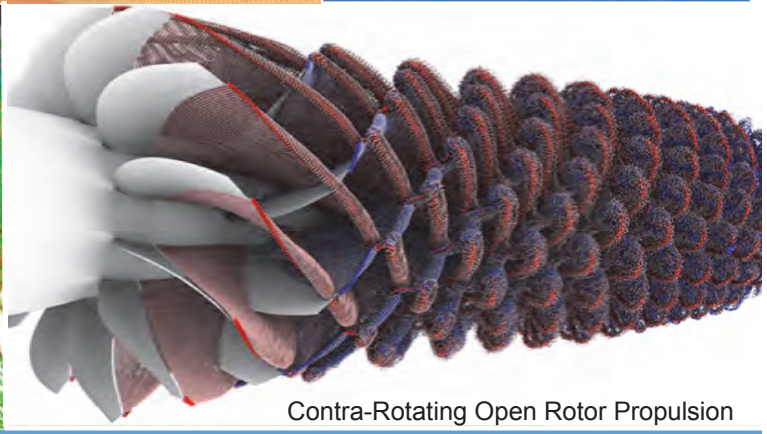








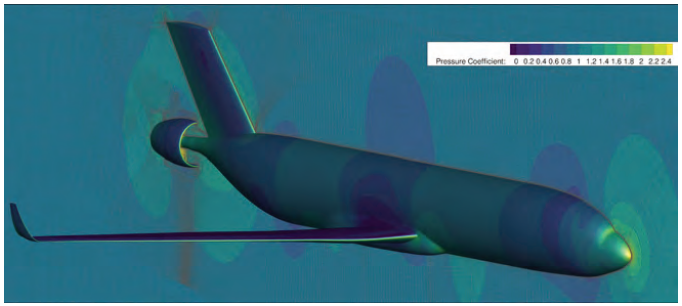


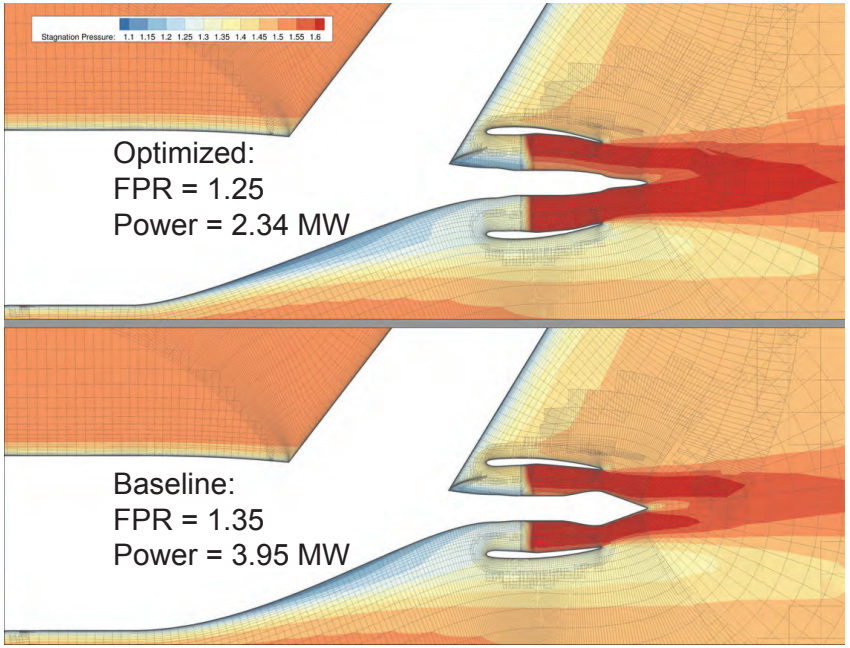


From conceptual to detailed design

HIGH FIDELITY VISCOUS STEADY DESIGN OPTIMIZATION

Aeropropulsive Optimization of STARC-ABL with OpenMDAO





Propulsion-Airframe Integration Technical Interchange Meeting, May 30-31, 2018

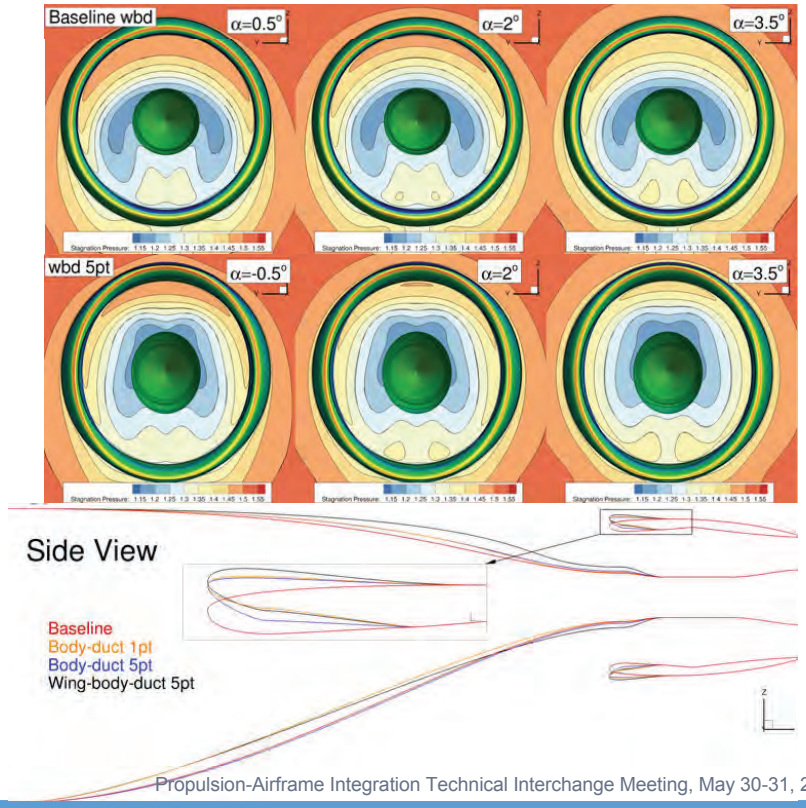
Propulsor Modeling

Actuator zone body force source term:

- **Equations solved are consistent in space, only add momentum and energy source**
- **Different models for different level of fidelity:**
  - Constant thrust or mass flow rate
  - Torque: Goldstein optimum radially varying tangeantial force
  - 2D blade element theory with specified loading or airfoil table
  - David Hall model if blade shape and RPM is known
- **Stators can be modeled with zone with no thrust and torque in opposite direction**
- **Input thrust and torque can be tied to NPSS output or other engine model**

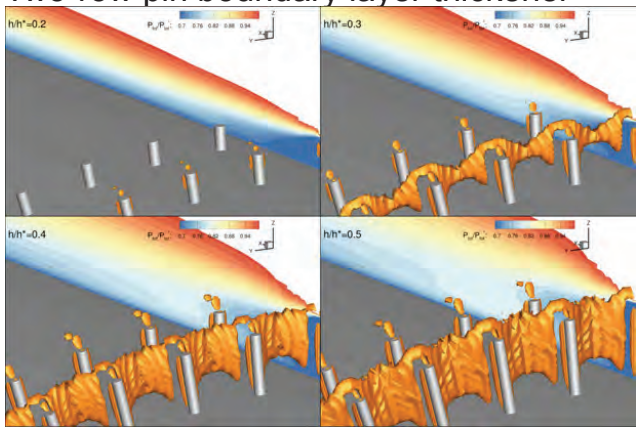
STARC-ABL Shape Optimization To Reduce Inlet Distortion

- **Parametric description of fuselage and inlet shape with thickness constraints**
- **Optimized shape reduces distortion by 50% at cruise**
- **Overset build-up approach helped identify effect of wing on distortion**

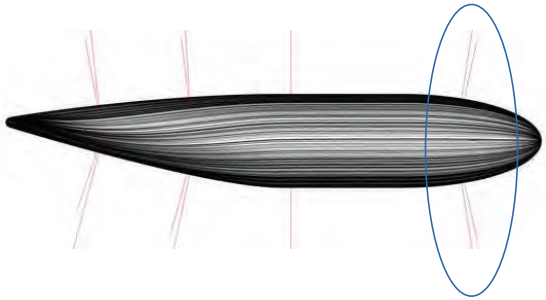


Tail Cone Thruster (TCT) Wind Tunnel Support

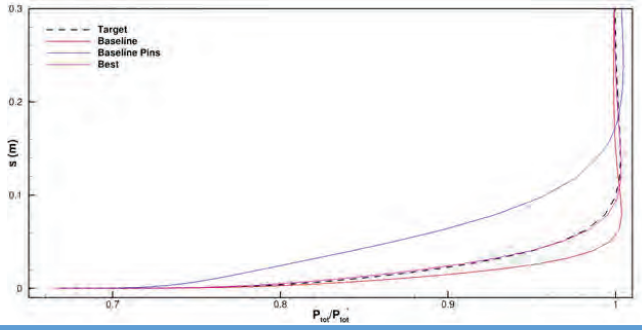
Two-row pin boundary layer thickener



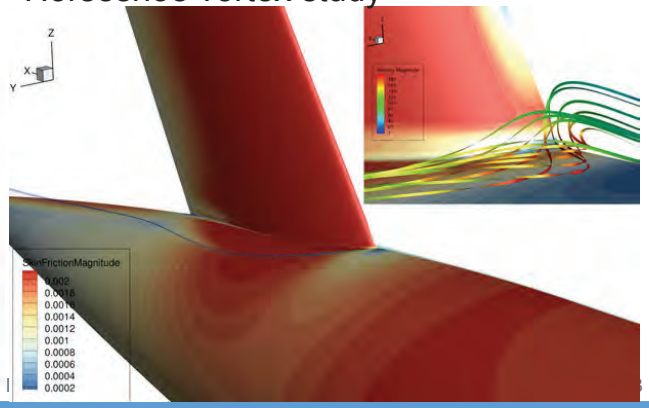
Match total pressure at 5 rake locations



We are able to match target boundary layer



Horseshoe vortex study

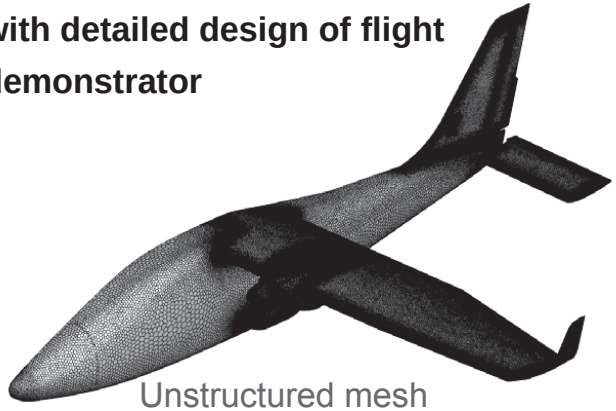


From preliminary to detailed design

HIGH FIDELITY VISCOUS STEADY PERFORMANCE ANALYSIS

X-57 Electric Research Aircraft

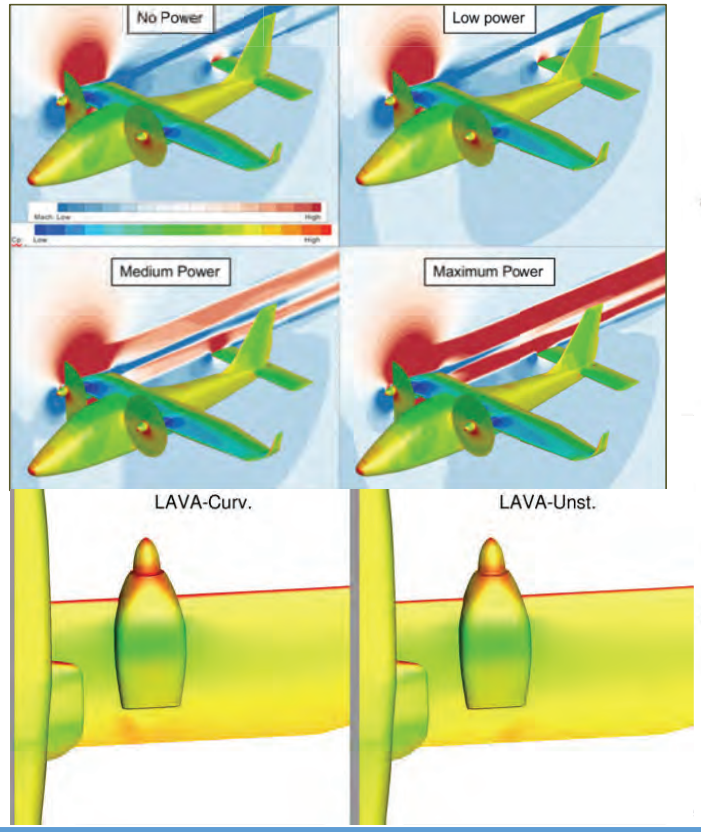
- **Predict X-57 performance for a variety of flight scenarios and propulsion configurations**
- **Validate CFD with wind tunnel experiments and across solvers**
- **Help aircraft designers at Armstrong with detailed design of flight demonstrator**

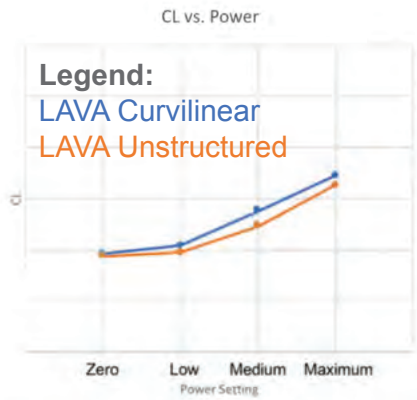


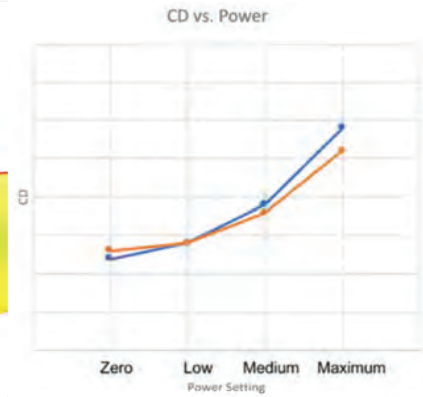
Unstructured mesh

Structured overset mesh

X-57 Propulsion Performance







0-31, 2018

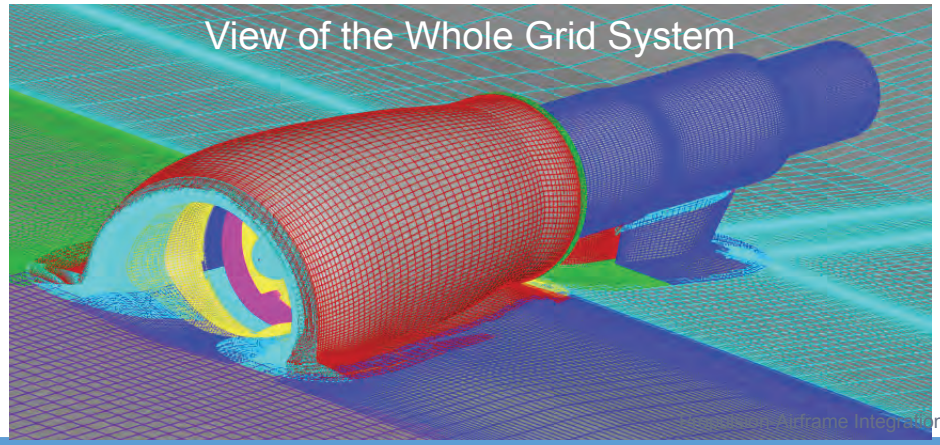
BLI2DTF: Predicting Fan Face Distortion

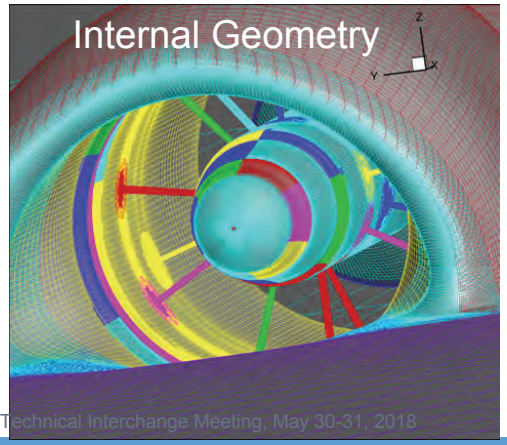
Goal

- Perform validation of CFD with different propulsion models in BLI configurations using comparisons with the experiment

Progress Summary

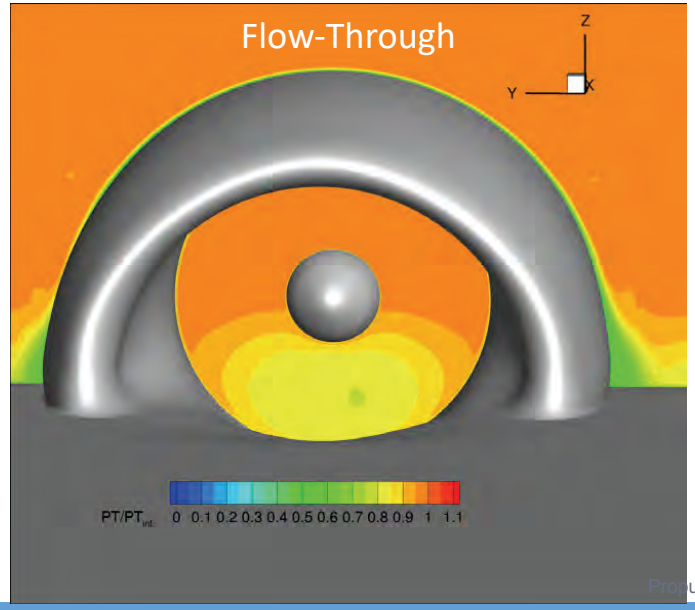
- Generated an overset, structured grid system
- Ran initial flow-through case for reference
- Ran initial powered case using a 3D actuator zone and targeting the experimental mass flow

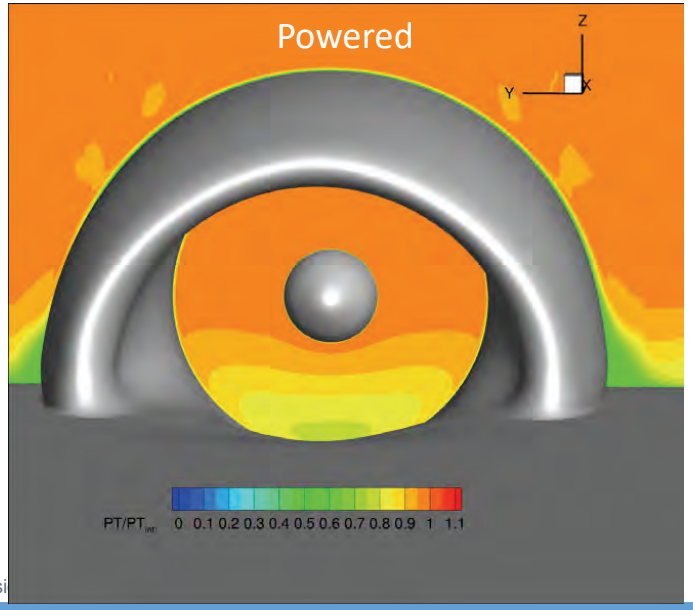




BLI2DTF: Predicting Fan Face Distortion

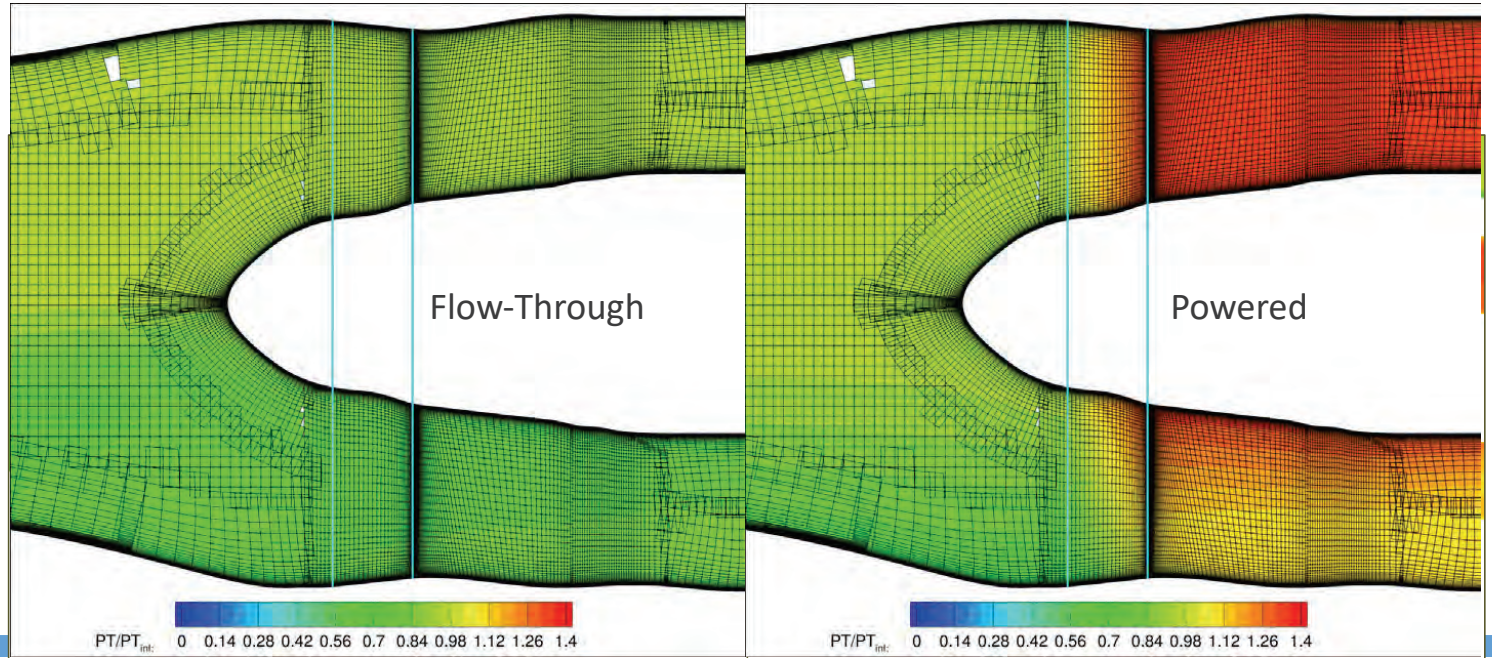
- Comparisons are between flow-through and powered case with the mass flow targeted to 110.66 lb/s (100.23 lb/s corrected).
- The figures below are plots of the total pressure ratio at the fan face





BLI2DTF: Predicting Fan Face Distortion

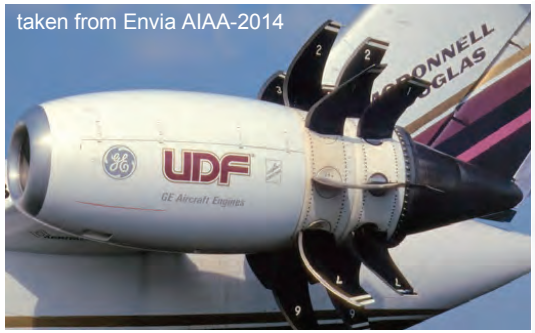
- Comparisons are between flow-through and powered case with the mass flow targeted to 110.66 lb/s (100.23 lb/s corrected). Will compare with experiment once we match geometry.
- Below plots are slices through the centerline of the nacelle with the total pressure ratio; teal lines are where the actuator zone starts and ends



Toward detailed design

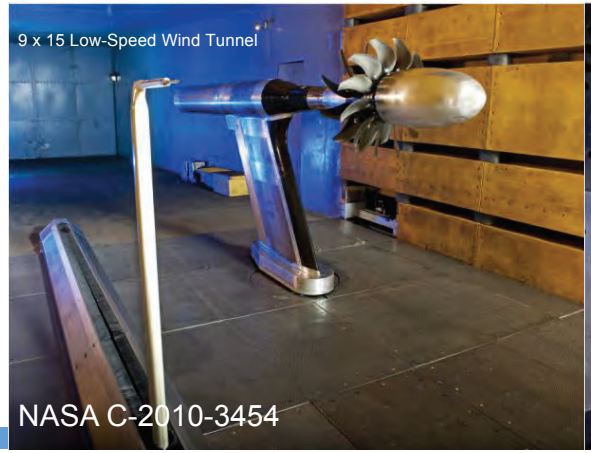
PROPULSION AND AIRFRAME NOISE PREDICTION

Predicting Noise: Open Rotor



GE36-UDF propfan demonstrator engine installed on MD-81 test bed aircraft (8x8)

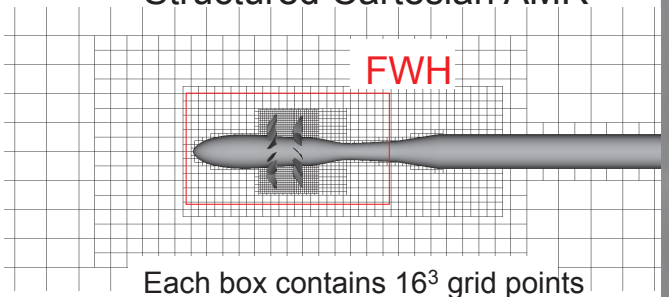
Modern contra-rotating open rotor engine design from CFM (12x10)



2018

Numerical Schlieren of Unsteady Flow Field

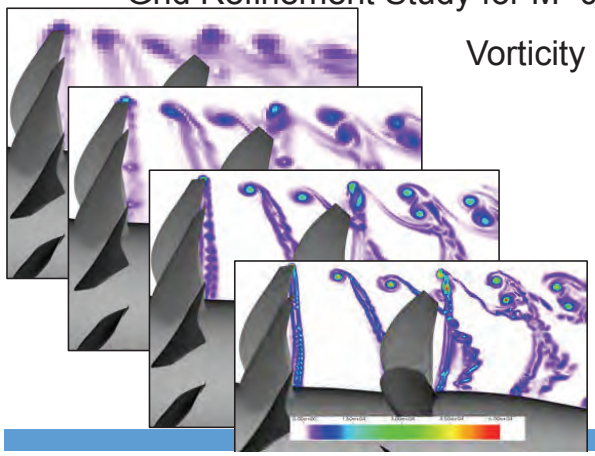
Structured Cartesian AMR

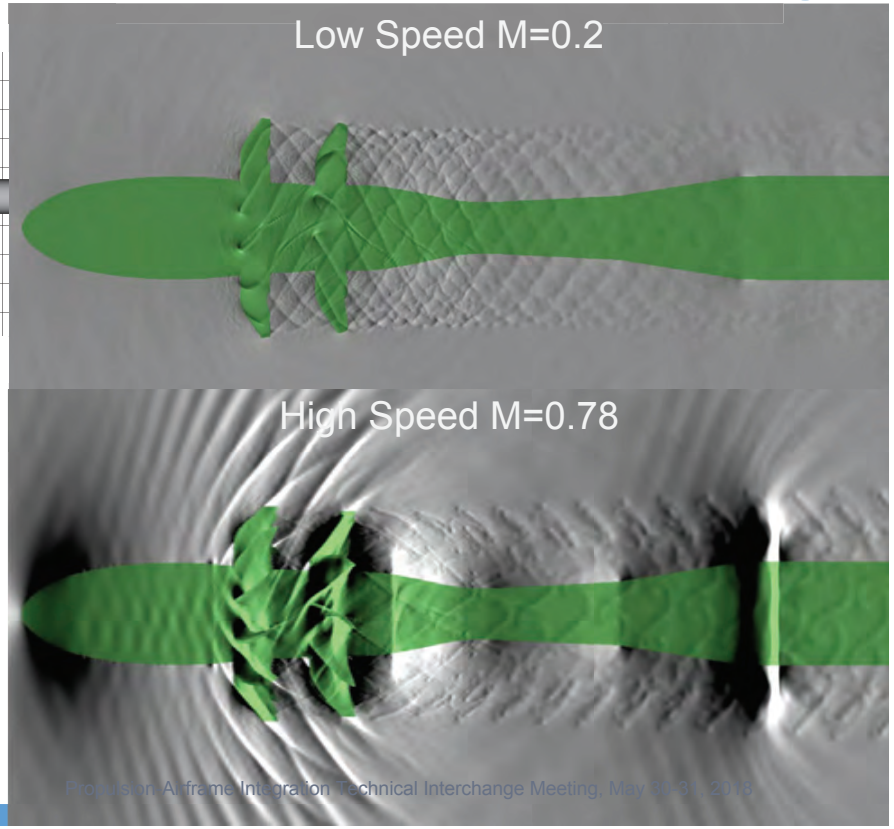


Each box contains 16^3 grid points

Grid Refinement Study for M=0.2:

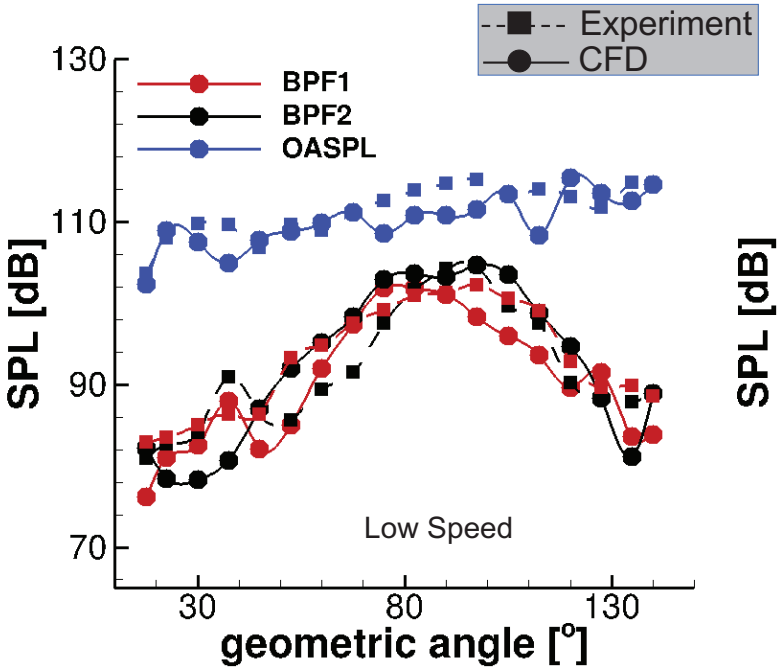
Vorticity



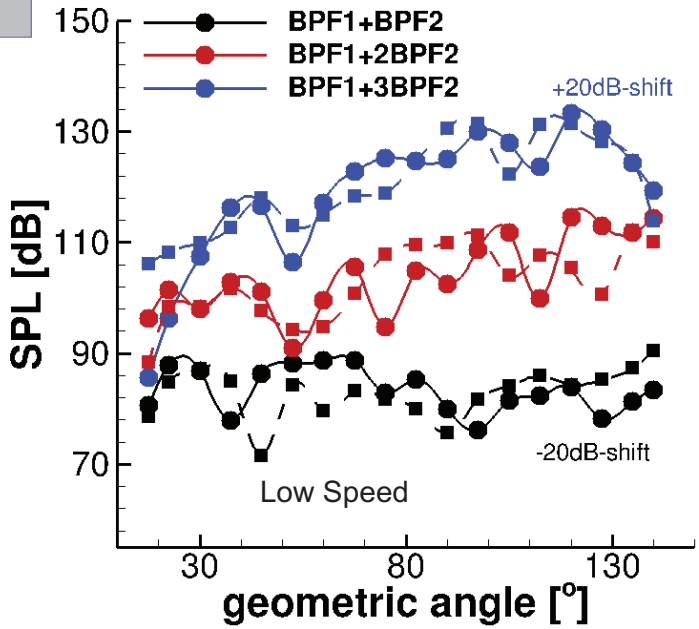


Experimental Validation of Open Rotor Noise

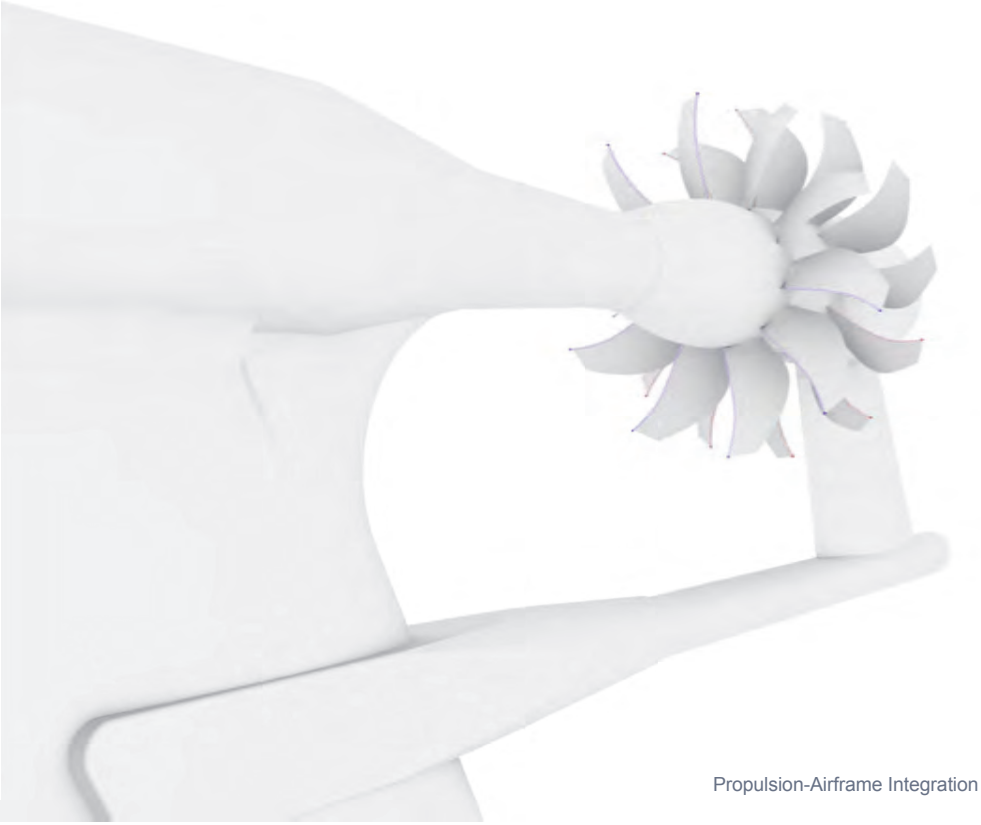
Fundamental Tones



Higher-Order Interactions



Investigating Installation Effects

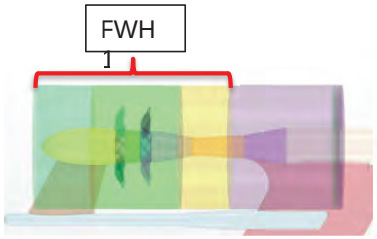


Seed colors:

- Green = Pylon Edge
- Red = FWD Blade Edges
- Blue= AFT Blade Edges

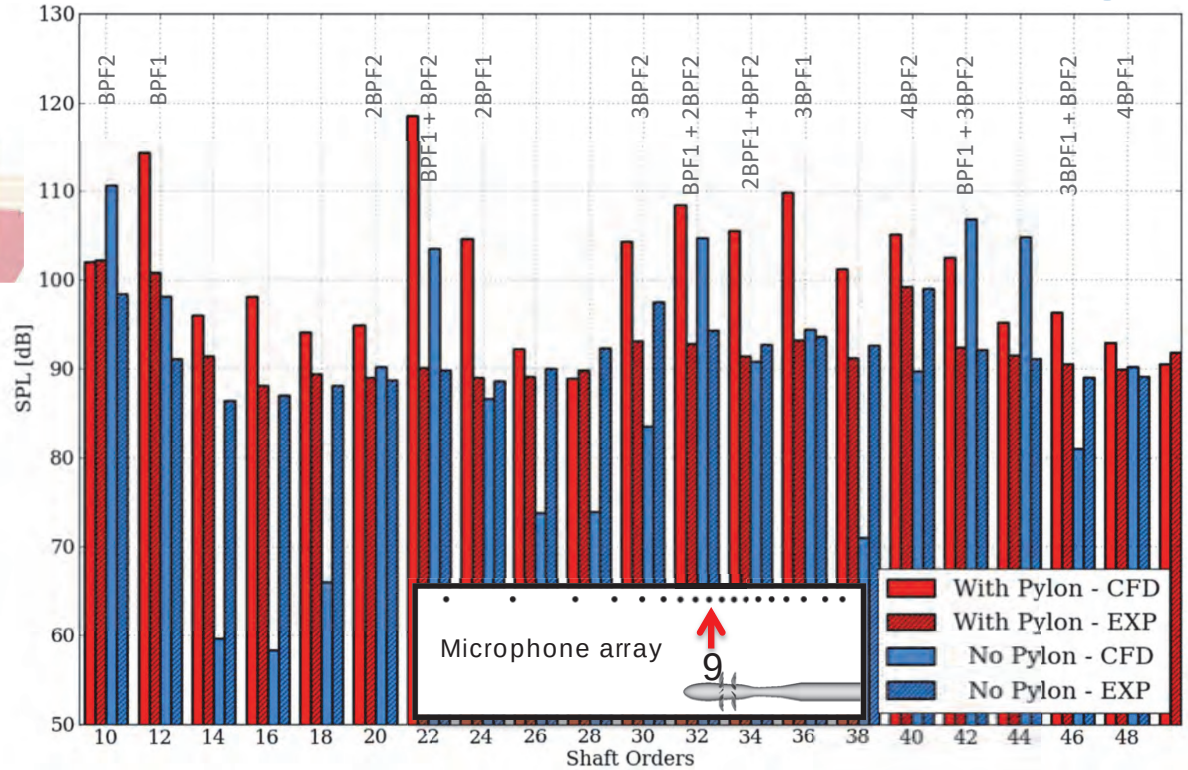
Investigating Installation Effects

FWH Surface:



Pylon vs no pylon results:

- Pylon runs had higher SPL at most shaft orders (Exp and CFD)
- Wall model improves results
- Blades chopping through pylon wake increase harmonic interactions



Predicting Urban Air Mobility Noise

- **Potential Noise Annoyances**
  - Rotor tones
  - Rotor-rotor interaction
  - Rotor-airframe interaction
- **Experimental validation with UAS**
  - Create best practices
  - Assess pros and cons of different methods

eVTOL aircraft concepts

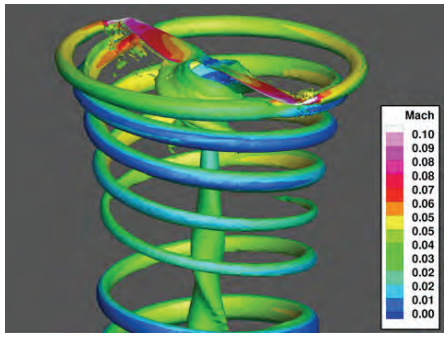
SUI Endurance drone

Predicting SUI Isolated Rotor Noise

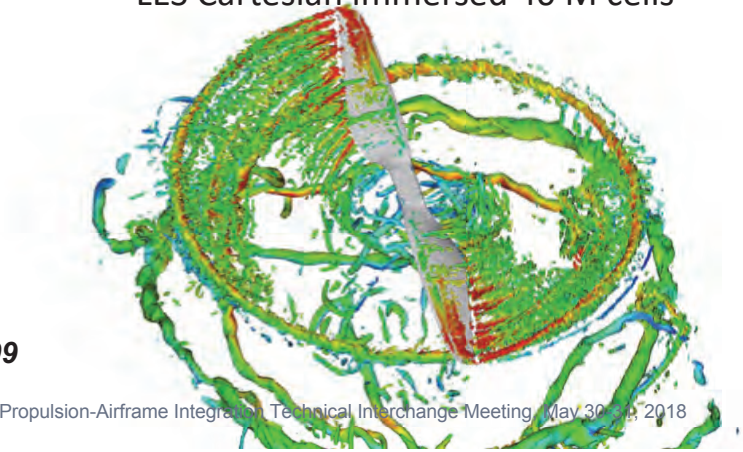
- **Build-up approach**
  - Single rotor first
  - Add other rotors
  - Add fuselage
- **Computational Methodology**
  - Overset Structured Grid/Solver
  - Cartesian AMR
- **Validation Comparison**
  - Integrated Loads
  - Far-field Acoustics

Data From Zawodny and Haskin AIAA-2017-3709

URANS curvilinear overset 6 M cells

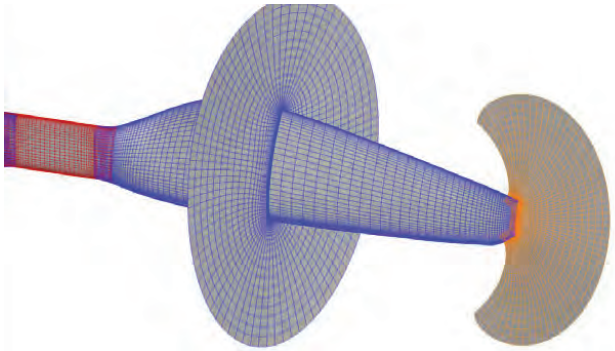


LES Cartesian immersed 40 M cells

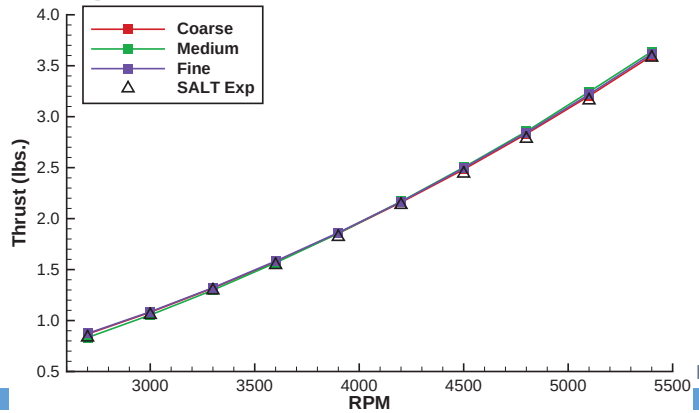


Experimental Validation of SUI Rotor Noise Predictions

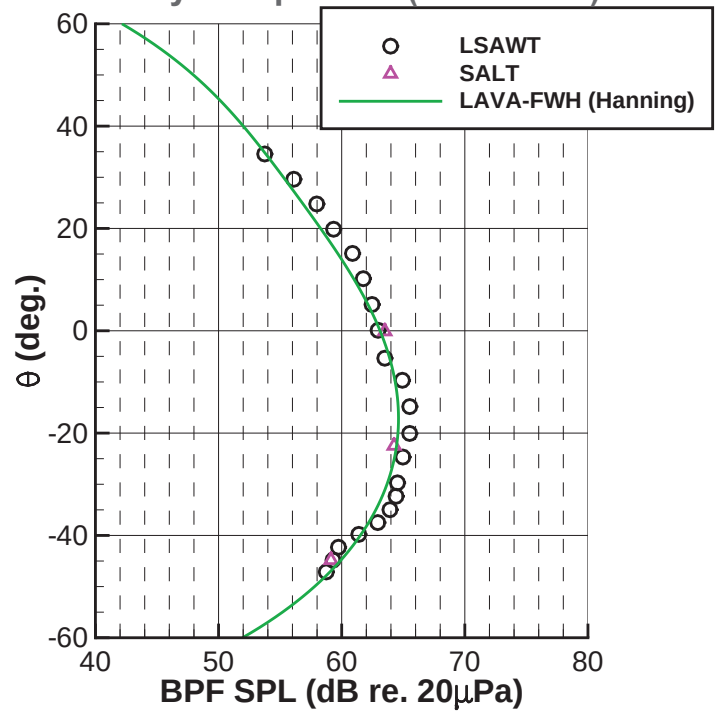
Structured Overset Grid



Integrated Loads: Thrust versus RPM



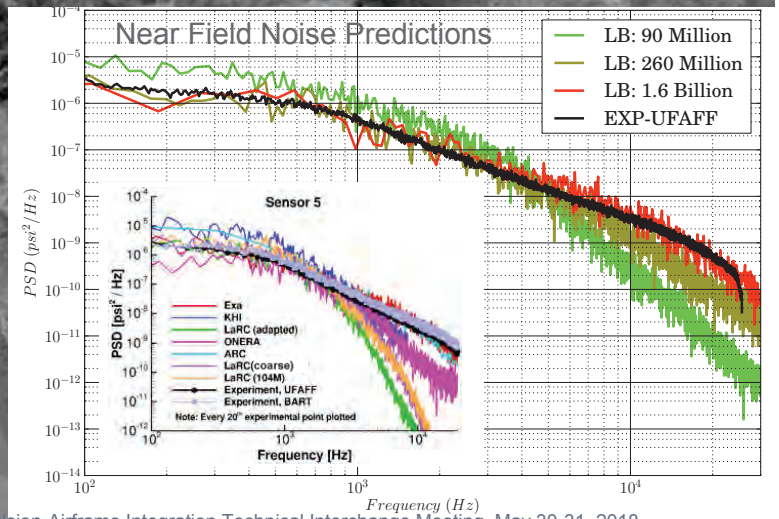
BPF Directivity Comparison (RPM=5400)



Predicting Landing Gear Broadband Noise

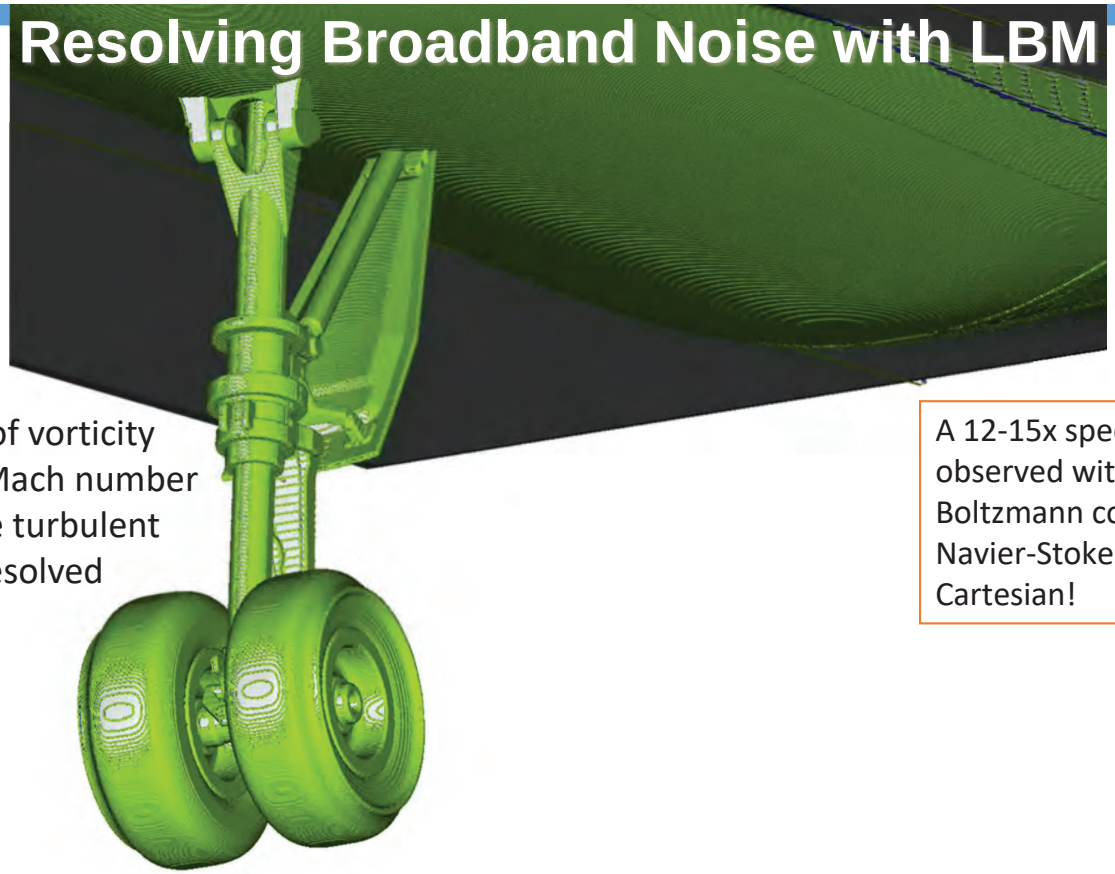
"Lattice Boltzmann and Navier-Stokes Cartesian CFD Approaches for Airframe Noise Predictions", Barad, Kocheemoolayil, Kiris, AIAA 2017-4404

LBM @ 1.6 billion – Velocity Magnitude at Centerline



Propulsion-Airframe Integration Technical Interchange Meeting, May 30-31, 2018

Resolving Broadband Noise with LBM



Isosurfaces of vorticity colored by Mach number showing fine turbulent structures resolved

A 12-15x speedup was observed with Lattice-Boltzmann compared to Navier-Stokes within LAVA Cartesian!

Summary

- **Different PAI challenges call for different strategies**
- **LAVA strives to provide flexibility**
  - **Structured curvilinear overset approach:**
    - High-fidelity viscous performance analysis (X-57)
    - Tonal noise predictions (SUI rotor)
    - Design optimization (STARC-ABL, TCT)
  - **Unstructured approach:**
    - High-fidelity viscous performance analysis (X-57)
  - **Cartesian AMR approach:**
    - Tonal noise predictions (open rotor, SUI)
    - Broadband noise predictions (landing gear)
- **It pays off to invest in new technologies like Lattice-Boltzmann**

Acknowledgements

LAVA team:

- Cetin Kiris (POC)
- Michael Barad
- Jeff Housman
- James Jensen
- Marie Denison
- Joseph Kocheemoolayil
- Gerrit Stich
- Francois Cadieux
- Jared Duensing
- Gaetan Kenway

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- Transformational Tools and Technologies (T^3)
- Advanced Air Transport Technology (AATT)
- Commercial Supersonic Transport (CST)
- Revolutionary Vertical Lift Technology (RVLT)

Computer time provided by:

- NASA Advanced Supercomputing (NAS)

Particle and schlieren visualizations provided by:

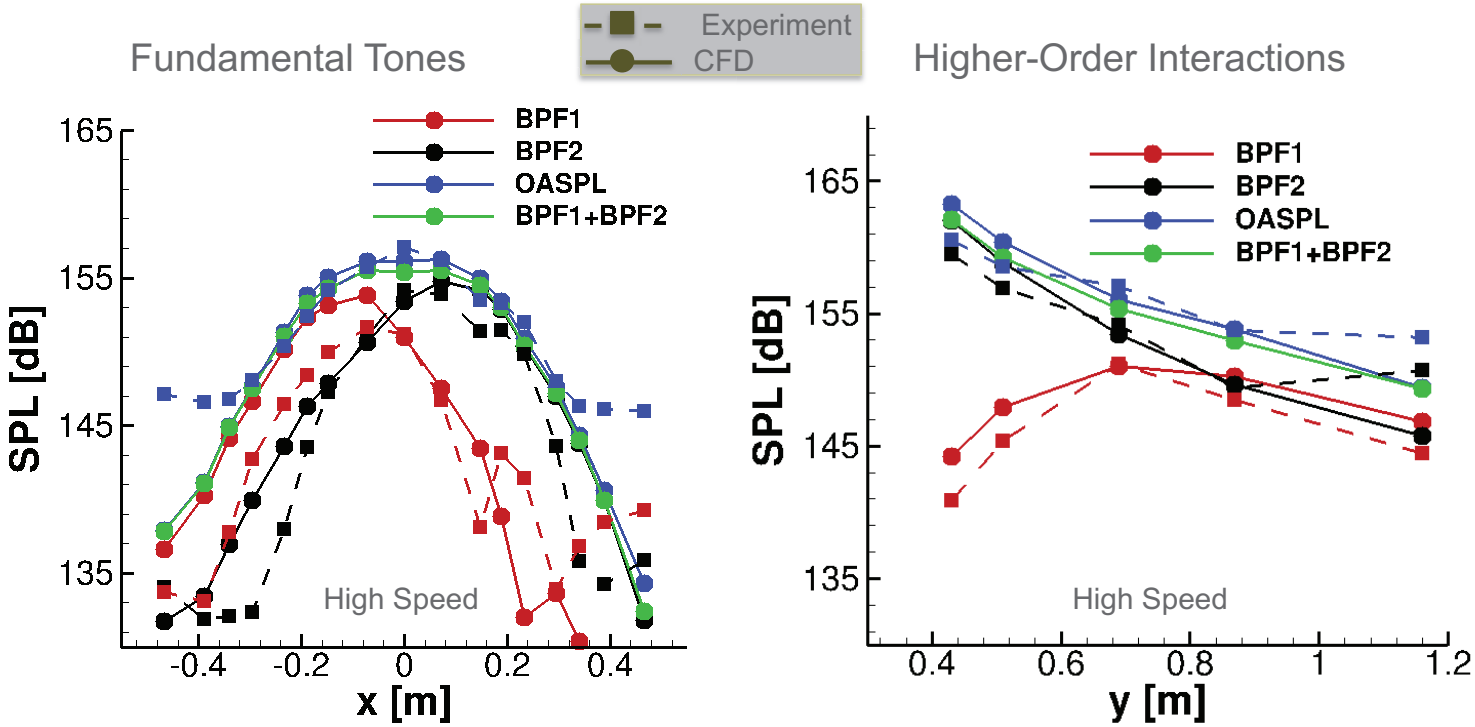
- Timothy Sandstrom
- Patrick Moran

BACKUP SLIDES

Ongoing Development Efforts

- **Turbulent wall-layer modeling for Cartesian methods**
- **Moving geometry capability for Lattice-Boltzmann**
- **Integration of more multi-disciplinary capabilities in design optimization and in predictive simulations: structural dynamics, fluid-structure interaction**

Experimental Validation of Open Rotor Noise



Propulsion-Airframe Integration Technical Interchange Meeting, May 30-31, 2018

National Aeronautics and Space Administration

Numerical Simulations (and Test Methods) of a Quiet SuperSonic Technology (QueSST) Aircraft Preliminary Design

David Friedlander, Raymond Castner, and Christopher Heath

(NASA Glenn Research Center)

www.nasa.gov

Outline

- Introduction
- Wind Tunnel Test Campaign
- Accompanying Computational Fluid Dynamic (CFD) Efforts

Introduction

- NASA has a new X-Plane mission: the Low-Boom Flight Demonstration.
  - The QueSST aircraft preliminary design is the intended design to move forward for the Low Boom Flight Demonstrator X-Plane.
  - The aircraft, designed at Lockheed Martin, was tested for aerodynamics and propulsion at the NASA Glenn Research Center 8- by 6- foot supersonic wind tunnel in the first half of 2017.

Wind Tunnel Test Campaign

Low Boom Flight Demonstrator

- Preliminary design vehicle
- Single pilot x-plane
- Mach 1.43
- Replicate sonic boom of commercial aircraft
- Propulsion shielded by airframe
- Top centerline inlet challenges
- Diverter-less bump inlet

8- by 6- Foot Supersonic Wind Tunnel Model Description

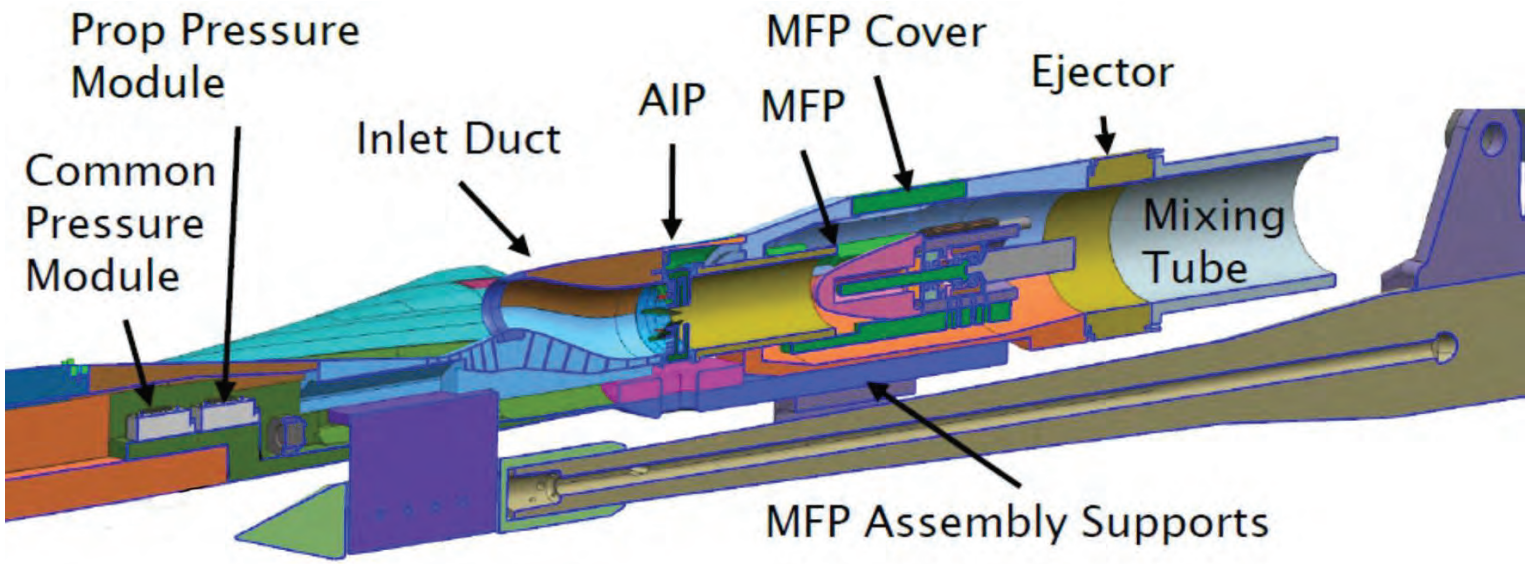
- Aerodynamic and propulsion
- C607 and C608 inlet configurations
- Key features:
  - Long nose
  - Canards
  - Camera fairing
  - Vortex generators
  - Centerline top mounted diverter-less bump inlet

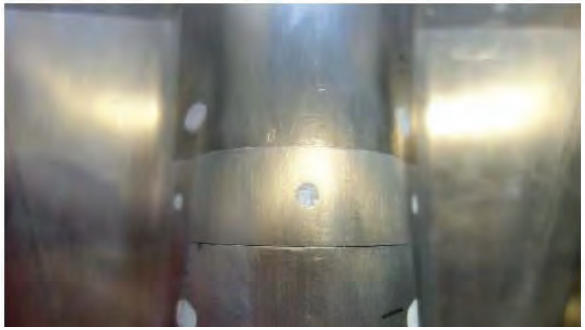
Propulsion-airframe integration testing

- Performance largely unknown for this top-mounted supersonic inlet
- CFD prediction uncertainty
- Needs drove model to 9.5% scale
- Largest full vehicle in 8x6 SWT
- 3-inch diameter inlet
- Reynolds number 4 times lower than flight
- CFD performed at both flight and wind tunnel conditions

Model

- Four vortex generator configurations
- Two inlet types, C607 and C608
- 40-probe AIP array, steady-state
- Calibrated mass-flow plug
- Air ejector for subsonic operation
- Angle of attack:
  - supersonic -2° to 5°
  - transonic -2° to 8°
  - subsonic -4° to 14°.


Prop Pressure Module
Common Pressure Module
Inlet Duct
AIP
MFP
MFP Cover
Ejector
Mixing Tube
MFP Assembly Supports



C607 No vortex generator

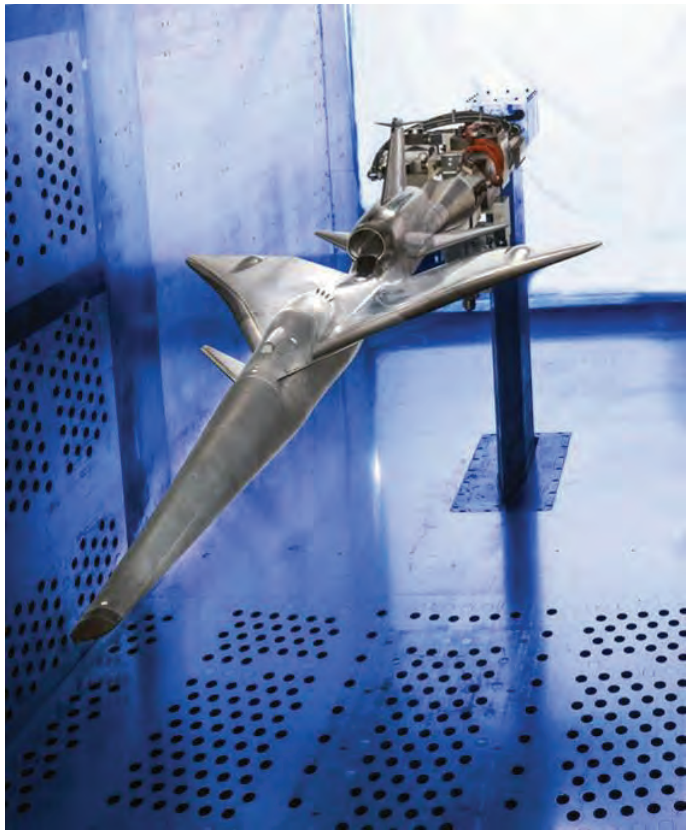
C607 Baseline, 8 VG's at 15˚ 0.263 in. high, 0.421 in. chord

C607 Alternate, 16 VG's at 20˚ 0.053 in. high, 0.263 in. chord

C608 Baseline, 8 VG's at 20˚ 0.105 in. high, 0.526 in. chord

Summary/Conclusions

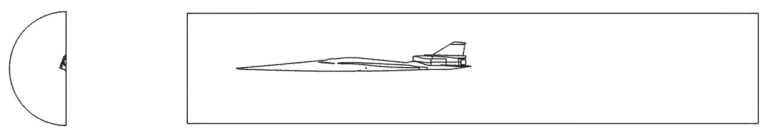
- Top mounted inlet performance critical to vehicle preliminary design
- Full vehicle plus inlet model was a successful approach, 9.5% scale
- Inlet Data was successfully collected:
  - Supersonic recovery and distortion were insensitive to α
  - Sensitive at $\beta = -2^{\circ}$
  - Dramatically affected by vortex generators
  - High subsonic performance, except for the static condition



Accompanying CFD Efforts

Geometry

- Simulations used a 9.5% scale version of the full aircraft geometry, including the C607 version of the inlet.
  - The scale was identical to the scale of the model tested in the 8- by 6- foot supersonic wind tunnel.
  - Due to symmetry, only half of the aircraft was modeled.



Front View Side View

Numerical Modeling – Flow Solver

- FUN3D was used for all 3D RANS CFD simulations.
  - Node-based, production level code developed and maintained at the NASA Langley Research Center.
  - Can solve 2D/3D Euler and RANS equations.
  - Can perform adjoint-based mesh refinement.

Numerical Modeling – Parameter Matrix

- The following combinations of parameters were tried:

Case #	Boundary-Layer Cell Type	Adaptation Metric	Adaptation Cycles
1	Tetrahedral	NA	0
2	Tetrahedral	Linear Pressure Sensor	8
3	Pentahedral	NA	0
4	Pentahedral	Pressure Box	8
5	Tetrahedral	Pressure Box	8*
6	Tetrahedral	Pressure Box	16*
7	Pentahedral	Pressure Box	8*
8	Pentahedral	Pressure Box	16*

*reduced number of additional nodes/adaptation cycle.

Numerical Modeling – Initial/Manually Refined Grids (Procedure)

- Pointwise grid generation software was used to generate an unstructured surface grid.
- The AFLR3 code was used to generate the unstructured volume grids.
  - Code is developed and maintained at the Mississippi State University.
  - Uses the Advancing Front/Local Reconstruction method.

Numerical Modeling – Initial/Manually Refined Grids (Information)

- Grid Sizes:

Boundary-Layer Cell Type	Number of Nodes
Initial Tetrahedral	33.4 Million
Initial Pentahedral	33.4 Million
Manually Refined Tetrahedral	92.3 Million
Manually Refined Pentahedral	91.8 Million

- Spacing off of the viscous surfaces for the initial grids was such that $y^+ < 0.2$.

Numerical Modeling – Flow Conditions

- Three different set points from the 8- by 6- foot wind tunnel test were chosen for comparison:

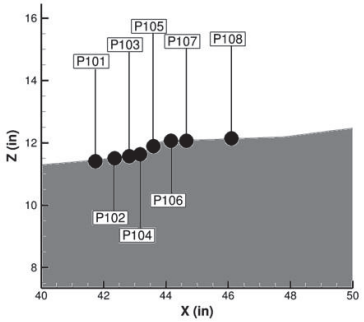
Mach Number	Angle of Attack (α, degrees)	Angle of Sideslip (β, degrees)
1.46	2.0	0.0
1.35	3.0	0.0
0.30	3.0	0.0

Only the results run at the freestream Mach number of 1.46 will be shown.
Additional results will be presented in the 2018 AIAA Aviation paper:
"Numerical Simulations of a Quiet SuperSonicTechnology (QueSST) Aircraft Preliminary Design"

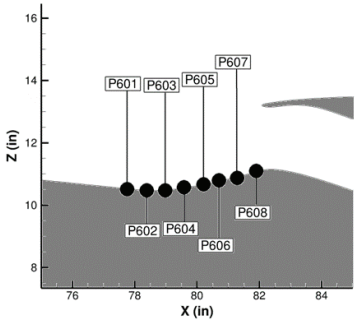
- The Spalart-Allmaras (SA) turbulence model was used for all simulations.

Results – Station Locations

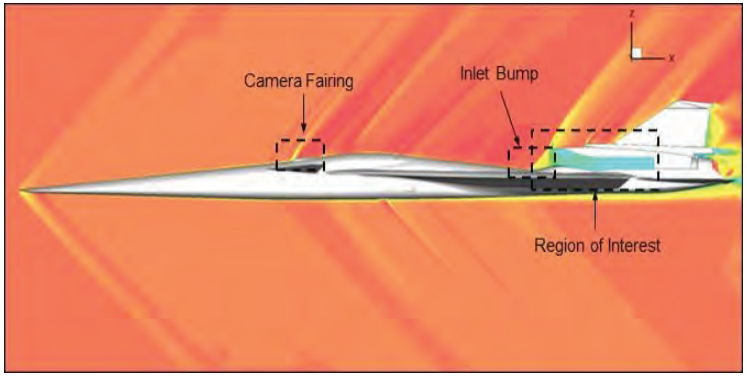
- Concerned with the centerline pressure measurements at the camera fairing and inlet bump regions.



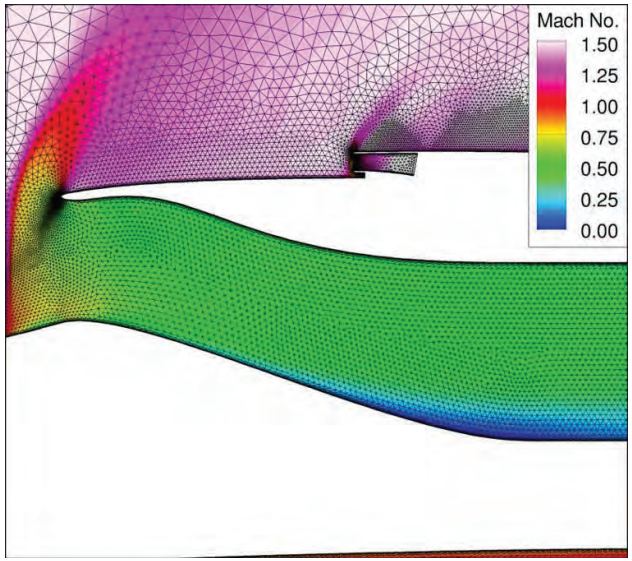
Camera Fairing Region

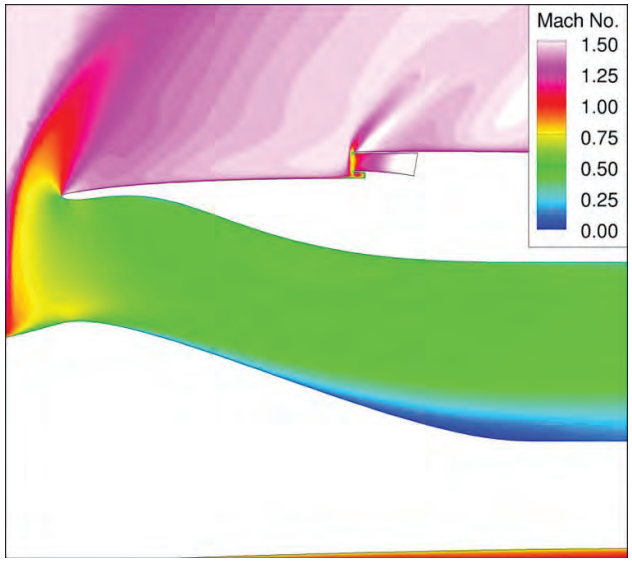


Inlet Bump Region



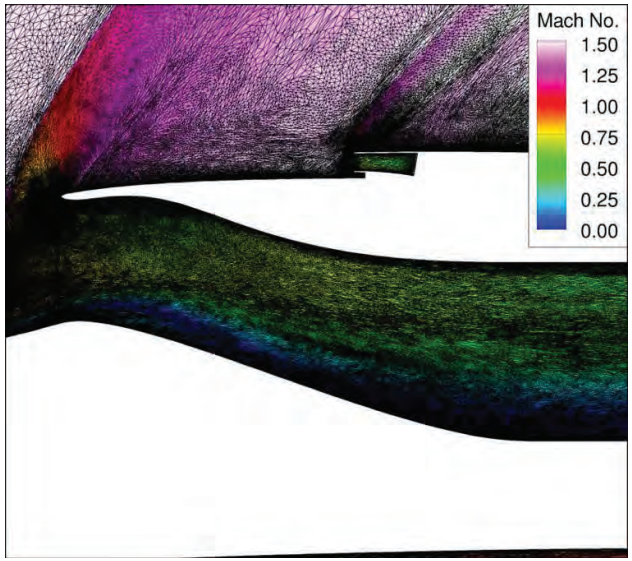
Results – Cell Type and Grid Adaptation Metric

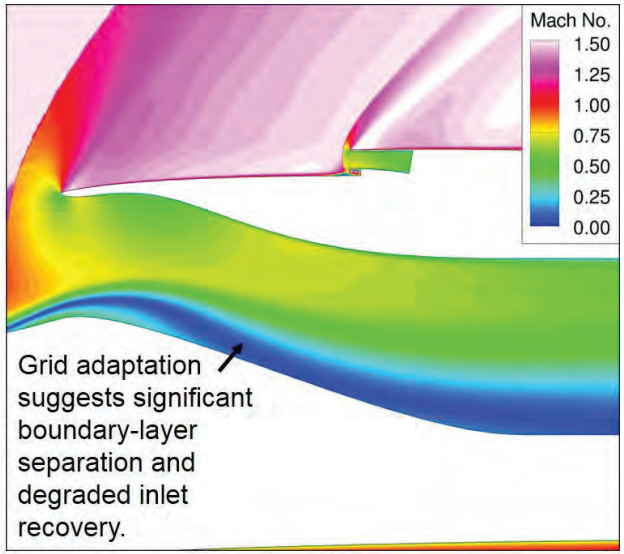




Initial tetrahedral boundary-layer grid (Case #1)

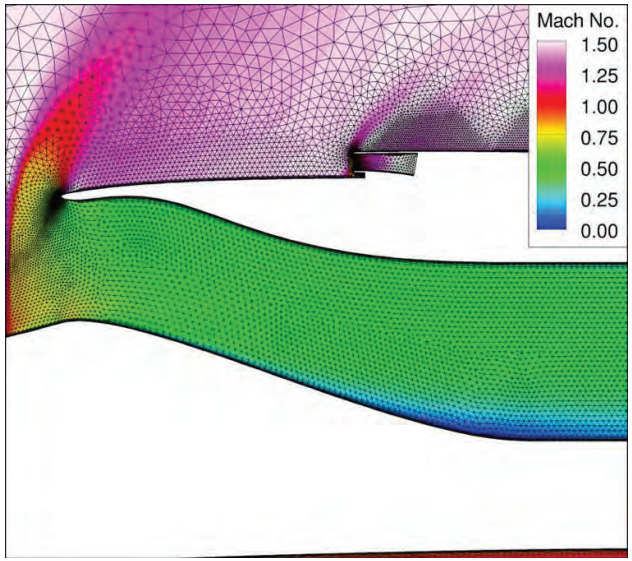
Results – Cell Type and Grid Adaptation Metric

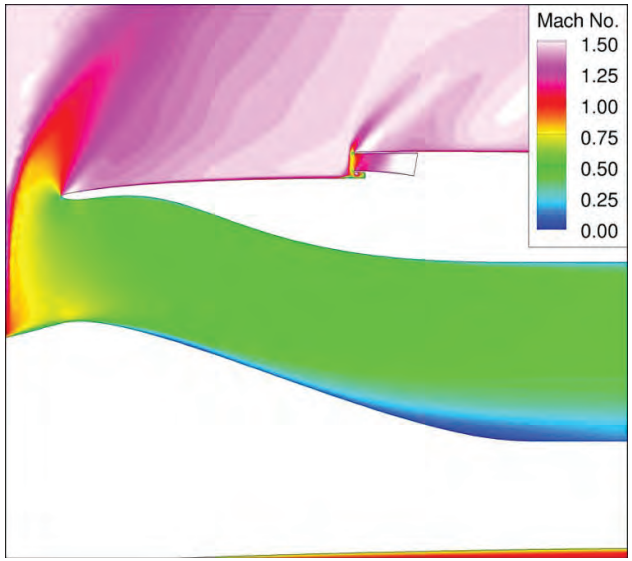




8 adaptation cycle tetrahedral boundary-layer grid (Case #2)
(Linear Pressure Sensor)

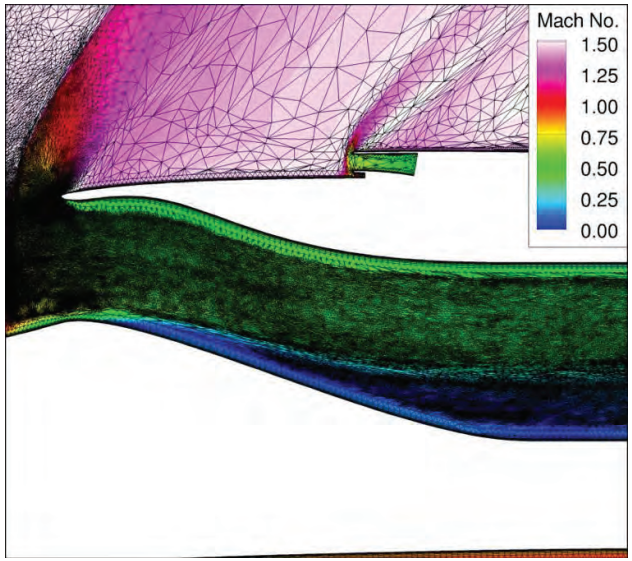
Results – Cell Type and Grid Adaptation Metric

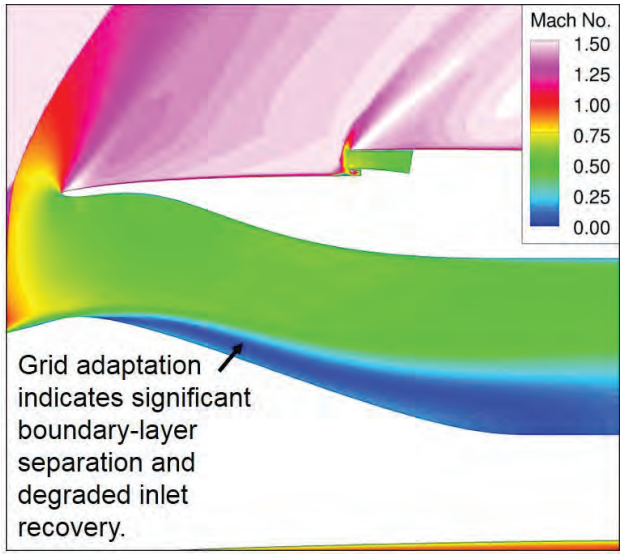




Initial pentahedral boundary-layer grid (Case #3)

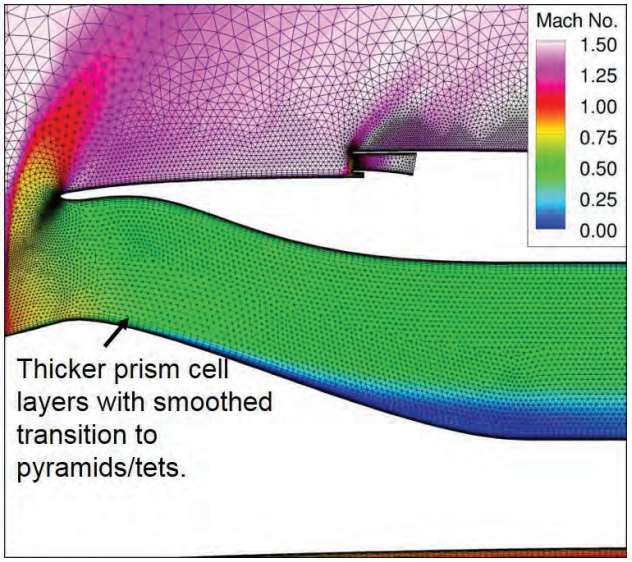
Results – Cell Type and Grid Adaptation Metric

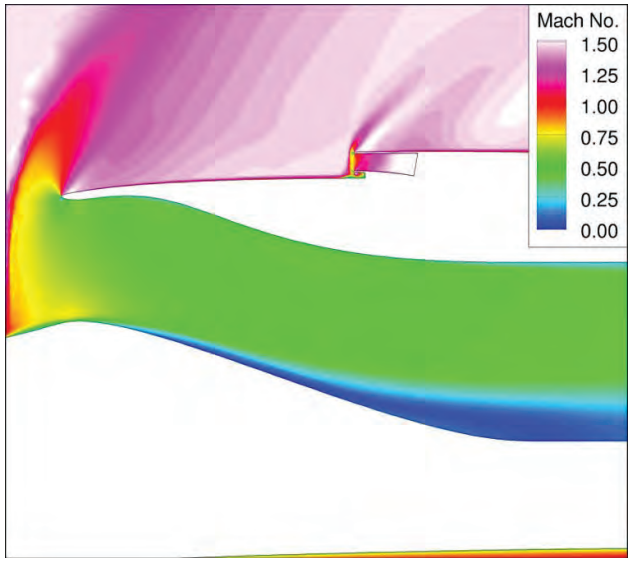




8 adaptation cycle pentahedral boundary-layer grid (Case #4)
(Pressure Box)

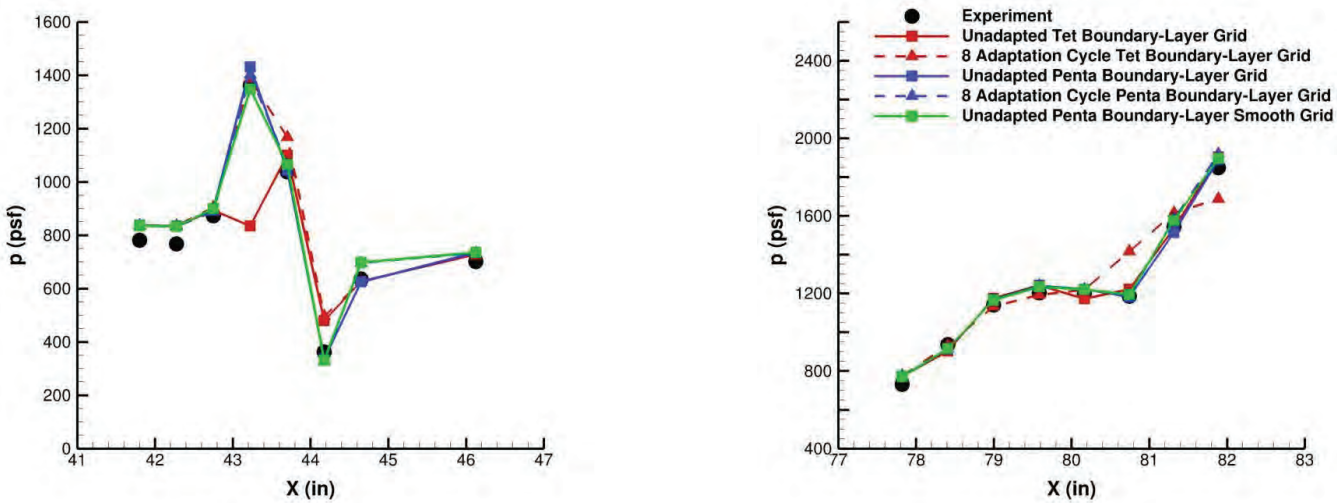
Results – Cell Type and Grid Adaptation Metric





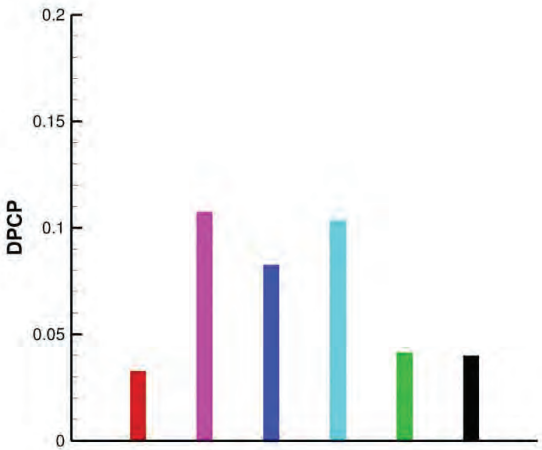
Initial pentahedral boundary-layer smooth grid (Case #3A)

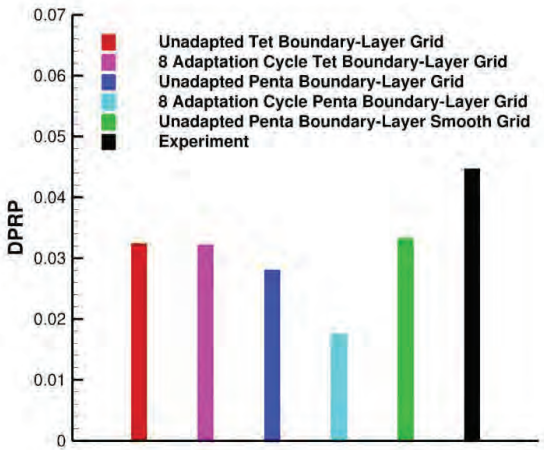
Results – Cell Type and Grid Adaptation Metric



Pressure measurements at the camera fairing (left) and inlet bump (right) regions

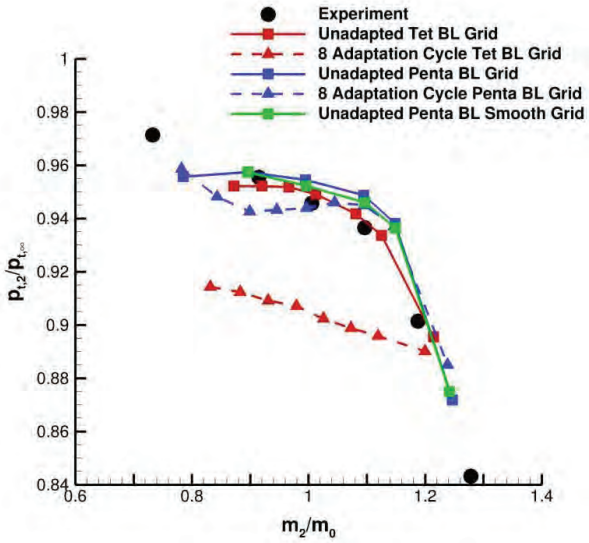
Results – Cell Type and Grid Adaptation Metric



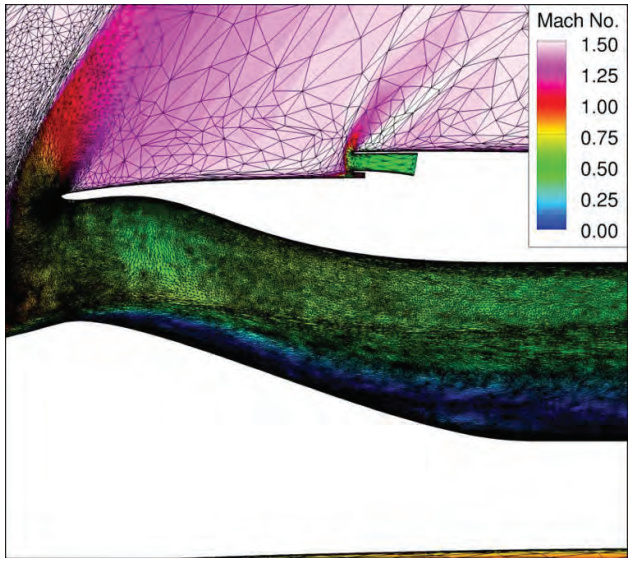


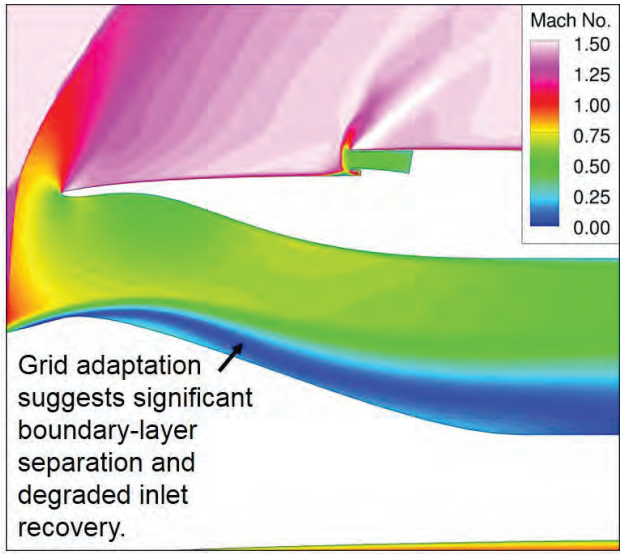
Inlet circumferential distortion (left) and radial distortion (right)

Results – Cell Type and Grid Adaptation Metric



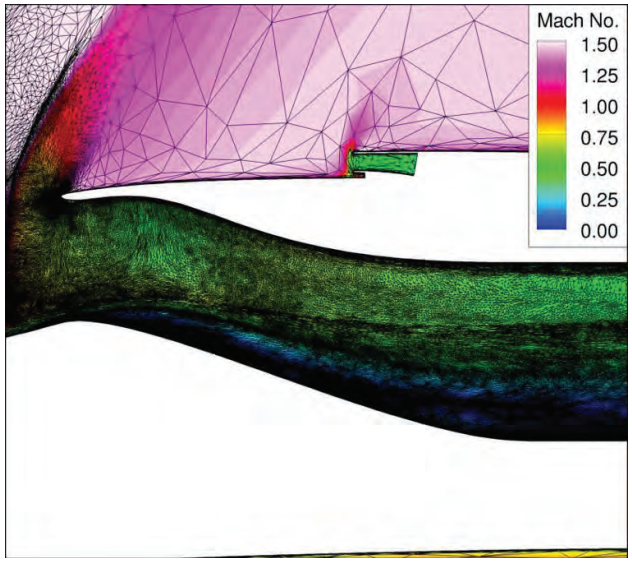
Results – Number of Adaptation Cycles

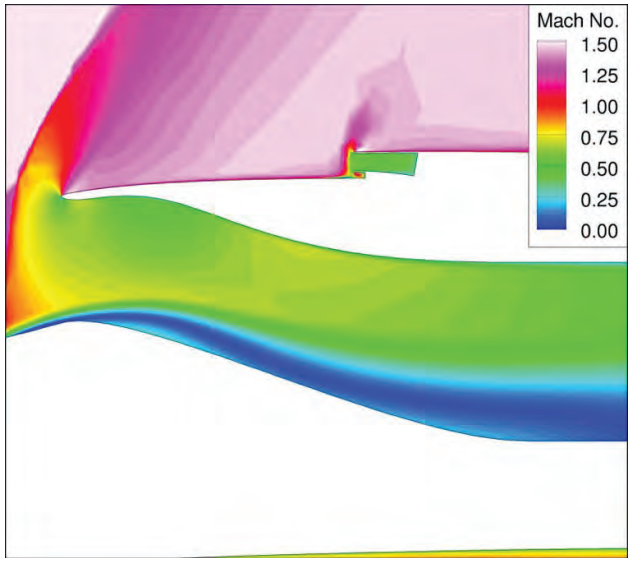




8 adaptation cycle tetrahedral boundary-layer grid (Case #5)
(Pressure Box)

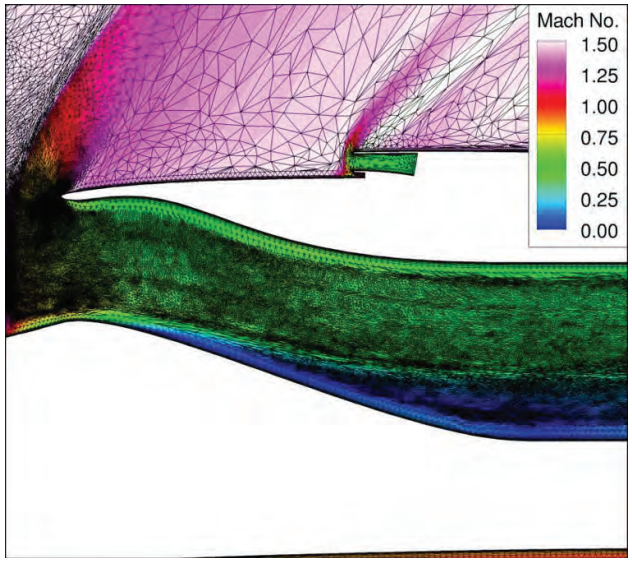
Results – Number of Adaptation Cycles

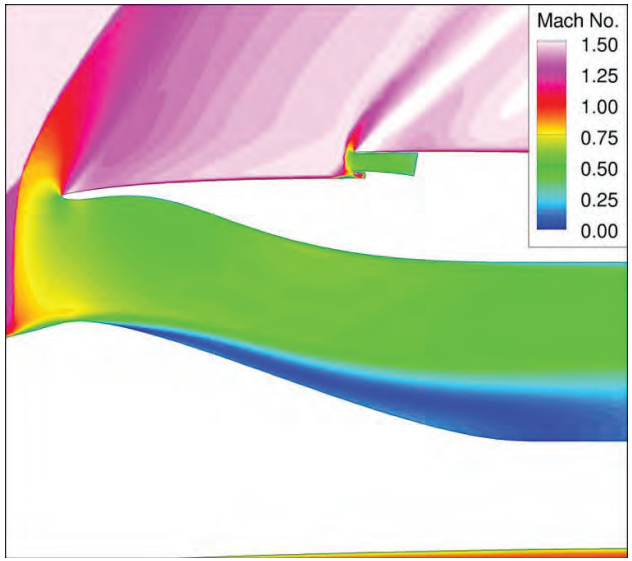




16 adaptation cycle tetrahedral boundary-layer grid (Case #6)
(Pressure Box)

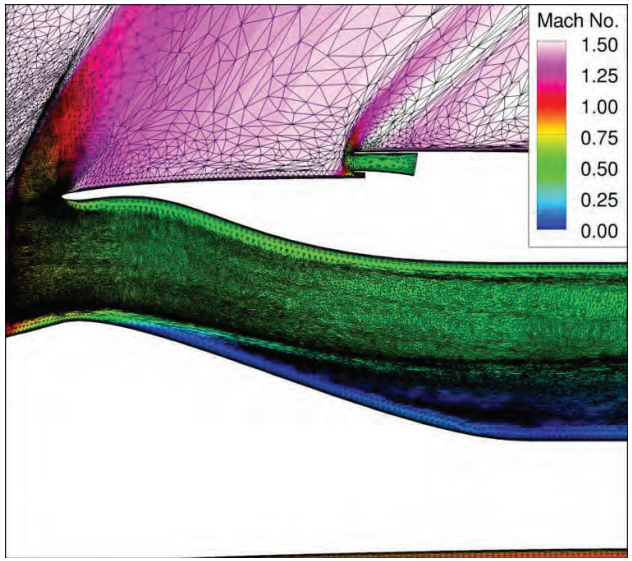
Results – Number of Adaptation Cycles

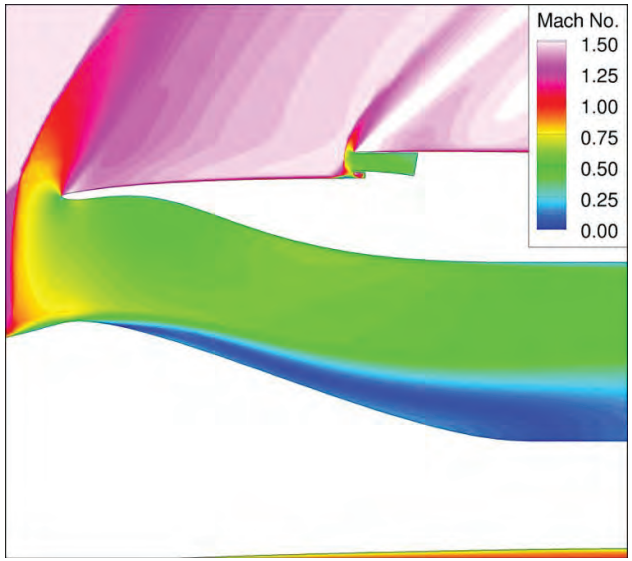




8 adaptation cycle pentahedral boundary-layer grid (Case #7)
(Pressure Box)

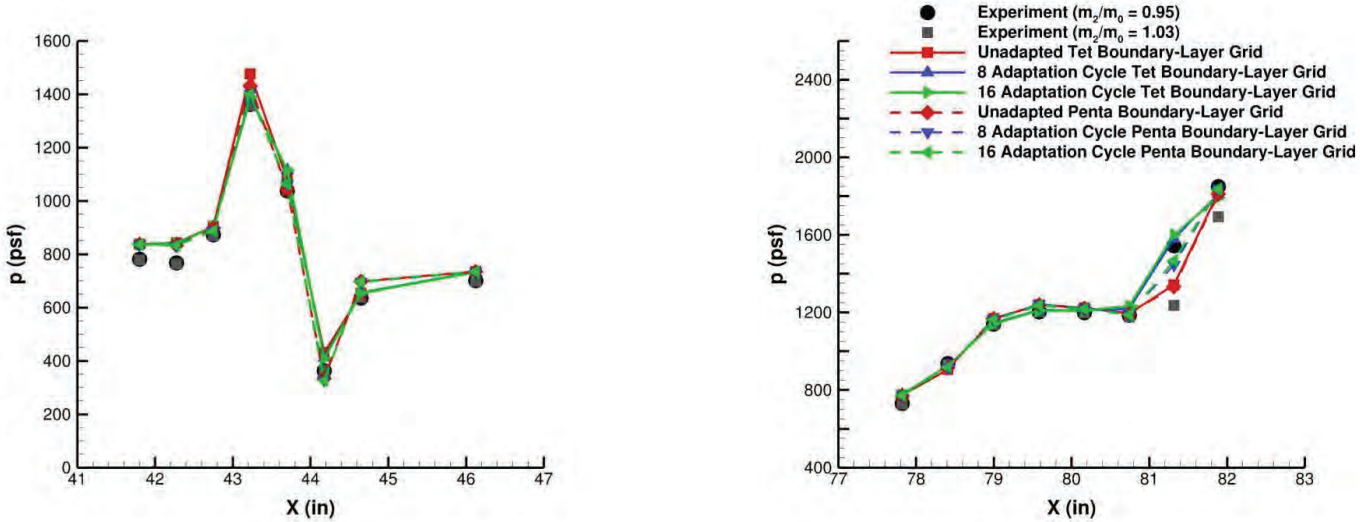
Results – Number of Adaptation Cycles





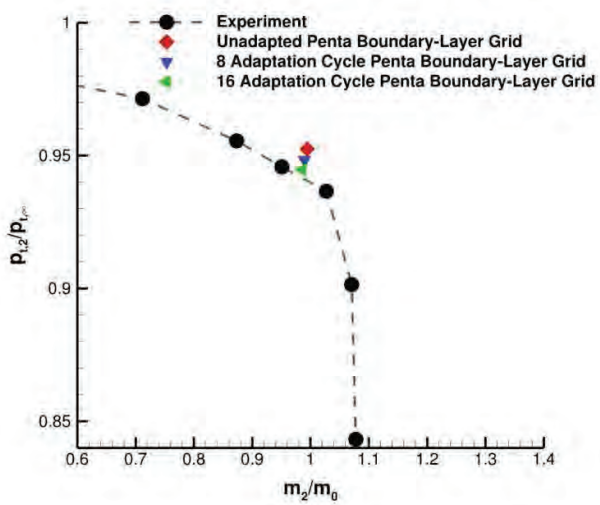
16 adaptation cycle pentahedral boundary-layer grid (Case #8)
(Pressure Box)

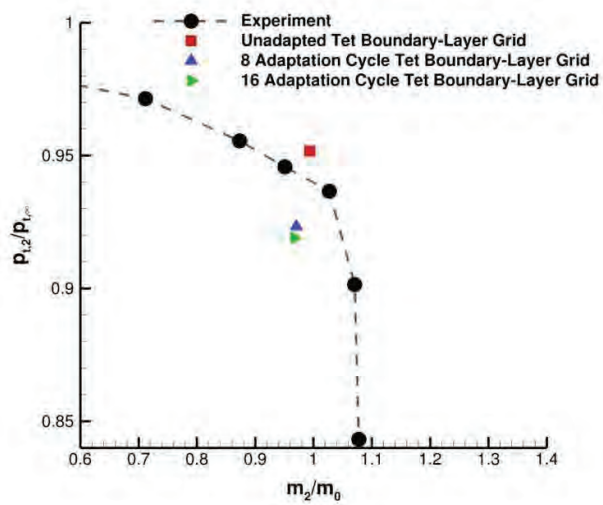
Results – Number of Adaptation Cycles



Pressure measurements at the camera fairing (left) and inlet bump (right) regions

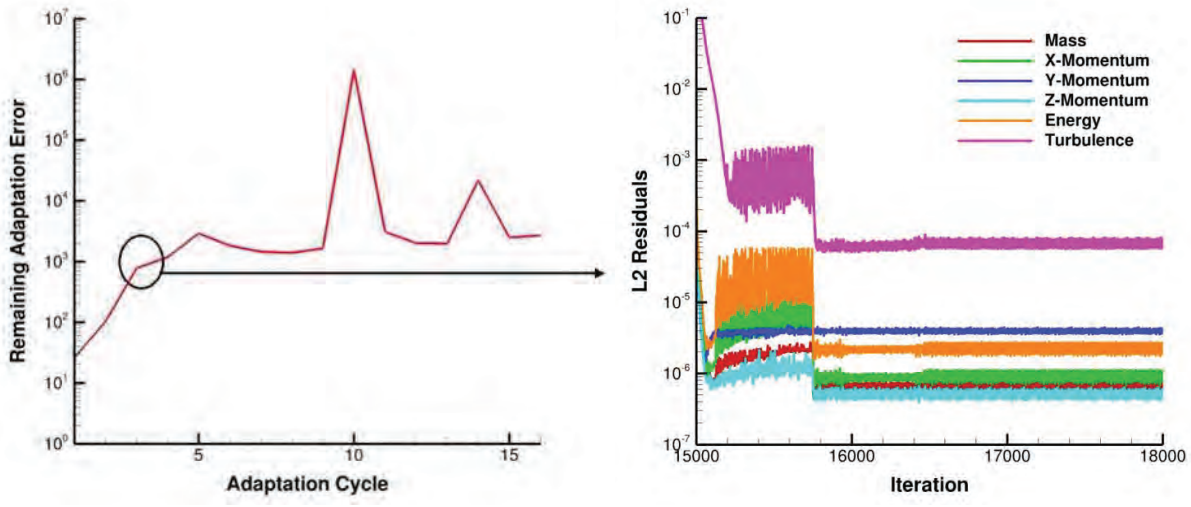
Results – Number of Adaptation Cycles





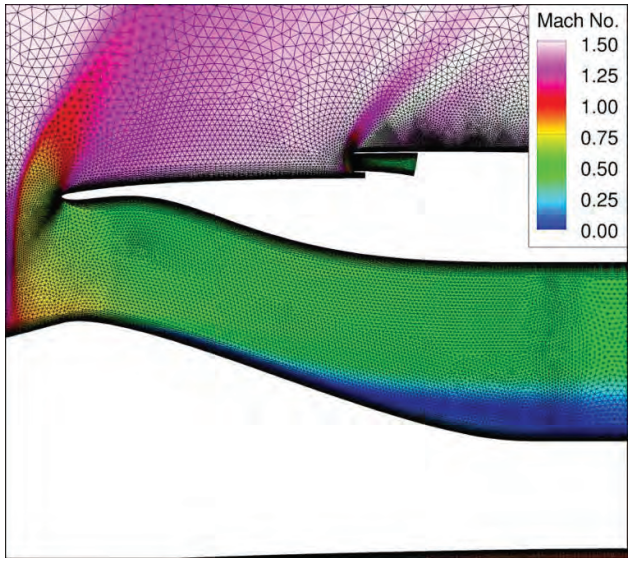
40-point total pressure recovery plots for the pentahedral boundary-layer grids (left) and tetrahedral boundary-layer grids (right)

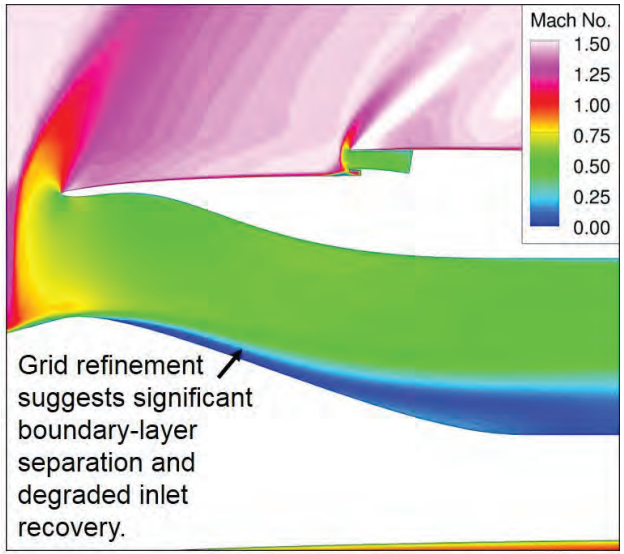
Results – Adaptation Error Estimate



Remaining Adaptation Error = ([Flow Residual Embedded Mesh] x [Adjoint Interpolation Error])
+ ([Adjoint Residual on Embedded Mesh] x [Flow Interpolation Error])

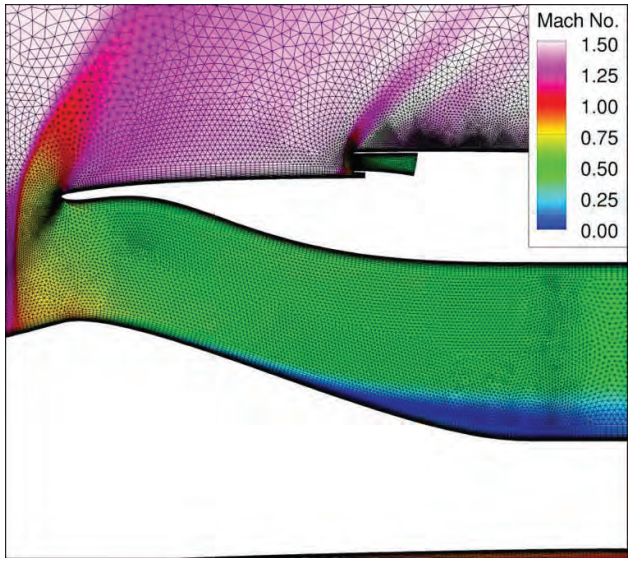
Results – Manually Refined Grids

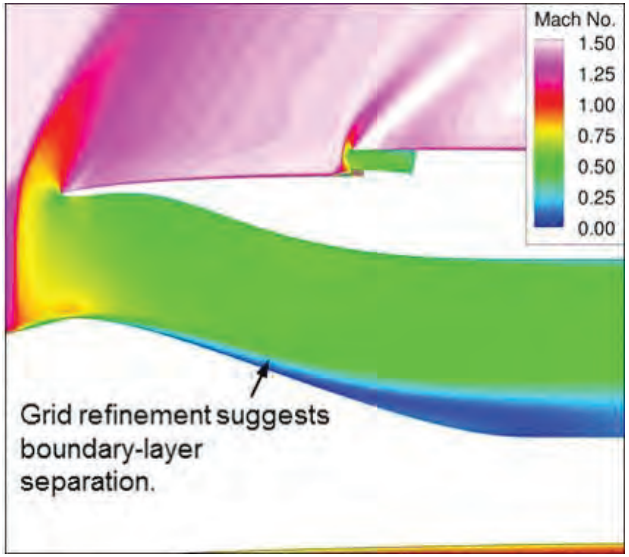




Manually refined tetrahedral boundary-layer grid

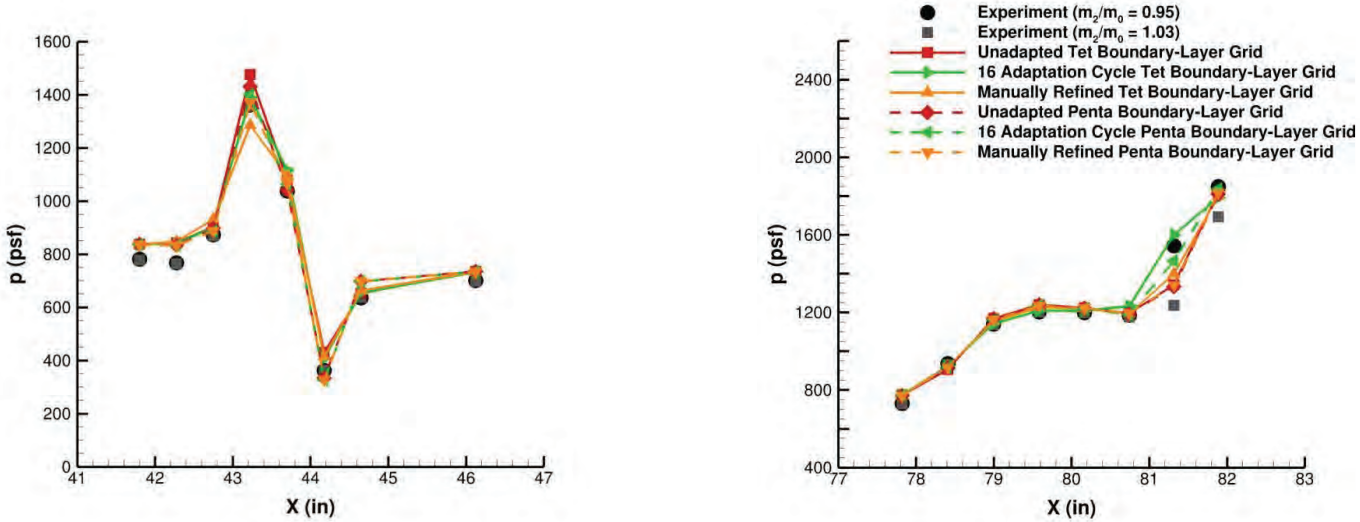
Results – Manually Refined Grids





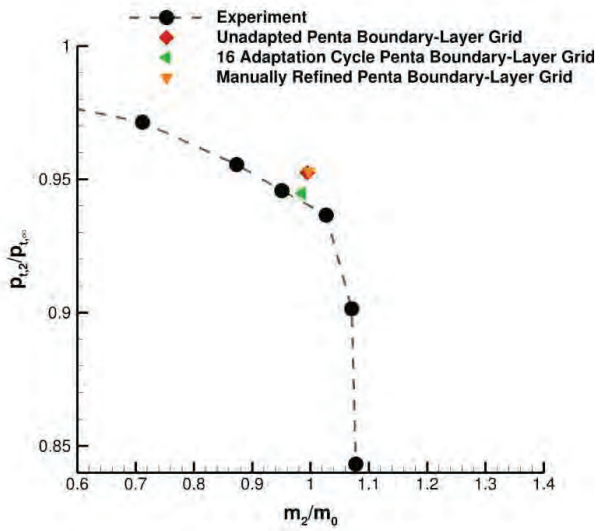
Manually refined pentahedral boundary-layer grid

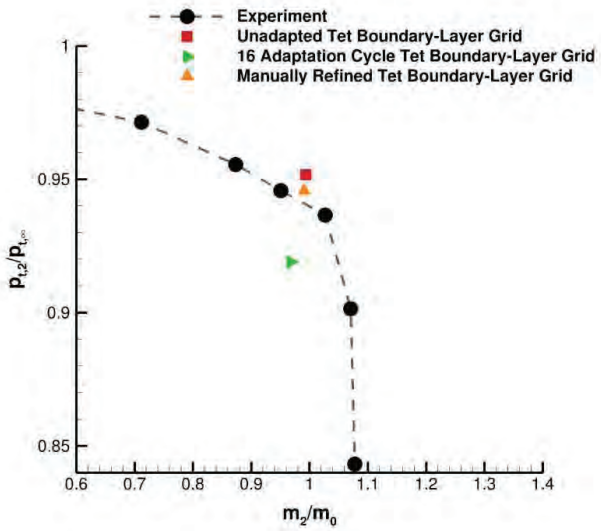
Results – Manually Refined Grids



Pressure measurements at the camera fairing (left) and inlet bump (right) regions

Results – Manually Refined Grids





40-point total pressure recovery plots for the pentahedral boundary-layer grids (left) and tetrahedral boundary-layer grids (right)

Summary

- A QueSST aircraft preliminary design was simulated using RANS CFD at 9.5% test-scale conditions in order to help determine inlet performance.

Conclusions (Part 1)

- It was shown that there is a high uncertainty associated with these CFD simulations as they were not shown to be grid independent. This was true regardless of…
  - the type of cells near the boundary-layer regions.
  - whether the adjoint-mesh refinement was used vs. manual grid refinement.
  - the number of adaptation refinement cycles.
  - the adaptation metric used.

Conclusions (Part 2)

- There is a high uncertainty in the CFD simulations if a grid refinement study is not performed or if the simulations are not anchored to experimental data.

NASA/CP—2018-219955

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National Aeronautics and Space Administration

National Aeronautics and Space Administration

BLI^{2}DTF Testing in the 8x6'

Boundary-Layer-Ingesting Inlet / Distortion-Tolerant Fan

Propulsion-Airframe Integration Technical Interchange Meeting

May 31, 2018

Supported by: NASA Advanced Air Transport Technology Project
Integrated Boundary Layer Ingestion Subproject

www.nasa.gov

Overview

- Motivations
- The BLI^{2}DTF Experiment Overview
- Tunnel Calibration
- Rotating Rake Arrays
- Lessons Learned

National Aeronautics and Space Administration

The Current State of Propulsion Airframe Integration is…

Credit: Public Domain / Adrian Pingstone

Credit: US Navy

Credit: USAF / MSgt Val Gempis

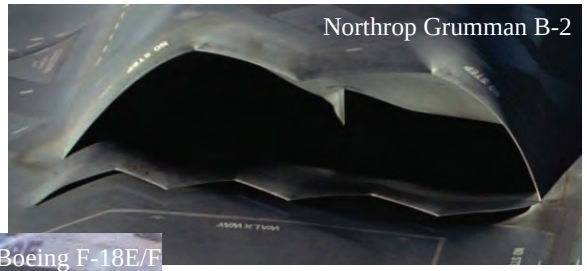
Credit: CC BY-SA 2.0 / Tomas Del Coro

Credit: USAF / MSgt Donald R. Allen

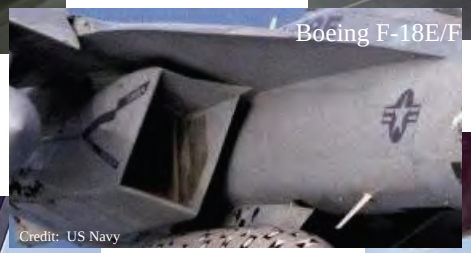
National Aeronautics and Space Administration

Boundary Layer Avoidance, Diversion and Removal

Credit: Public Domain / Adrian Pingstone



Credit: USAF / MSgt Val Gempis



Credit: US Navy

Credit: CC BY-SA 2.0 / Tomas Del Coro

Credit: USAF

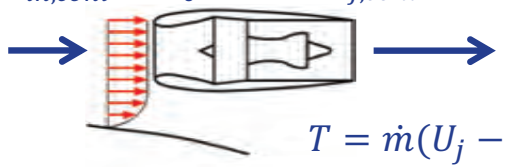
Boundary Layer Ingestion: Benefits and Application

Because average inlet velocity is lower for BLI, jet velocity is also lower when thrust and airflow are fixed.

BLI offers significant **propulsive** efficiency and fuel burn benefits relative to conventional propulsion.

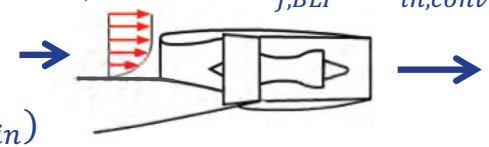
Conventional Propulsion

$U_{in,conv} = U_0$ $\quad U_{j,conv}$



Boundary Layer Ingesting Propulsion

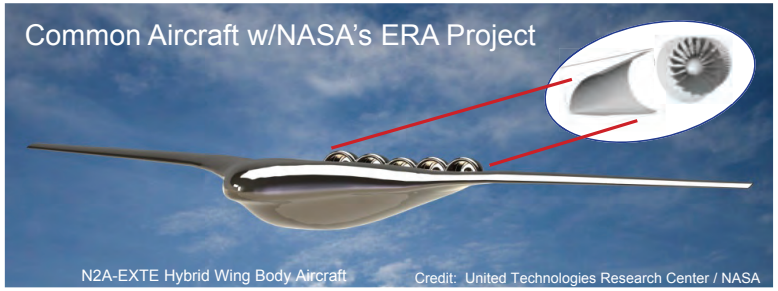
$U_{in,BLI} < U_0$ $\quad U_{j,BLI} < U_{in,conv}$



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

$$P = \dot{m}(U_j^2 - U_{in}^2)$$

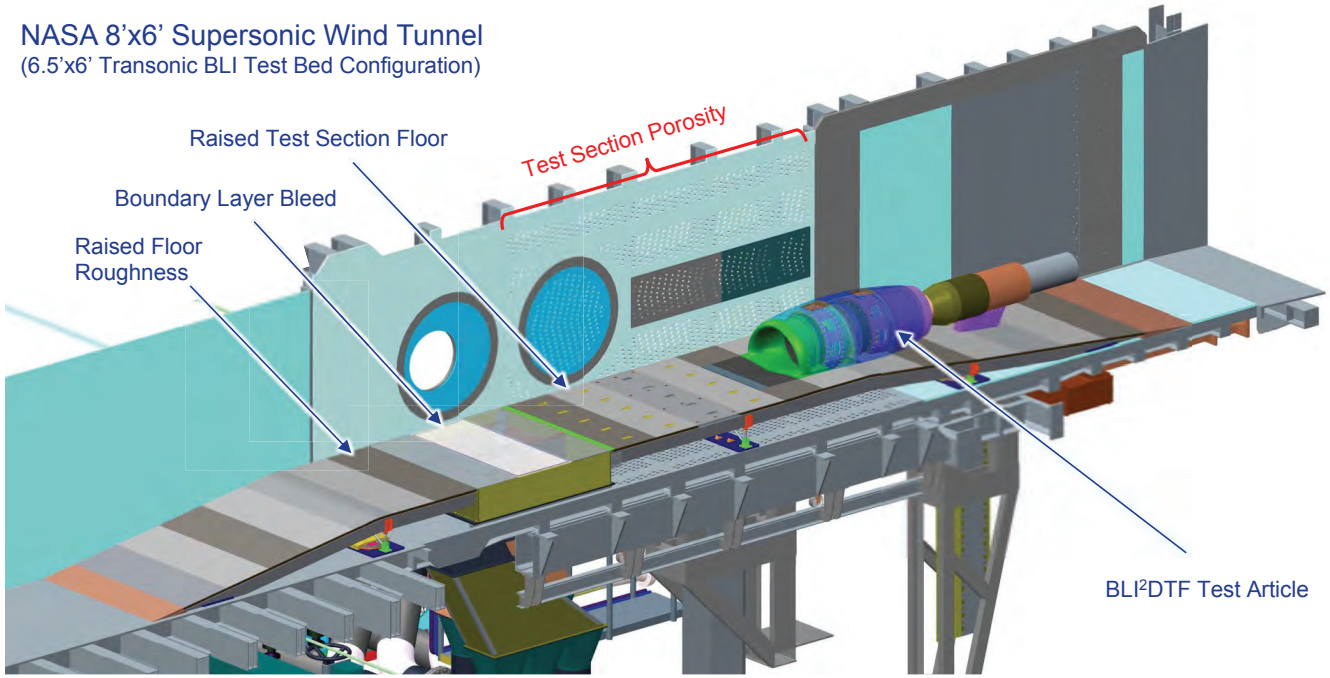
Our reference configuration was the N2A-EXTE HWB aircraft, but other configurations could benefit from BLI.



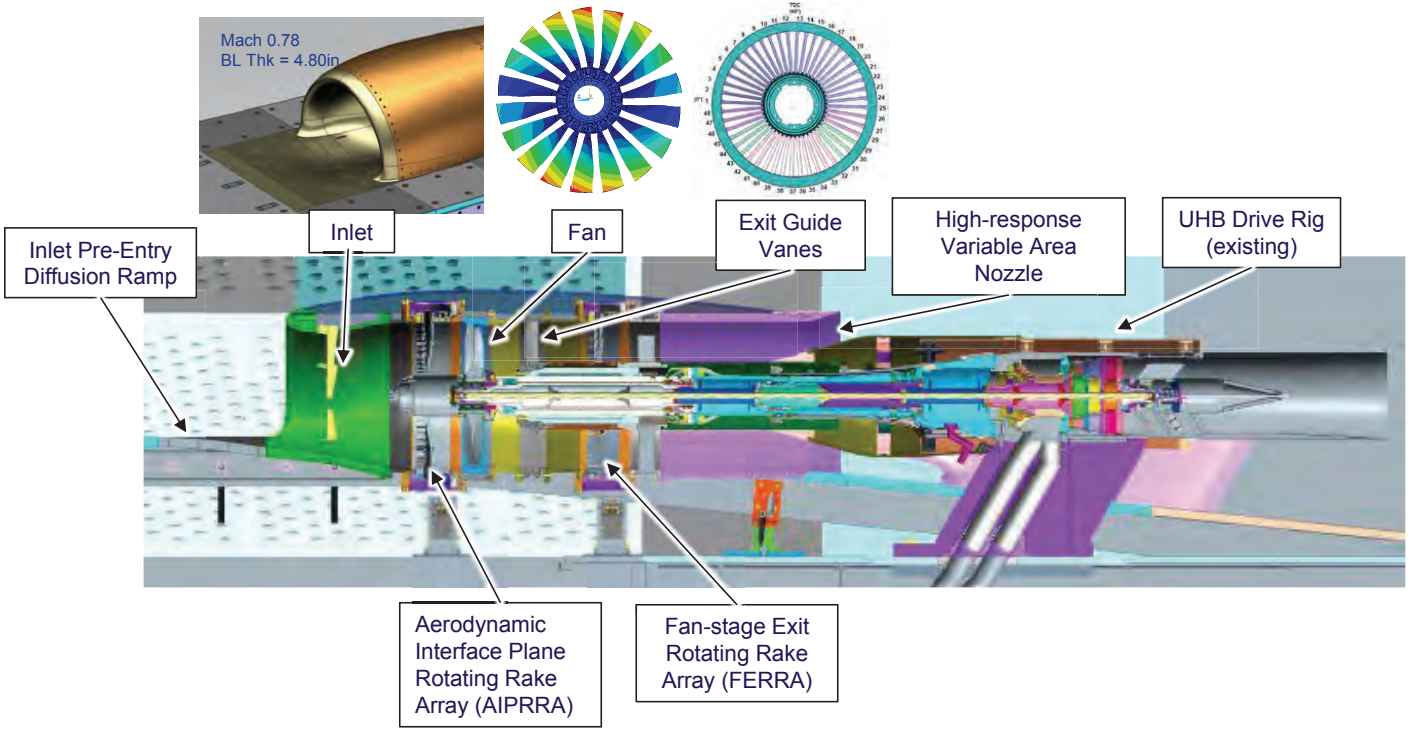
National Aeronautics and Space Administration

Boundary-Layer-Ingesting Inlet / Distortion-Tolerant Fan (BLI^{2}DTF) Experiment

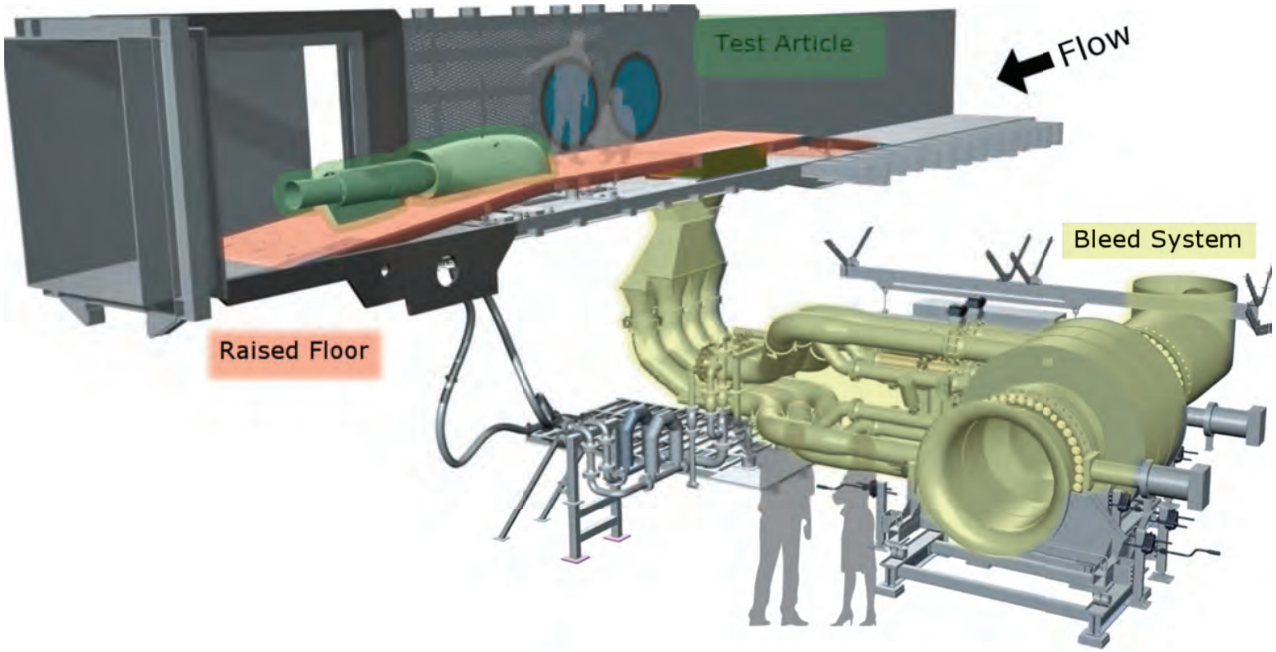
NASA 8'x6' Supersonic Wind Tunnel
(6.5'x6' Transonic BLI Test Bed Configuration)



Integrated BLI^{2}DTF Test Article



6.5’x6’ Transonic Embedded Propulsor Testbed



National Aeronautics and Space Administration

It Takes Many People

United Technologies Research Center

Vantage Partners, LLC

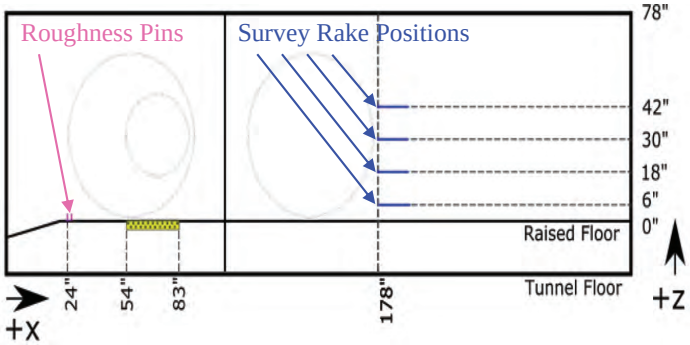
VirginiaTech

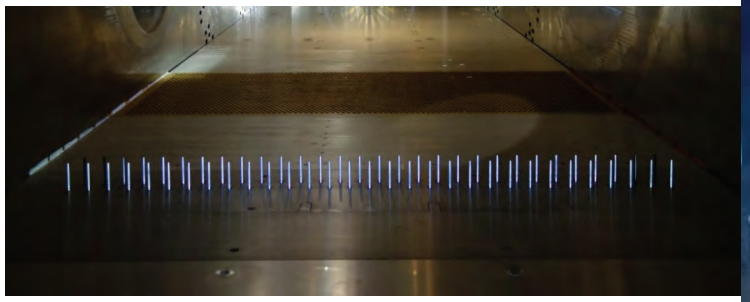
QuantiTech

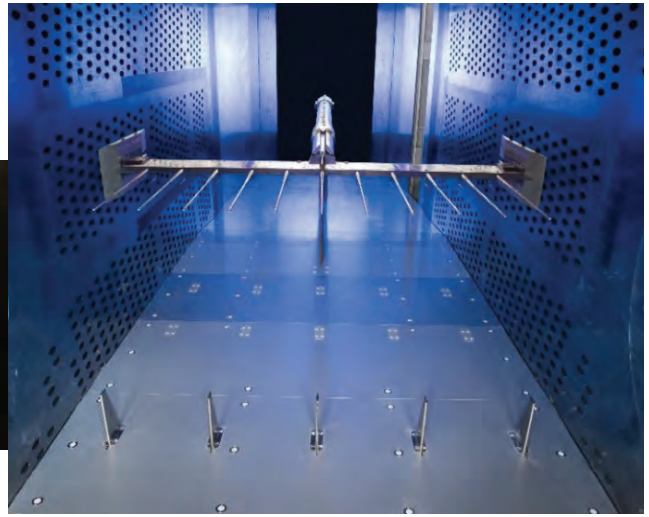
Supported by: NASA Advanced Air Transport Technology Project
Integrated Boundary Layer Ingestion Subproject

Modified Test Section Calibrations

- Measured P_t, T_t using full-span rake at several axial and vertical stations
- Measured boundary layer P_t on floor, walls, ceiling

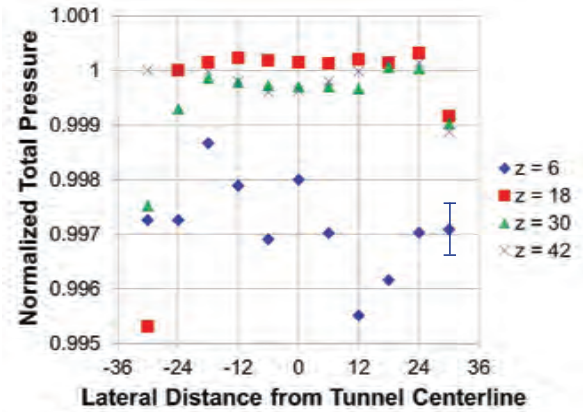


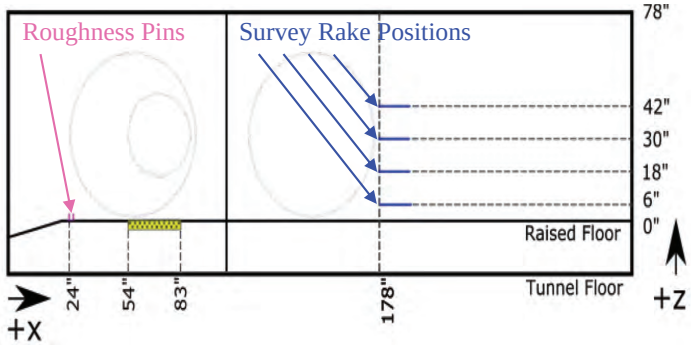


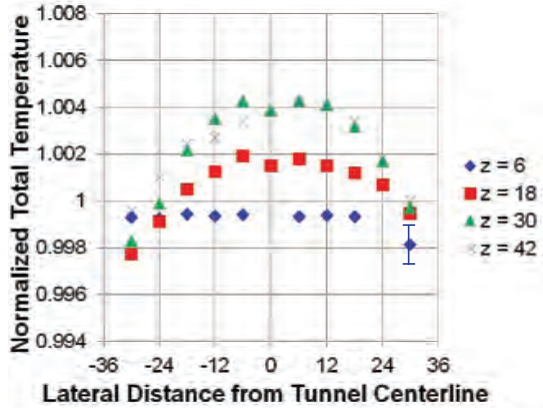


Required Freestream Flow Distribution Achieved

- Uniform Core Freestream Total Pressure and Total Temperature
- Scatter in z=6” Total Pressure Distribution Due to Boundary Layer Edge
- Near Wind Tunnel Wall Total Temperature Gradients Were Larger Than Expected







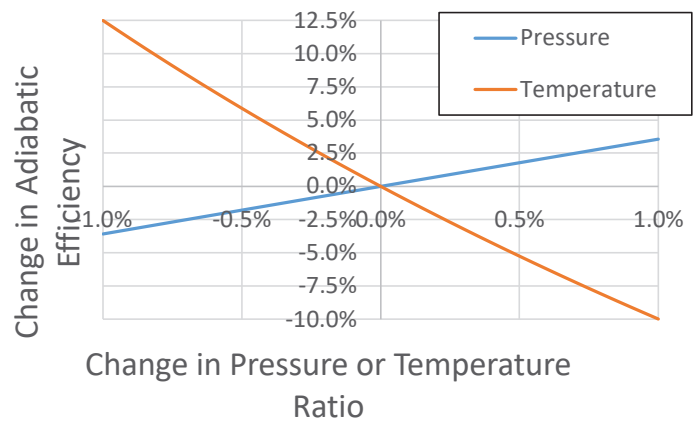
The Adiabatic Efficiency Measurement Challenge

- When fan stage pressure ratio (s_P) and stage temperature ratio (s_T) are close to unity, measurement of adiabatic efficiency becomes challenging
- Accurate measurement of entrance/exit conditions is critical

$$\eta_A = \frac{s_P^{\frac{\gamma-1}{\gamma}} - 1}{s_T - 1}$$

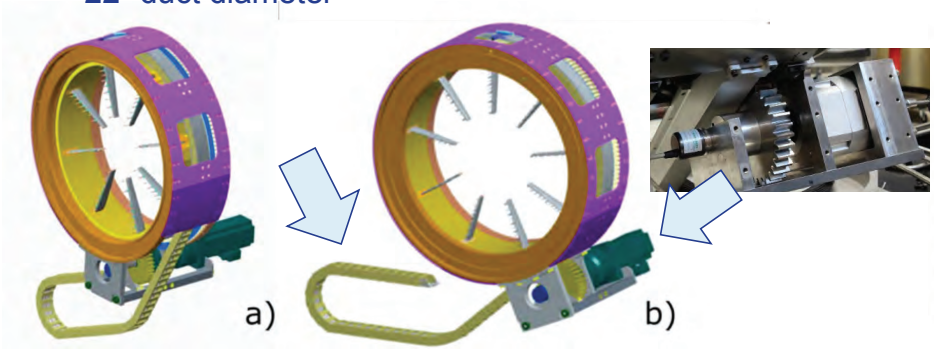
$$s_P = \frac{P_{T,Fan_stage_exit}}{P_{T,Aerodynamic_interface_plane}}$$

$$s_T = \frac{T_{T,Fan_stage_exit}}{T_{T,Aerodynamic_interface_plane}}$$

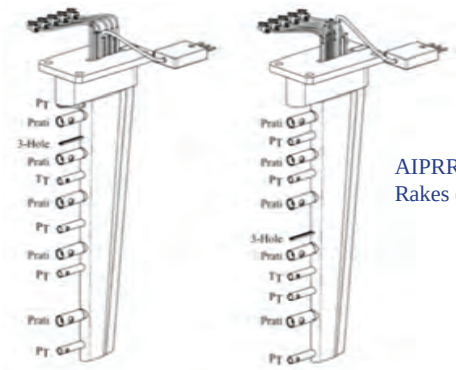


Rotating Rake Arrays

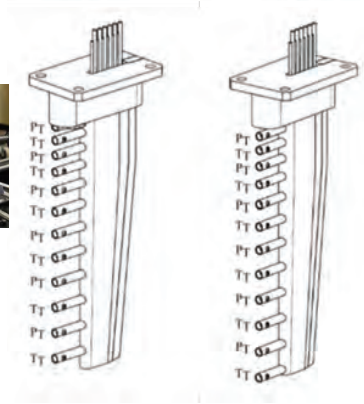
- Rotating Rake Arrays (RRAs) measured P_T (steady and dynamic), T_T, P_S, angularity → pressure/temperature ratios, stage efficiency, mass flow
- High data density achieved through rotations and probe arrangements (FERRA 24 radial x 72 circumferential measurements; AIPRRA P_T 13 x 72)
- Modular RRAs can be removed from rig and rakes can be removed/replaced
- 22” duct diameter



a) Aerodynamic Interface Plane RRA; b) Fan-stage Exit RRA



AIPRRA Rakes (2 types)

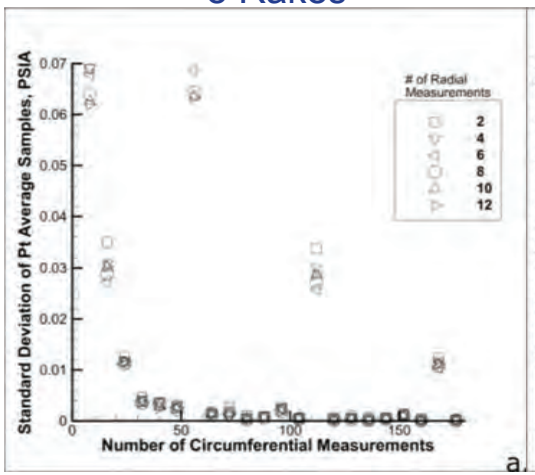


FERRA Rakes (4 types; P_T and T_T reversed on types not shown)

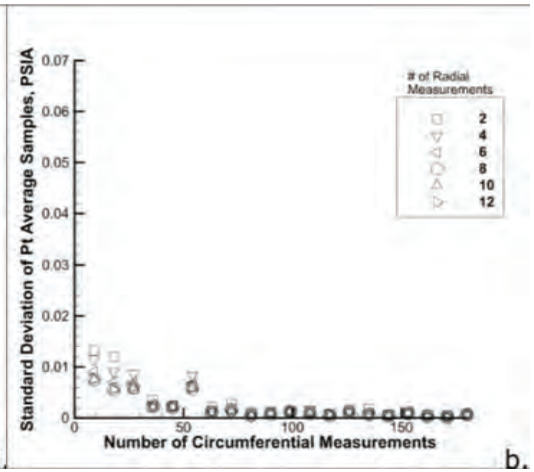
FERRA P_T Simulated Survey Results

"Spikes" appear in data at 56, 112, 168 circumferential measurements

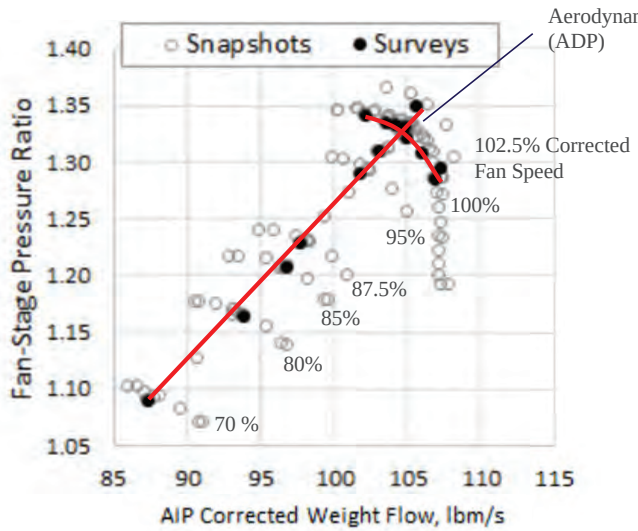
8 Rakes

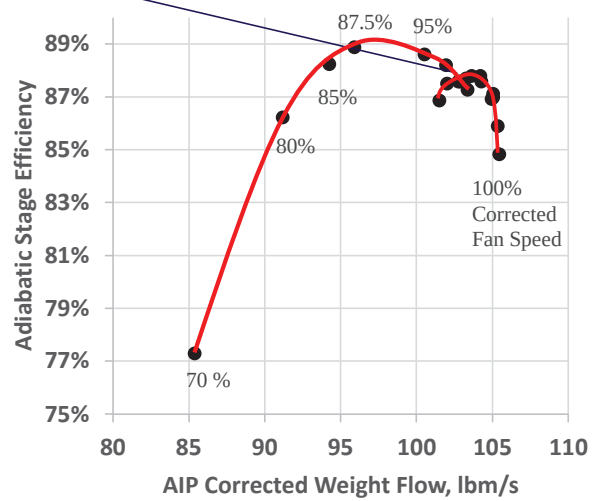


9 Rakes



Survey Results



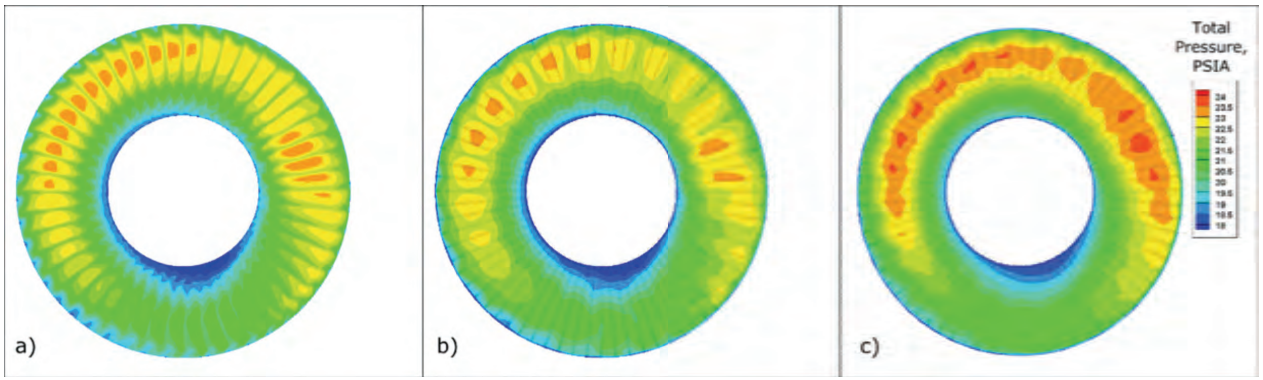


Surveys were taken at 15 operating conditions.
119 non-survey “snapshots” were recorded.

Survey Resolution for Averages

CFD | CFD -> Expt Pts | Experiment

Pt



At 72 circumferential samples, the EGV wakes still aren't resolved, but it's good enough for performance calculation.
Our studies have shown that the snapshot points (9 circumferential samples) can be enhanced to give reasonable performance estimates.

Lessons Learned

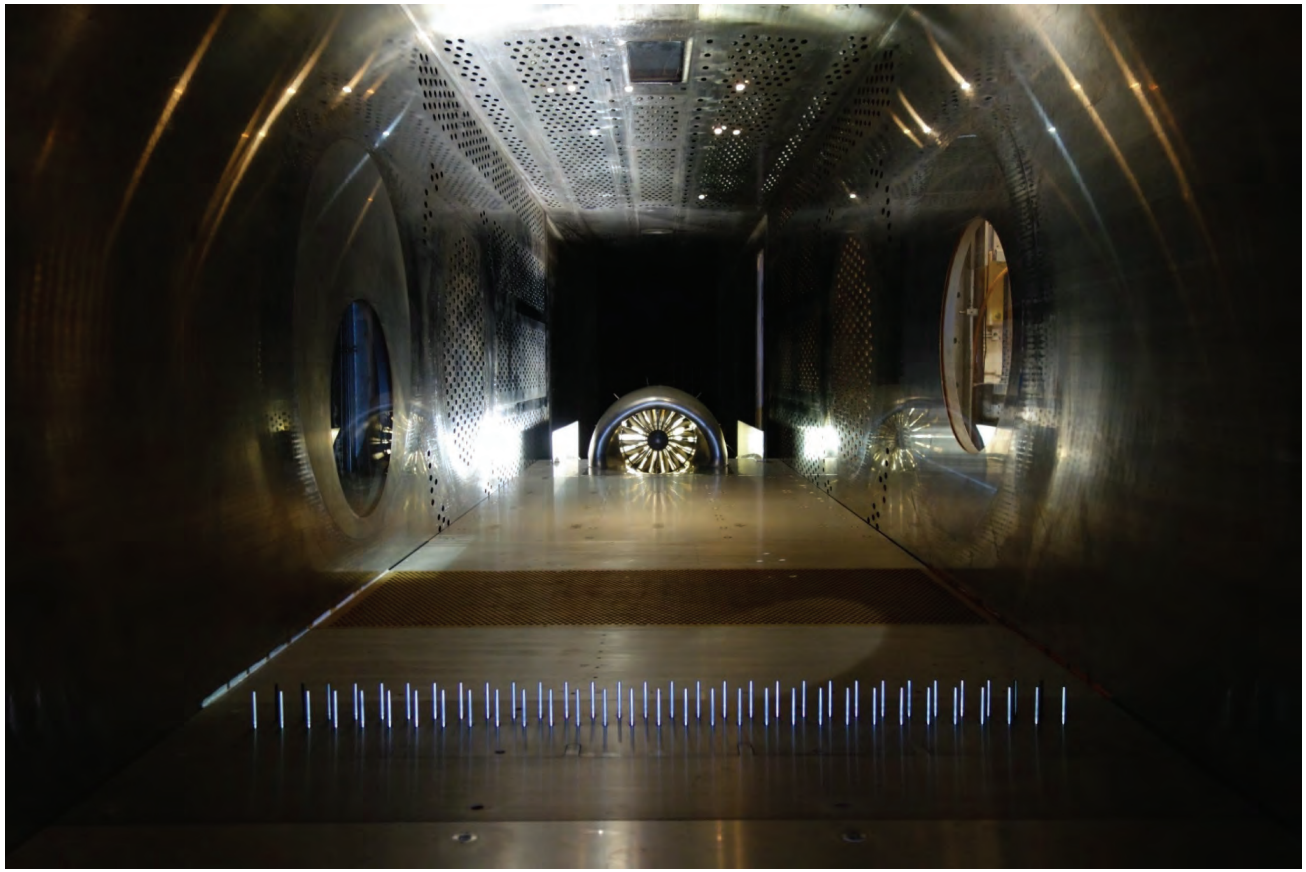
- You Probably Don't Know your Tunnel Flow as Well as You Think You Do
  - Centerline vs near walls
  - Small differences (e.g. 2°F) can be important
- Finding Peak Efficiency is not Trivial
  - All the pieces have to be put together
- Rotating Rakes Work, but the Details Matter
  - Rake design
  - Survey density
- Lower resolution data can be enhanced to make reasonable performance estimates

Further Reading (1 of 2)

- Ferrar, O'Brien, Ng, Florea, and Arend. ***Active Control of Flow in Serpentine Inlets for Blended Wing-Body Aircraft***
- Florea, Reba, Vanslooten, Sharma, Stucky, O'Brien, and Arend. ***Preliminary Design for Embedded Engine Systems***
- Hardin, et al., ***Aircraft System Study of Boundary Layer Ingesting Propulsion***
- Florea, Matalanis, Hardin, Stucky, and Shabbir. ***Parametric Analysis and Design for Embedded Engine Inlets***
- Bakhle, Reddy, Herrick, Shabbir, and Florea. ***Aeromechanics Analysis of a Boundary Layer Ingesting Fan***
- Arend, Tillman, and O'Brien. ***Generation after Next Propulsor Research: Robust Design for Embedded Engine Systems***
- Suder, Delaat, Hughes, Arend, and Celestina. *NASA* ***Environmentally Responsible Aviation Project's Propulsion Technology Phase I Overview and Highlights of Accomplishments***
- Giuliani, Chen, Beach, and Bakhle. ***Numerical Simulation of Boundary Layer Ingesting (BLI) Inlet/Fan Interaction***

Further Reading (2 of 2)

- Bakhle, Reddy, and Coroneos. ***Forced Response Analysis of a Fan with Boundary Layer Inlet Distortion***
- Ochs, Tillman, Joo, and Voytovych. ***CFD-based Analysis of Boundary Layer Ingesting Propulsion***
- Wolter, Arend, Hirt, and Gazzaniga. ***Development of a Rotating Rake Array for Boundary-Layer-Ingesting Fan-Stage Measurements***
- Arend, Wolter, Hirt, Provenza, Gazzaniga, Cousins, Hardin, and Sharma. ***Experimental Evaluation of an Embedded Boundary Layer Ingesting Propulsor for Highly Efficient Subsonic Cruise Aircraft***
- Cousins, Voytovych, Tillman, and Gray. ***Design of a Distortion-Tolerant Fan for a Boundary-Layer Ingesting Embedded Engine Application***
- Hirt, Arend, Wolter, and Johnson. ***Development of a Flow Field for Testing a Boundary-Layer-Ingesting Propulsor***
- Hirt, Wolter, Arend, Hearn, Hardin, Gazzaniga. ***Performance Calculations for a Boundary-Layer-Ingesting Fan Stage From Sparse Measurements***
- Hardin, Cousins, Wolter, Arend, Hirt. ***Data Analysis Techniques for Fan Performance in Highly-Distorted Flows from Boundary Layer Ingesting Inlets***



National Aeronautics and Space Administration

www.nasa.gov

Vibroacoustic Loads on the Aft Deck and Sidewalls of a Planar Multistream Supersonic Nozzle

Charles E. Tinney
Applied Research Laboratories
The University of Texas at Austin
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512-550-2269

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Public release authorization code: 88ABW-2016-6579

Applied Research Laboratories
The University of Texas at Austin

Dr. Karl Fisher, Executive Director

- Organized research unit reporting to the VP Research at UT Austin
  - Dr. Karl Fisher: Executive Director
- Navy University Affiliated Research Center (UARC) founded in 1945
  - One of five such labs (U. Washington, Penn State, Johns Hopkins, Hawaii)
  - Asst Secretary of Defense, Research & Engineering (ASD R&E) charter and management plan
  - Frequently involved as a trusted technical agent of government program office
- *Core mission is to bridge basic research in academia with prototyping and applied engineering solutions for government and industry.*

- Sponsorship: Primarily Navy,

  -though current funding portfolio includes many other federal agencies (Army, Air Force, DARPA, NASA, NSF) and industry
- Secure Facility at the J.J. Pickle Research Campus with staff accustomed to working with classified and proprietary information
- Current staff: ~650 total
  - 325 research staff (20% PhD, 30% MS/MA, 50% BS/BA)
  - 75–150 students (all U.S. citizens)
- ~$110M Research Funding Level per Year (all soft money)

Advanced Technology Lab

- High Frequency Acoustics
  - Target physics
  - Environment
  - Signal Processing
- High Resolution Sonar
  - Obstacle Avoidance
  - Under Ice
  - Swimmer Detection
  - Mine Hunting and Avoidance
  - Bottom Mapping
- Electromagnetic Systems
  - HF Communications
  - Millimeter Wave Sensors

Environmental Sciences Lab

- Low Frequency Acoustics
  - Environment
  - Signal Processing
  - Sensor Performance
  - Instrumentation
- ASW Applications
  - Undersea Surveillance
  - Tactical Towed Arrays and Hull Mounted Sensors
  - Multistatic Active Sonar
  - Acoustic Intelligence
- Seismic Systems
  - Unattended Ground Sensors

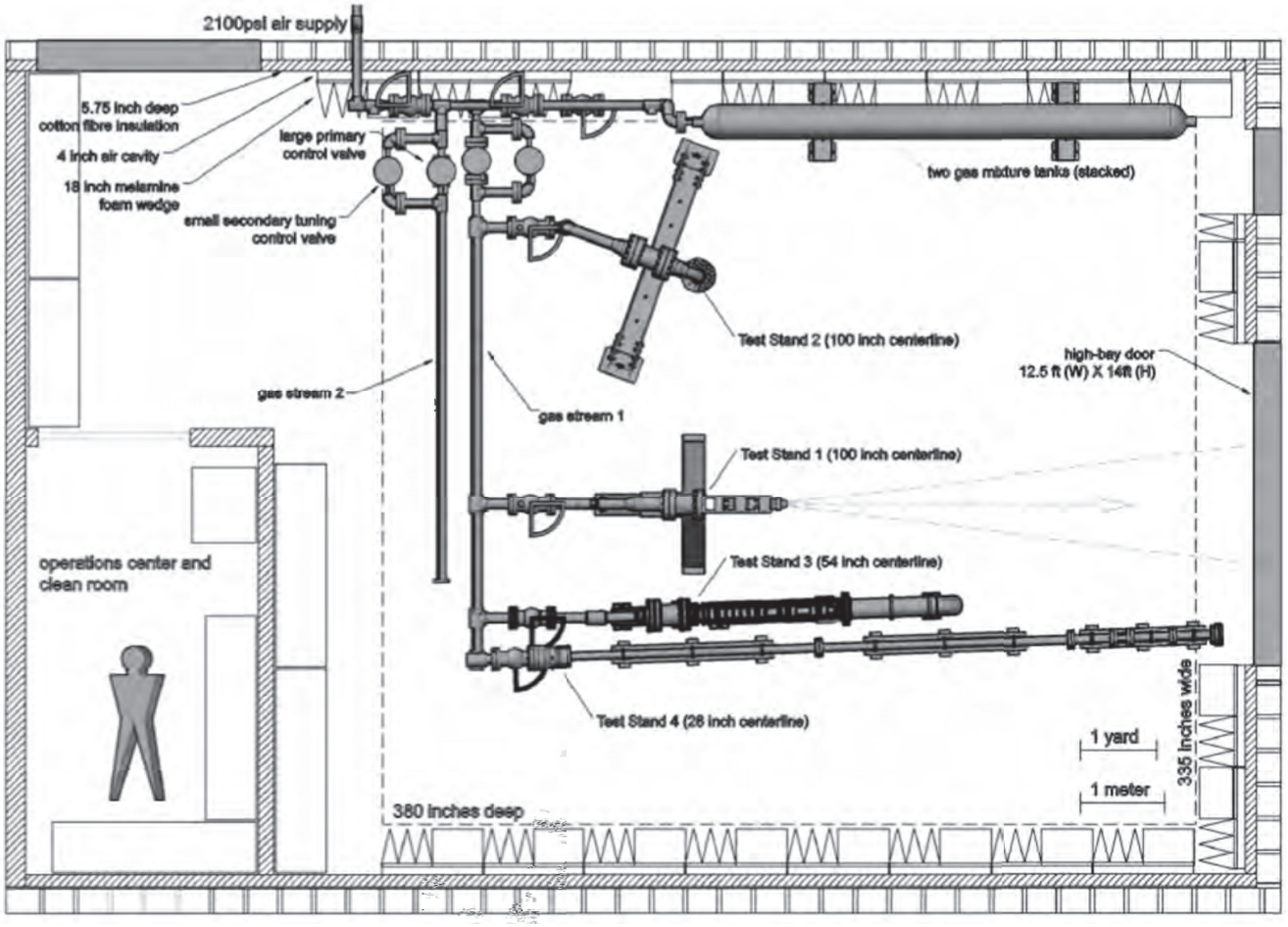
Space and Geophysics Lab

- Ionospheric Geophysics
  - Characterization of Ionosphere
  - Tomography
  - Electromagnetic Propagation
  - Instrumentation
- Applications
  - Worldwide GPS Monitoring
  - Precision Geodesy
  - Ionospheric/Tropospheric Corrections
  - RF emitter positioning
  - GPS Sled Track Survey
    - mm accuracy over 10 miles
  - Ionospheric Data Assimilation in 3D

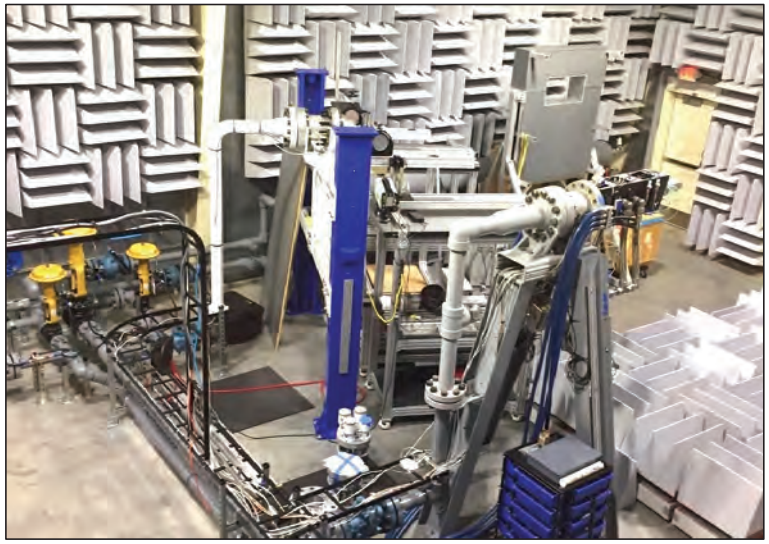
Signal and Information Sciences Lab

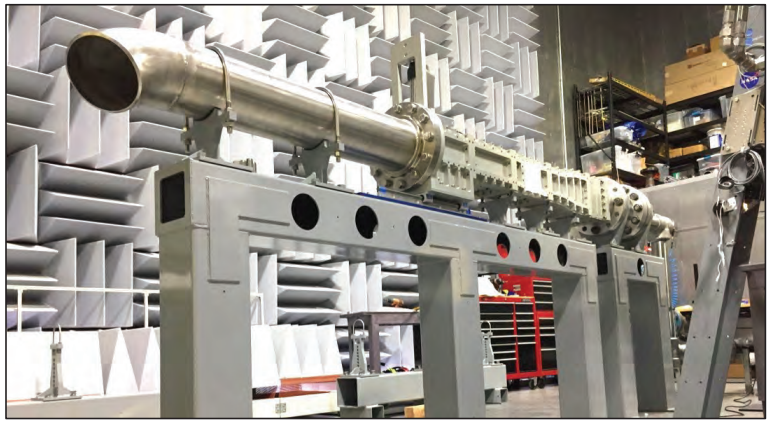
- Signal physics
  - Target Physics, Signal Processing, Automatic Detection and Classification
  - Signal Exploitation, reconstruction
- Autonomous systems for ACINT & MDA
- Non-linear acoustics/biomedical Ultrasound
- Chemical/Nuclear/Biological Detection
- Risk Assessment, Cyber Security and Physical Protection
- Modeling, simulation, data mining and content learning
- Space-based and terrestrial LIDAR
- **Fluid dynamics and Aeroacoustics**

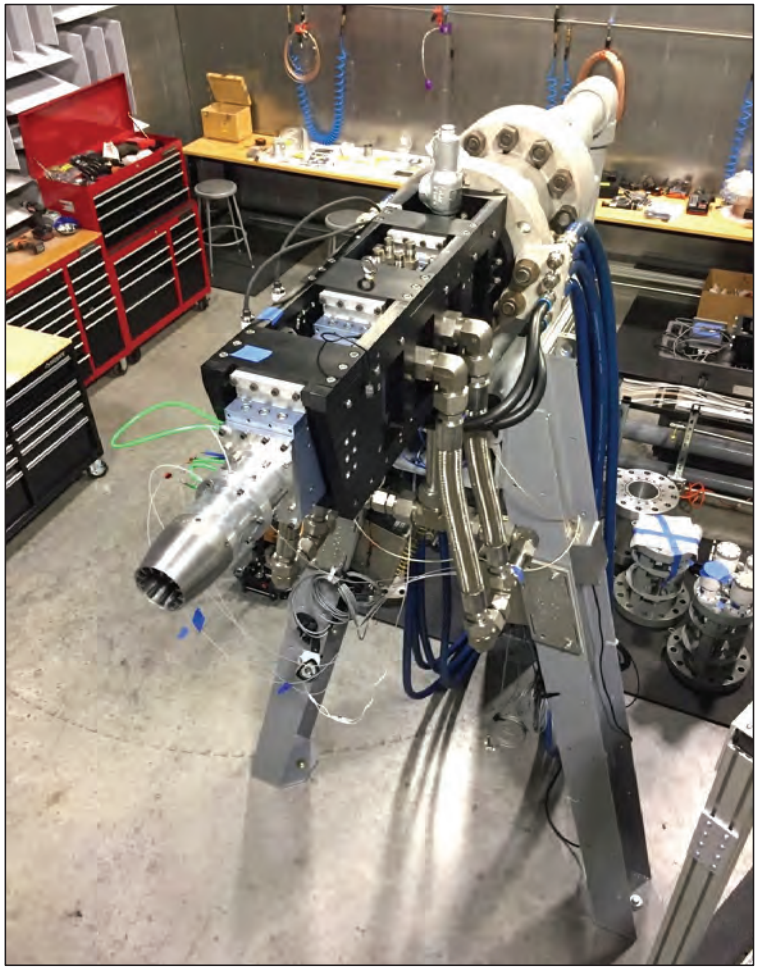
High speed flow facility at ARL-UT



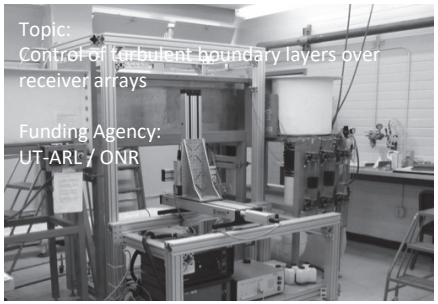
High speed flow facility at ARL-UT





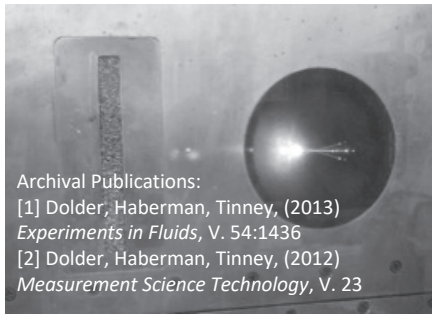


The University of Texas at Austin
APPLIED RESEARCH LABORATORIES

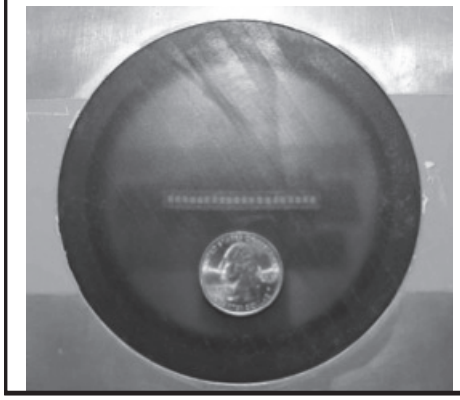


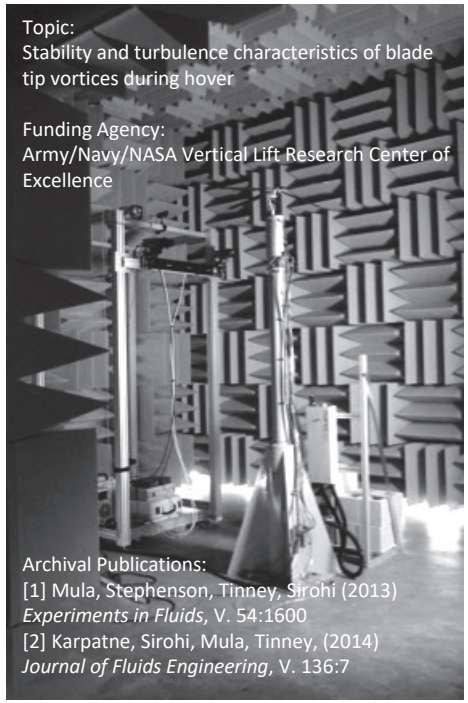
Topic:
Control of turbulent boundary layers over receiver arrays

Funding Agency:
UT-ARL / ONR



Archival Publications:
[1] Dolder, Haberman, Tinney, (2013) *Experiments in Fluids*, V. 54:1436
[2] Dolder, Haberman, Tinney, (2012) *Measurement Science Technology*, V. 23

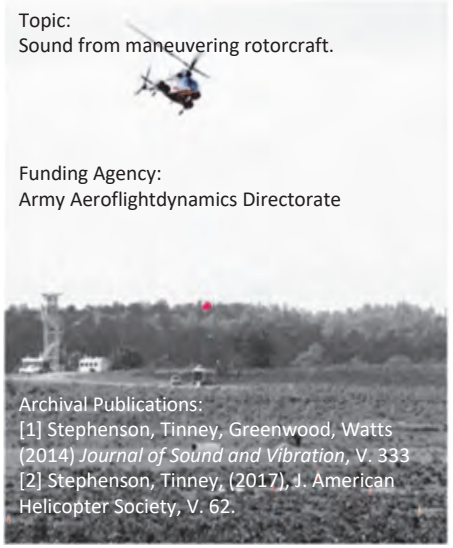




Topic:
Stability and turbulence characteristics of blade tip vortices during hover

Funding Agency:
Army/Navy/NASA Vertical Lift Research Center of Excellence

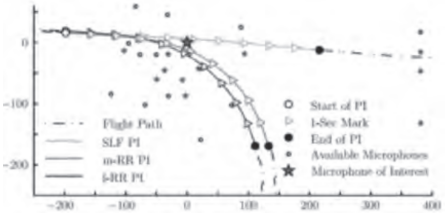
Archival Publications:
[1] Mula, Stephenson, Tinney, Sirohi (2013) *Experiments in Fluids*, V. 54:1600
[2] Karpatne, Sirohi, Mula, Tinney, (2014) *Journal of Fluids Engineering*, V. 136:7

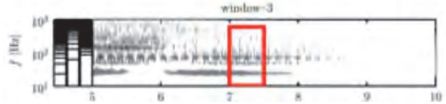


Topic:
Sound from maneuvering rotorcraft.

Funding Agency:
Army Aeroflightdynamics Directorate

Archival Publications:
[1] Stephenson, Tinney, Greenwood, Watts (2014) *Journal of Sound and Vibration*, V. 333
[2] Stephenson, Tinney, (2017), J. American Helicopter Society, V. 62.

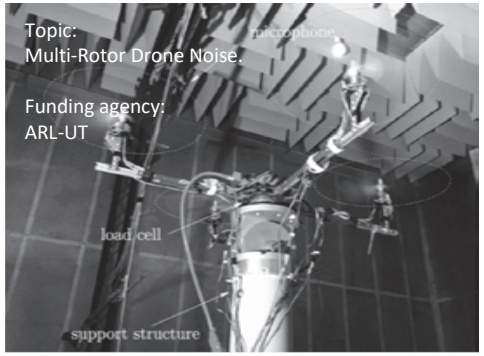


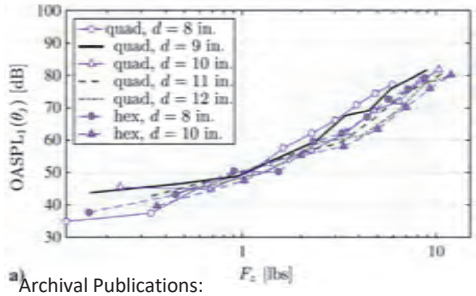


The University of Texas at Austin
APPLIED RESEARCH LABORATORIES

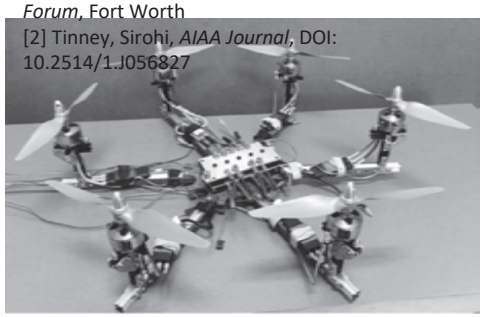
Topic:
Multi-Rotor Drone Noise.

Funding agency:
ARL-UT





Archival Publications:
[1] Tinney, Hill, Valdez, Sirohi, Cameron, *73rd AHS Forum*, Fort Worth
[2] Tinney, Sirohi, *AIAA Journal*, DOI: 10.2514/1.J056827



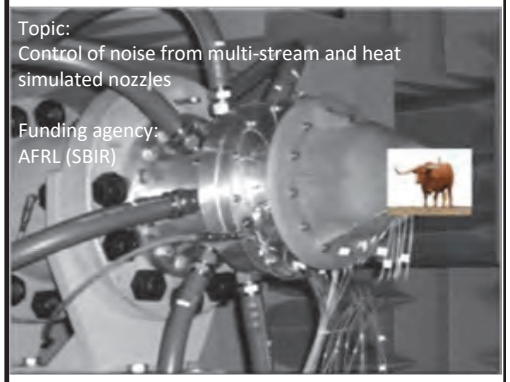
Topic:
Cumulative nonlinear acoustic waveform distortions from high-speed jets.

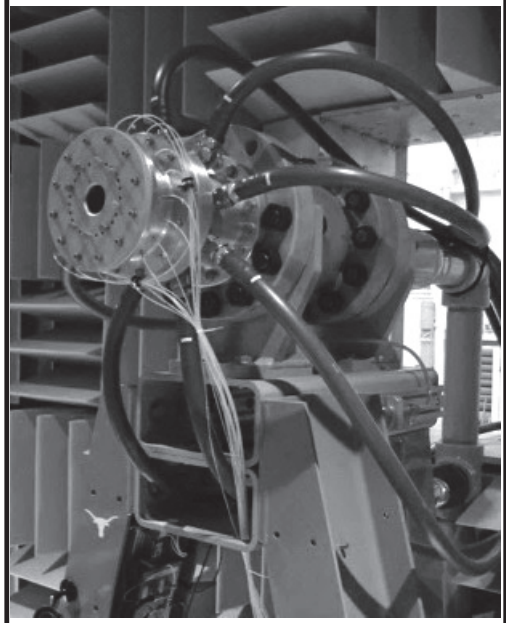
Funding Agency:
ONR

Archival Publications:
[1] Baars, Tinney, (2014)
Journal of Sound & Vibration, V. 333:12
[2] Baars, Tinney, Wochner, Hamilton, (2014)
Journal of Fluid Mechanics, V. 749

Topic:
Control of noise from multi-stream and heat simulated nozzles

Funding agency:
AFRL (SBIR)



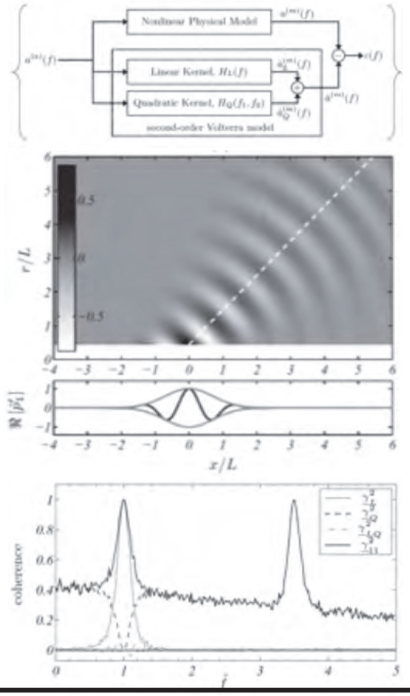


The University of Texas at Austin
APPLIED RESEARCH LABORATORIES

Topic:
Development of analysis techniques: Proper orthogonal decomposition-based spectral higher-order stochastic estimation.

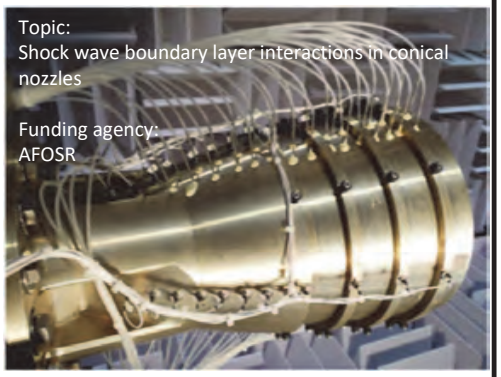
Funding Agency:
ONR

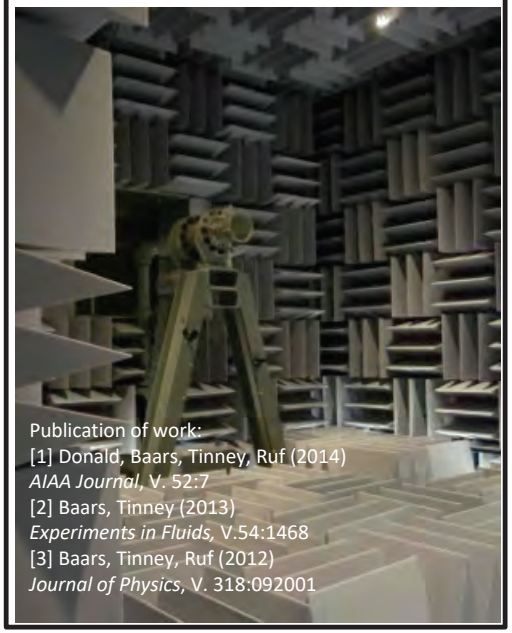
Archival Publications:
[1] Baars, Tinney (2014)
Physics of Fluids, V. 26:055112



Topic:
Shock wave boundary layer interactions in conical nozzles

Funding agency:
AFOSR

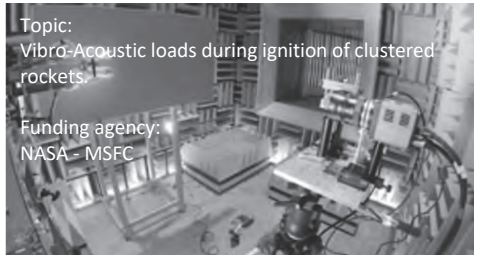




Publication of work:
[1] Donald, Baars, Tinney, Ruf (2014)
AIAA Journal, V. 52:7
[2] Baars, Tinney (2013)
Experiments in Fluids, V.54:1468
[3] Baars, Tinney, Ruf (2012)
Journal of Physics, V. 318:092001

Topic:
Vibro-Acoustic loads during ignition of clustered rockets.

Funding agency:
NASA - MSFC



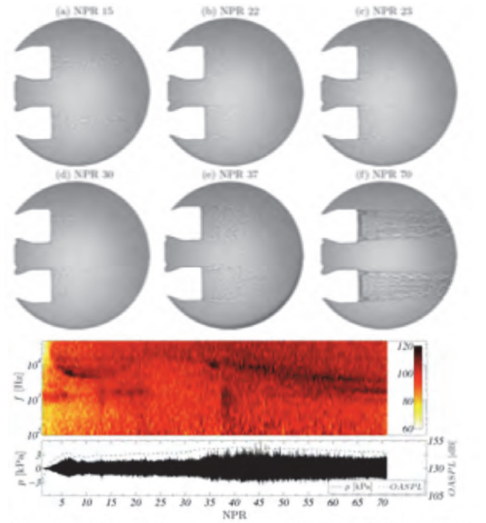
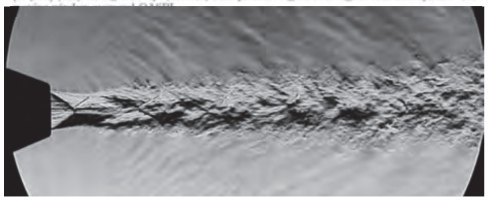
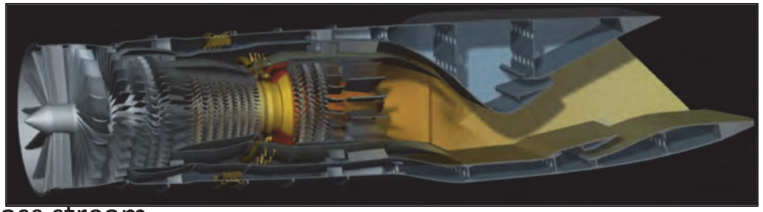


FIGURE 7. (top) Morlet wavelet power spectra expressed as 10 $\log_{10}(E(f,t)/\text{ref})$ [dB] (ref: [20 μPa]^2/Hz) during start-up. (bottom) Raw pressure signal from eighth-inch microphone with



I. Evolution of Jet Fighter Nozzle Design



- Fourth Generation Jet Fighter
  - Single / Twin **circular** nozzle geometries
    - F-14 Tomcat (1970)
    - F-15 Eagle (1972)
    - F-16 Falcon (1974)
    - YF-17, F-18 Hornet (1978)
    - Sukhoi Su-27 Flanker (1977)
    - Dassault Mirage 2000 (1978)
- Fifth Generation Jet Fighter
  - Single / Twin **planar** nozzle geometries
    - B-2 Spirit (1989)
    - YF-23 (1990)
    - F-22 Raptor (1991)
    - X-47B (2011)
- Sixth Generation Jet Fighter
  - Single / Twin **planar** nozzle with tertiary bypass stream
    - Turbofan during takeoff (subsonic to transonic)
    - Turbojet at higher supersonic Mach numbers

I. Evolution of Jet Fighter Nozzle Design

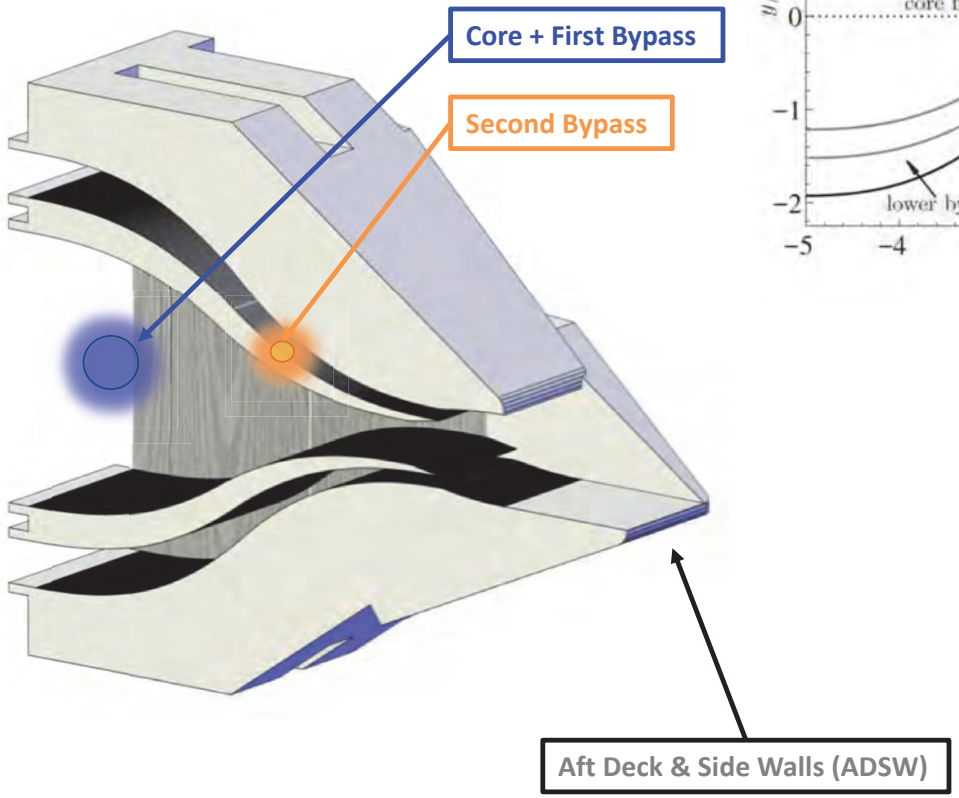
- **Benefits of the planar nozzle design:**
  - Reduction in overall pressure drag
  - Increased maneuverability with thrust vectoring and reversing
  - Lower observability
  - Reduction in maintenance costs through fewer moving parts

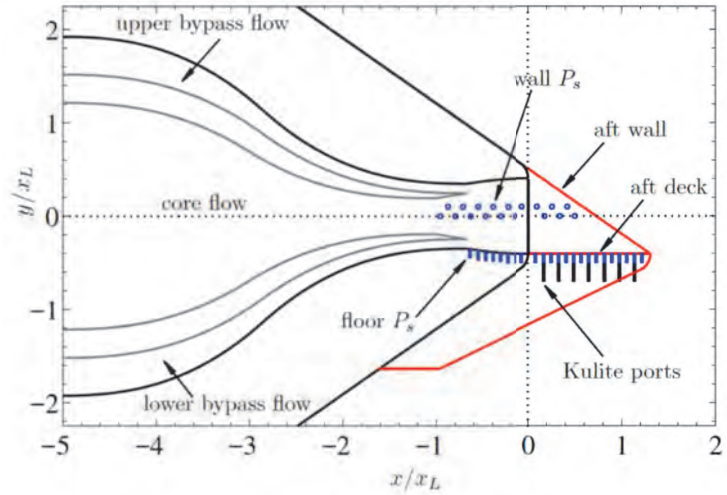
- **Pitfalls of the planar nozzle design:**
  - Poor structural efficiency encumbers weight penalty
    - Planar nozzle wall stressed in bending as opposed to hoop stress in axisymmetric nozzles
    - Weight restrictions elevate aeroelasticity effects
  - Planar nozzle always imperfectly expanded (plume shocks)
    - Shock-wave boundary layer interactions
    - Transonic resonance
    - Broadband shock associated noise
    - Sonic fatigue

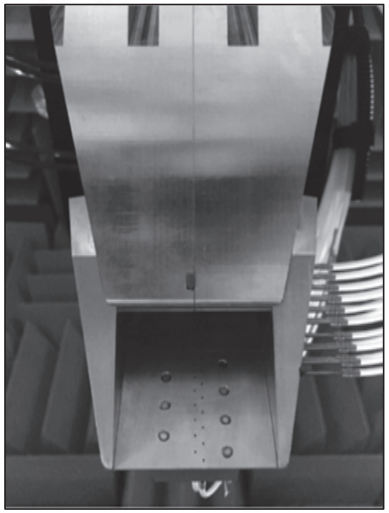
OBJECTIVE: provide a basic understanding for the vibroacoustic loads that form on Aft Deck and Side Walls of a planar multi-stream supersonic nozzle.

II. Experimental Arrangement

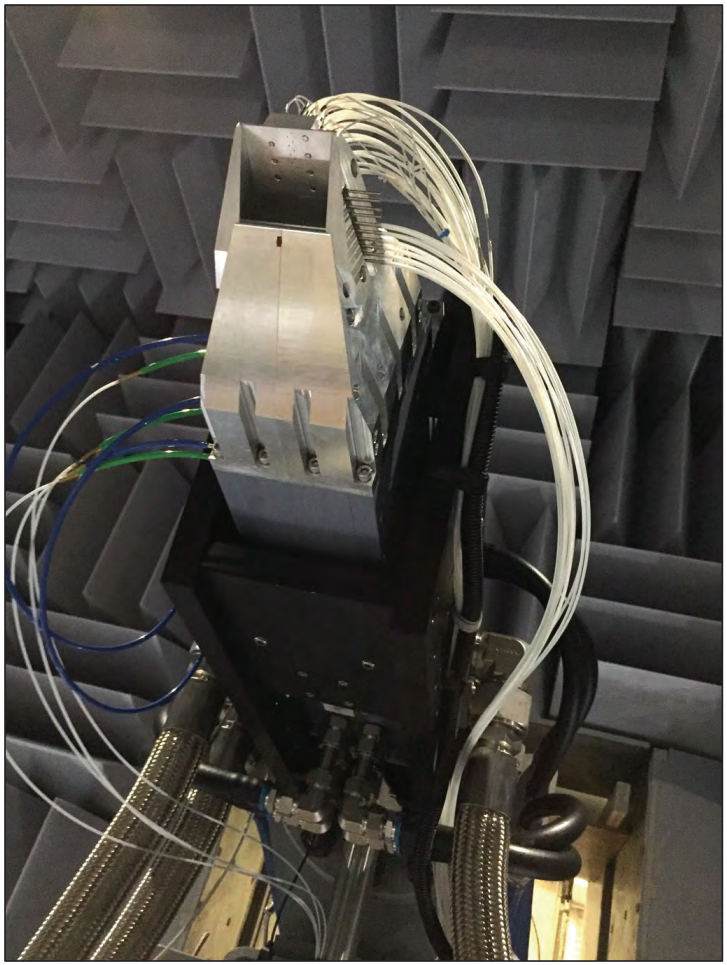
- 2:1 aspect ratio at nozzle exit
- Design NPR = 5, Mach 1.71

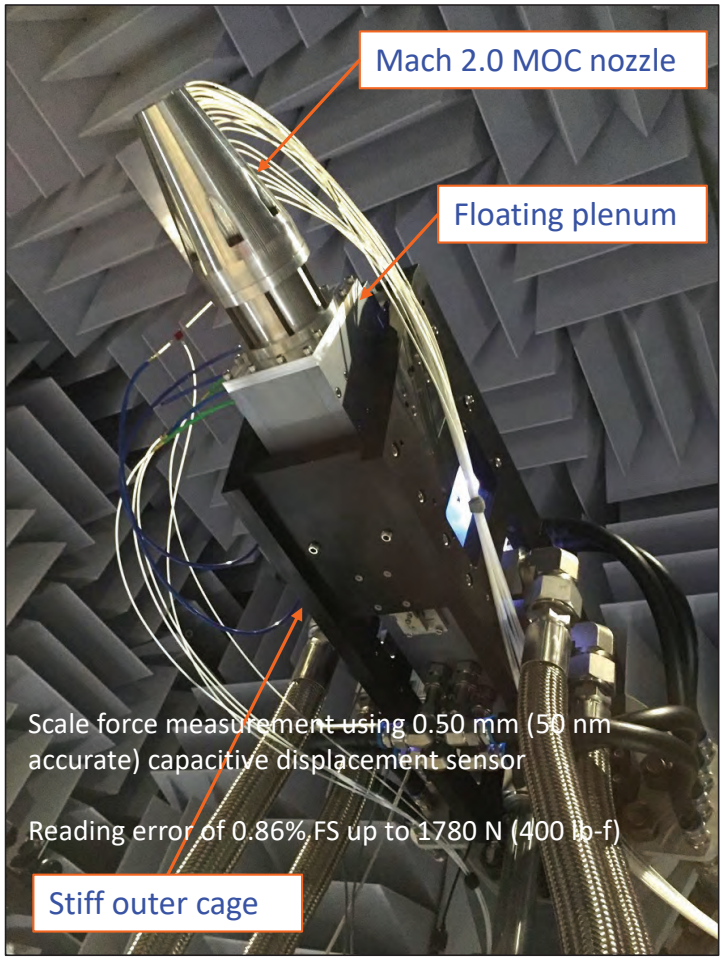






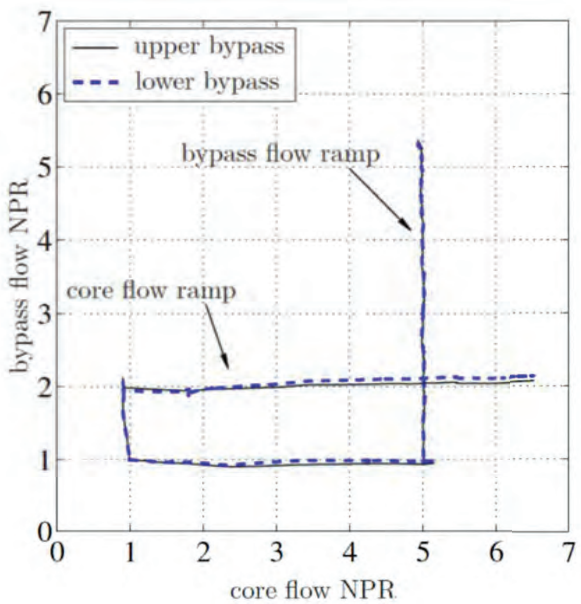
II. Experimental Arrangement

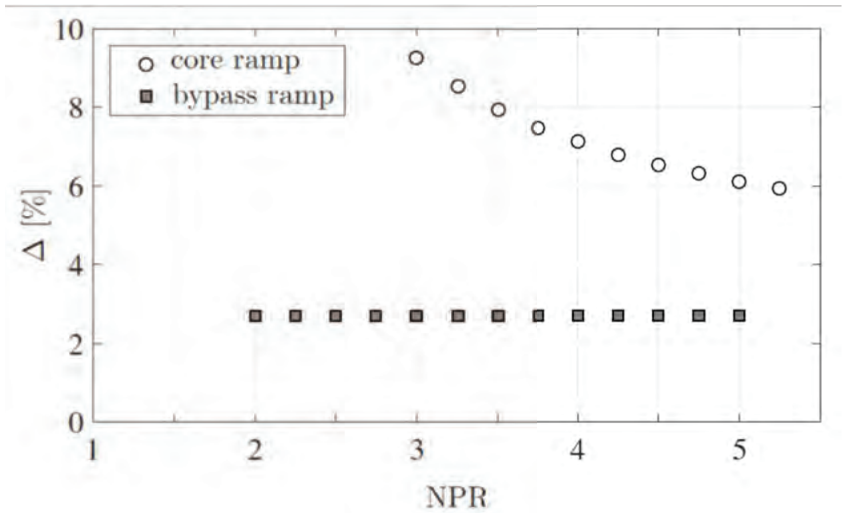




II. Experimental Arrangement

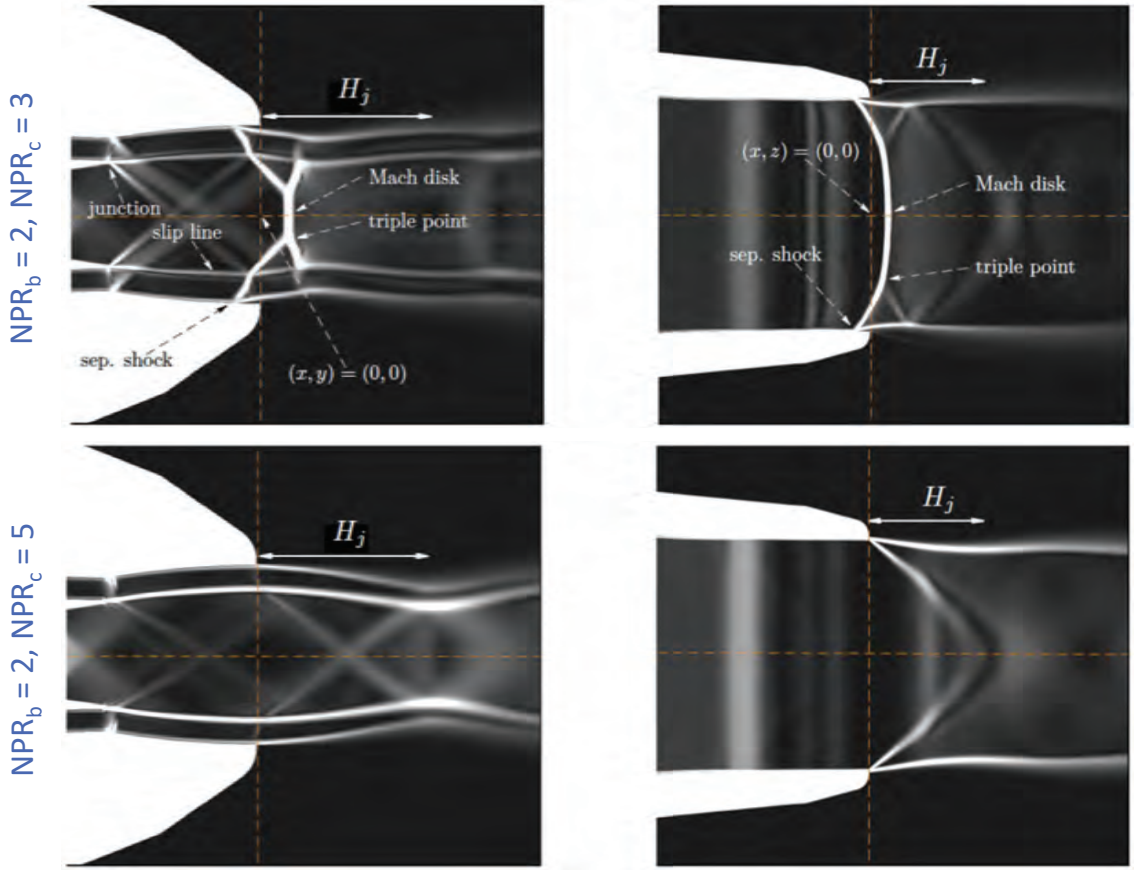
NPR_c	$\dot{m}_j$, kg/s	U_j, m/s	$\mathcal{F}_t$, N	M_j	$M_\dagger$	M_{co}	$D_{j,e}$, mm	L_p	ϕ, deg.
3.0	0.44	398	175	1.36	0.93	0.86	29.2	7.3	n/a
4.0	0.59	438	258	1.56	1.02	0.93	30.9	8.2	12
5.0	0.73	465	342	1.71	1.09	0.98	32.4	8.8	23





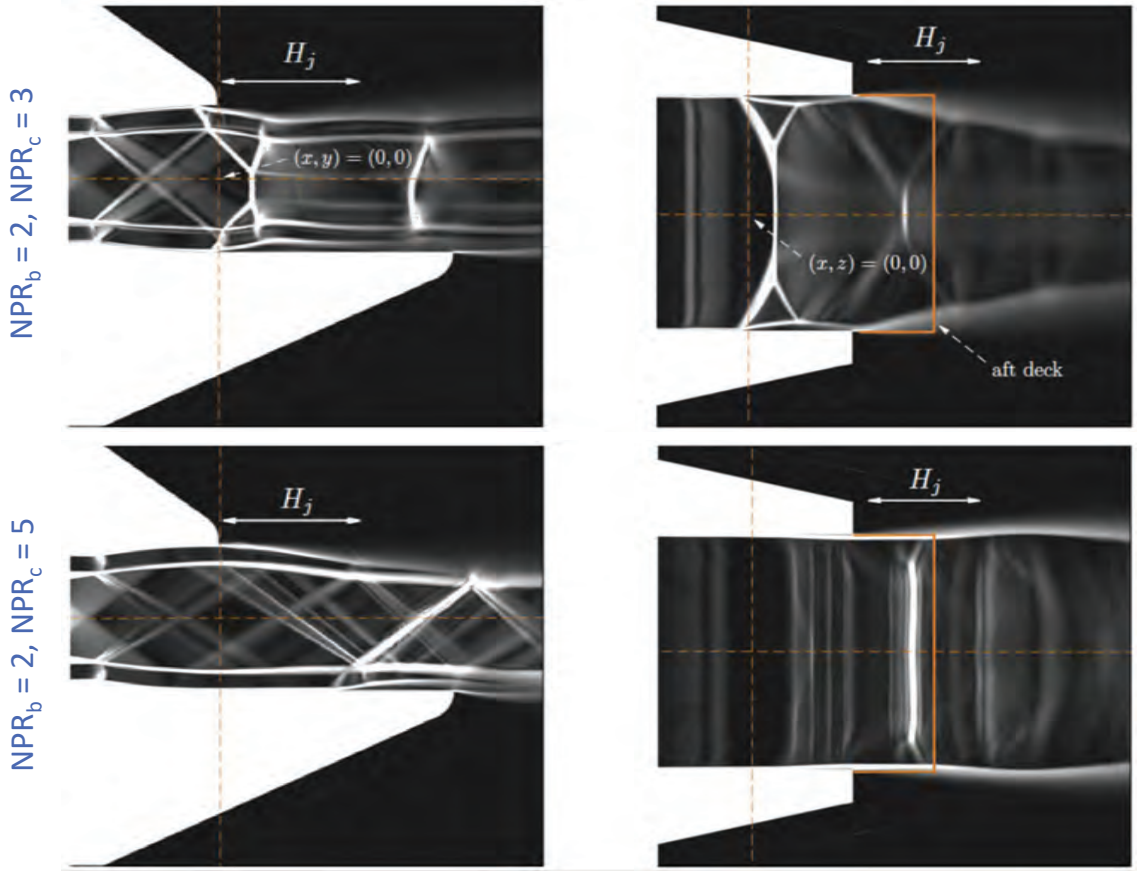
III. RANS Modeling using CRAFT CFD© Code.

- without ADSW



III. RANS Modeling using CRAFT CFD© Code.

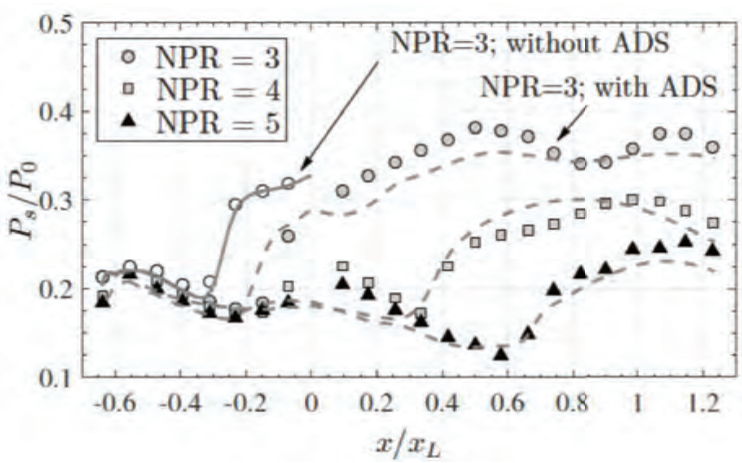
- with ADSW



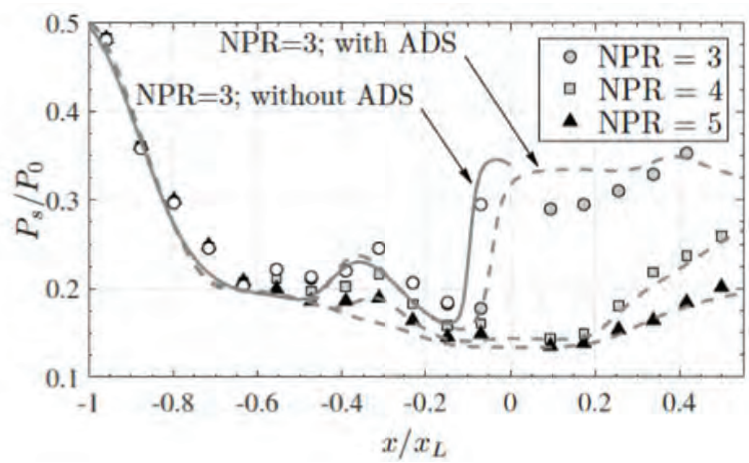
III. RANS Model validation

- Static wall pressure on nozzle floor and sidewalls
  - Experiment: Symbols
  - RANS: Lines

nozzle floor



nozzle sidewalls

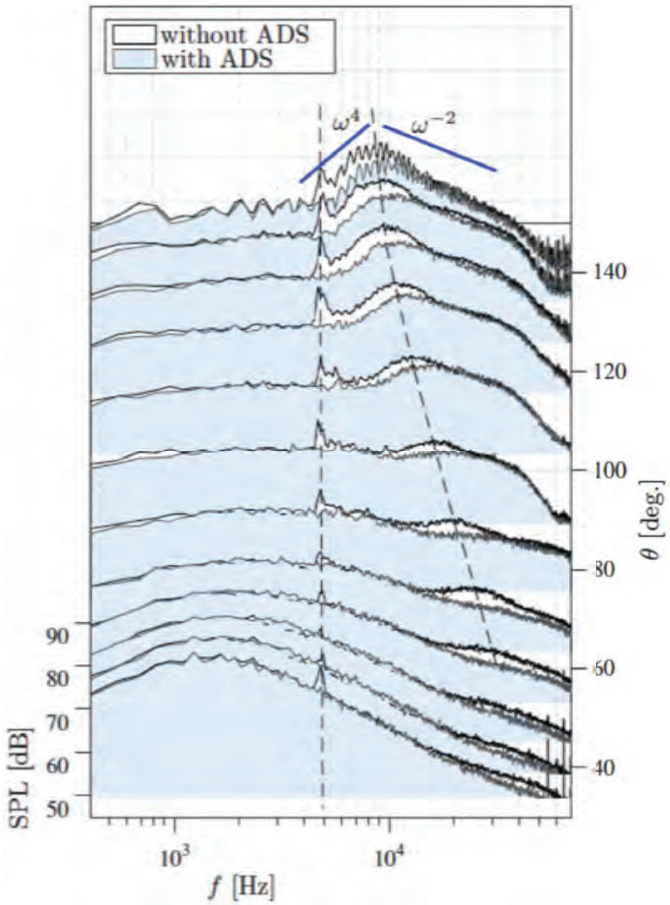


- ADSW inhibits entrainment of mass flow which causes a coanda effect to form on the nozzle aft deck
- Coanda effect pushes separation shock further downstream.

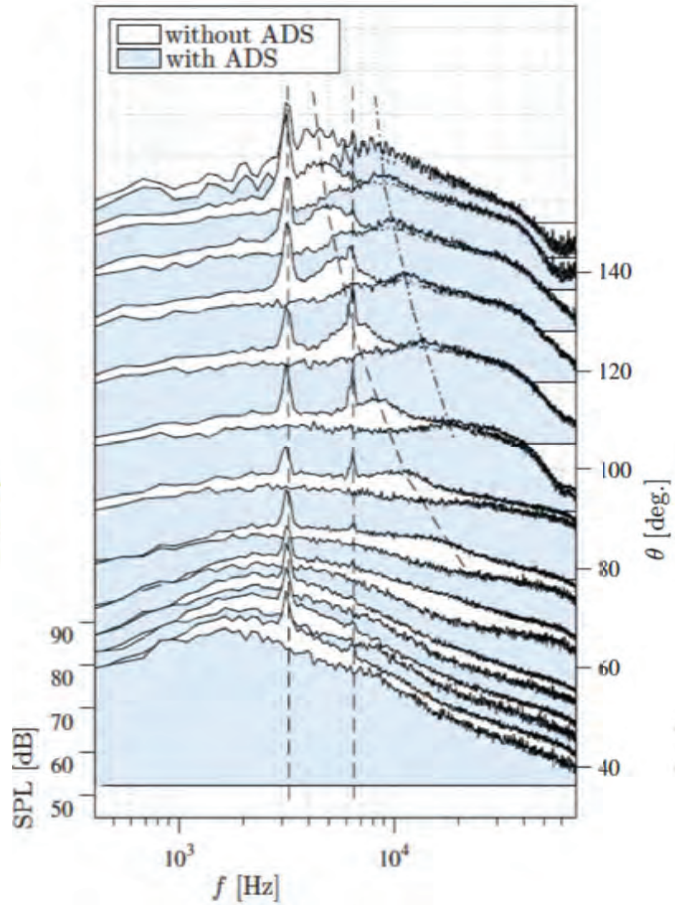
III. Far-Field Acoustics

- 1/8th inch GRAS mics

$NPR_b = 2$, $NPR_c = 3$

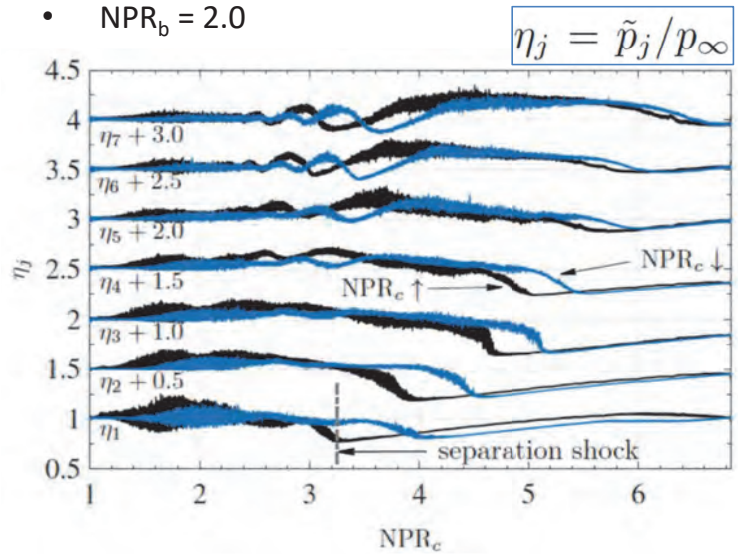


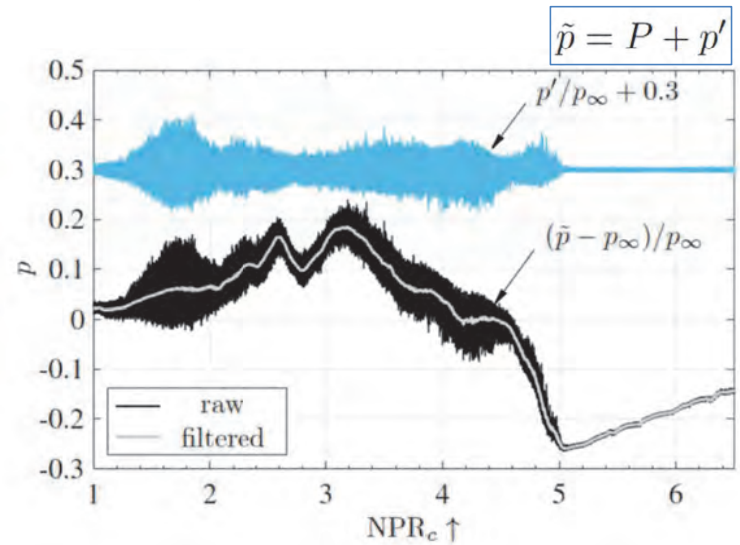
$NPR_b = 2$, $NPR_c = 5$

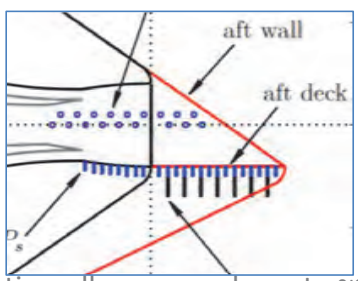


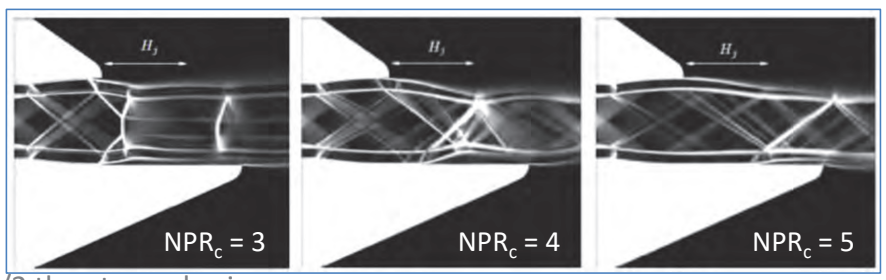
III. Dynamic Wall Pressure on Aft Deck

- Raw wall pressure during startup ($NPR_c \uparrow$) and shutdown ($NPR_c \downarrow$) of the nozzle core flow
- $NPR_b = 2.0$





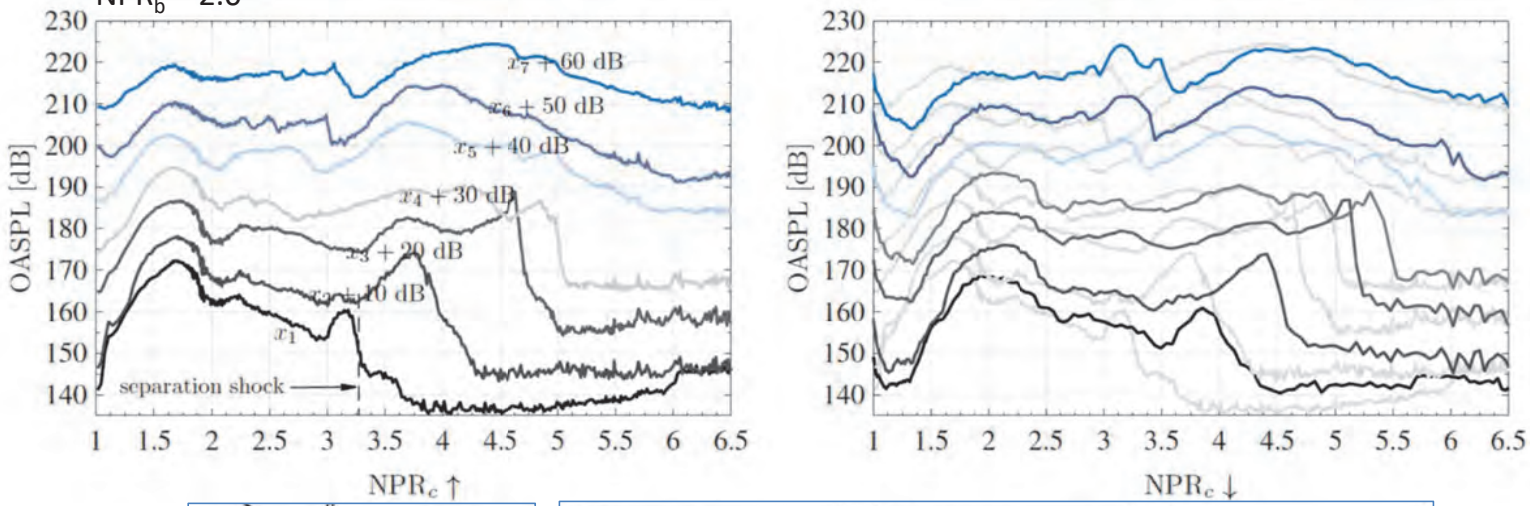


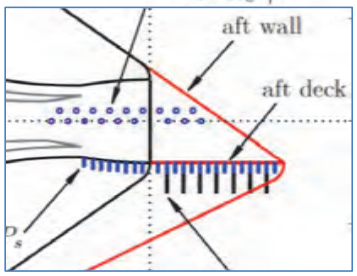


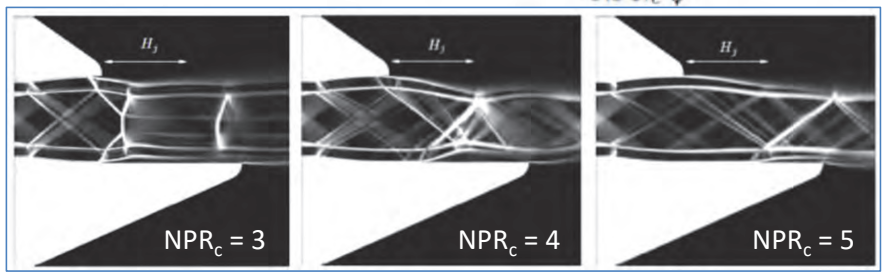
- Static wall pressure drops to ~1/2 the atmospheric pressure
- Flow and shock patterns exhibit hysteresis effect during startup and shutdown

III. Dynamic Wall Pressure on Aft Deck

- OASPL [dB, ref 20µPa] of fluctuating wall pressure during startup ($NPR_c \uparrow$) and shutdown ($NPR_c \downarrow$) of the nozzle core flow
- $NPR_b = 2.0$





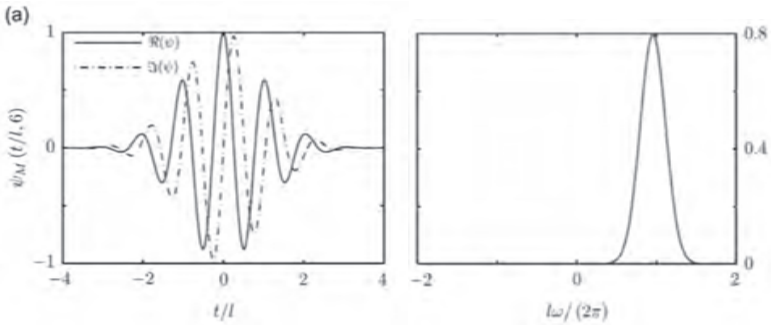


- Pressure loads vary significantly over operating conditions
- Pressure loads are in excess of 170dB in some cases

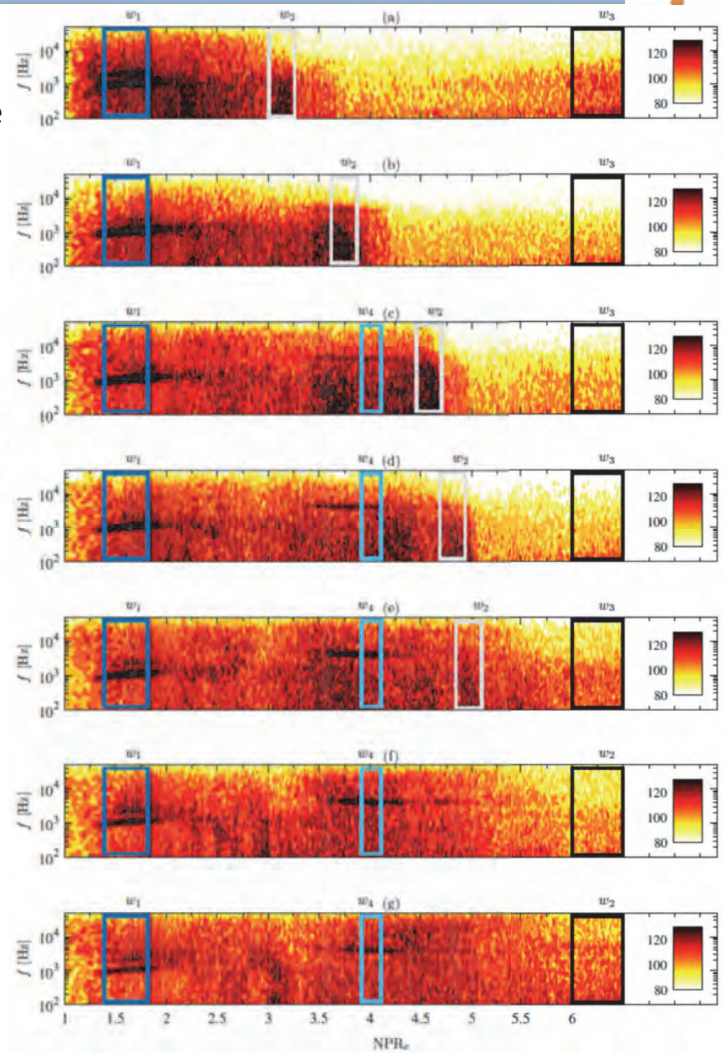
III. Wavelet Analysis

Kulite 1

- Time frequency analysis of fluctuating wall pressure during startup ($NPR_c \uparrow$) of the nozzle core flow
- $NPR_b = 2.0$
- Morlet wavelet



- w_1: transonic resonance
- w_2: separation shock (SWBLI)
- w_3: evolution of developing SS boundary layer
- w_4: transonic resonance

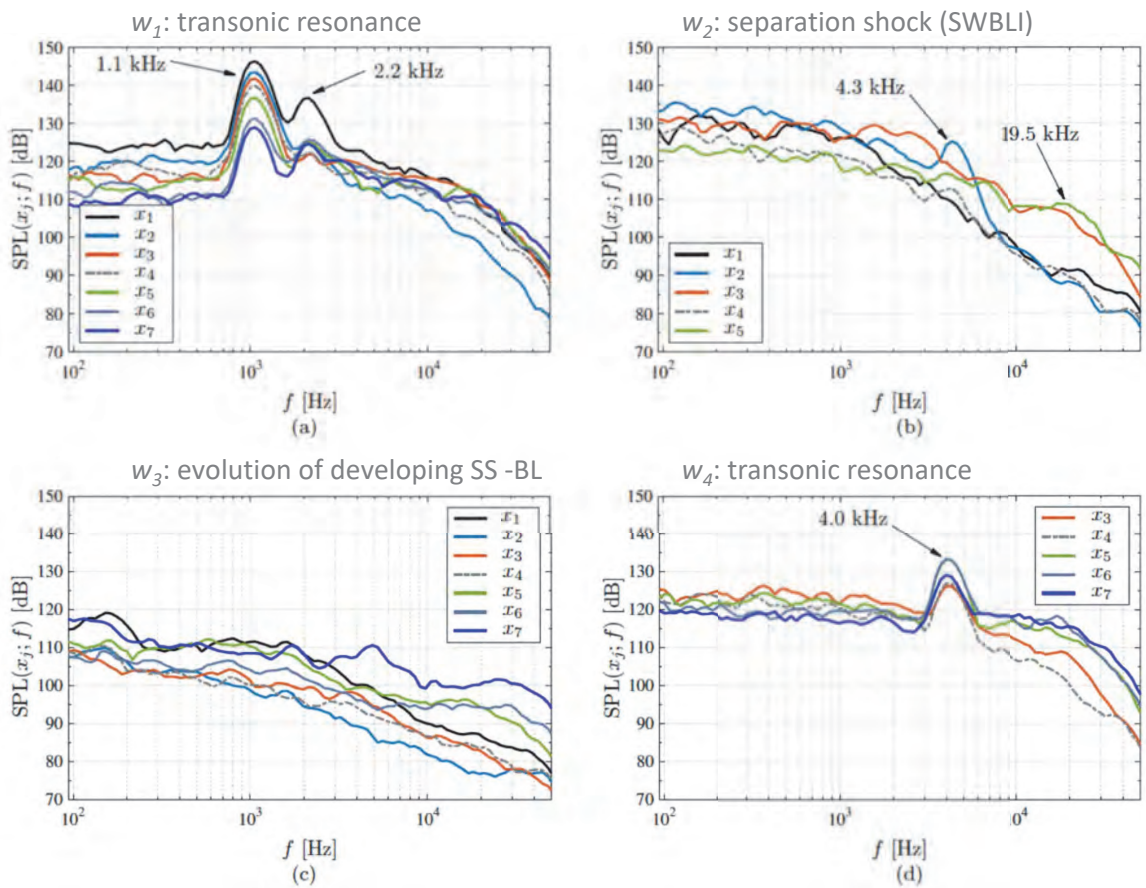


Kulite 7

Baars, Tinney (2015) ***Academic Press***
Farge (1992) ***Annual Review of Fluid Mechanics***

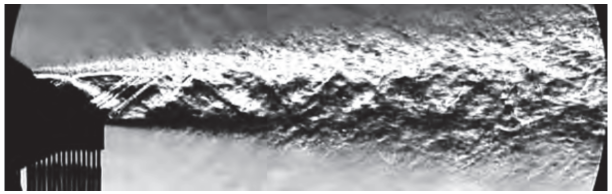
III. Wavelet Analysis

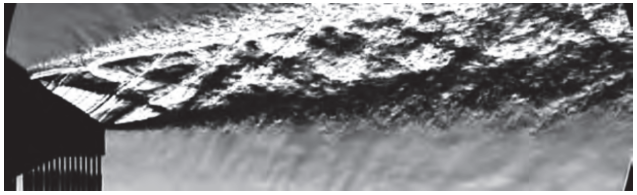
- Global wavelet spectra of fluctuating wall pressure during startup ($NPR_c \uparrow$) of the nozzle core flow
- $NPR_b = 2.0$



IV. Summary

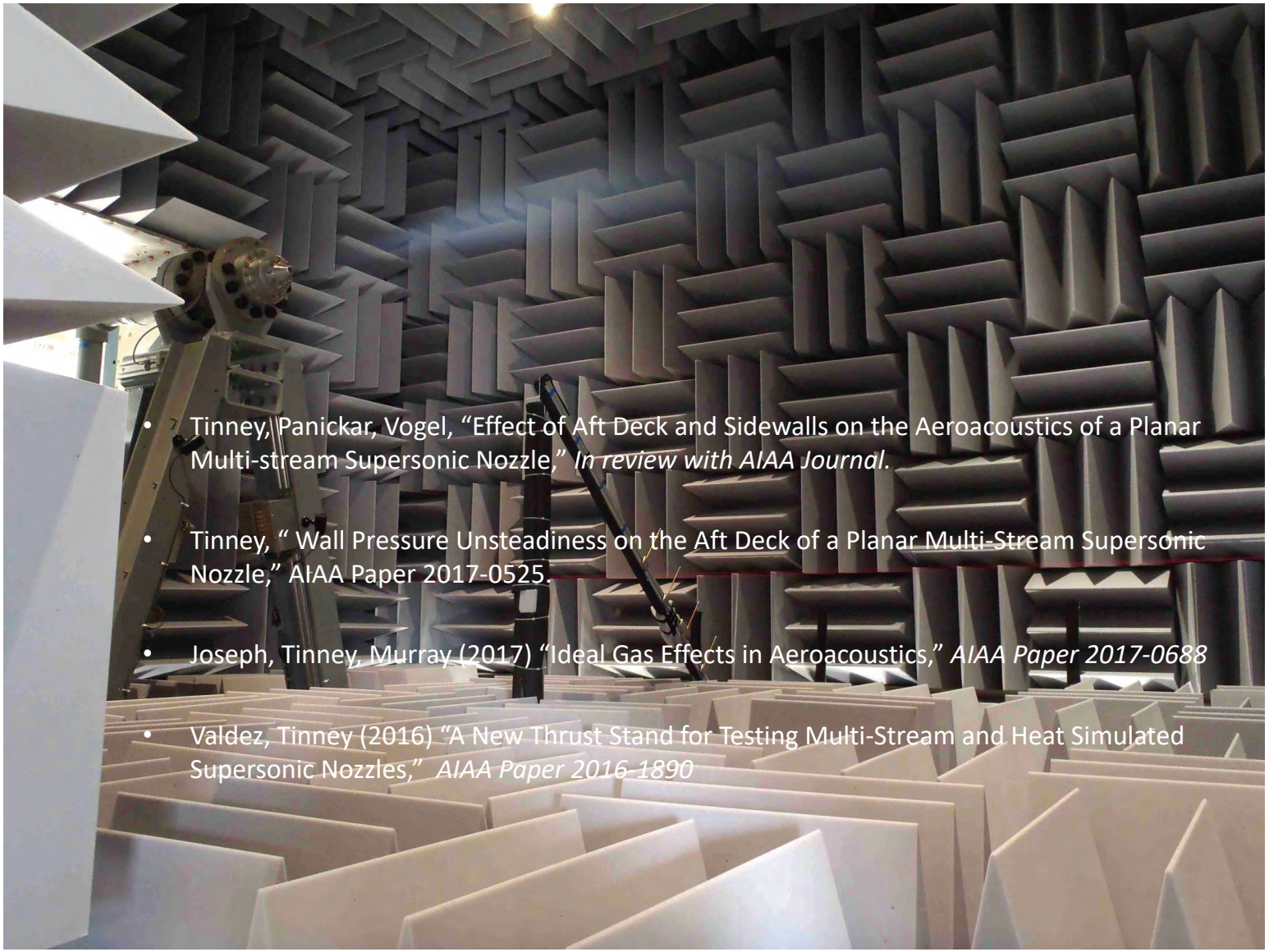
- Thrust
  - ADSW increases thrust by as much as 3%-8% percent
  - Asymmetries in the shock pattern vector the jet away from the ADSW





- Acoustics
  - ADSW reduces transonic resonance and BBSN at sideline angles.

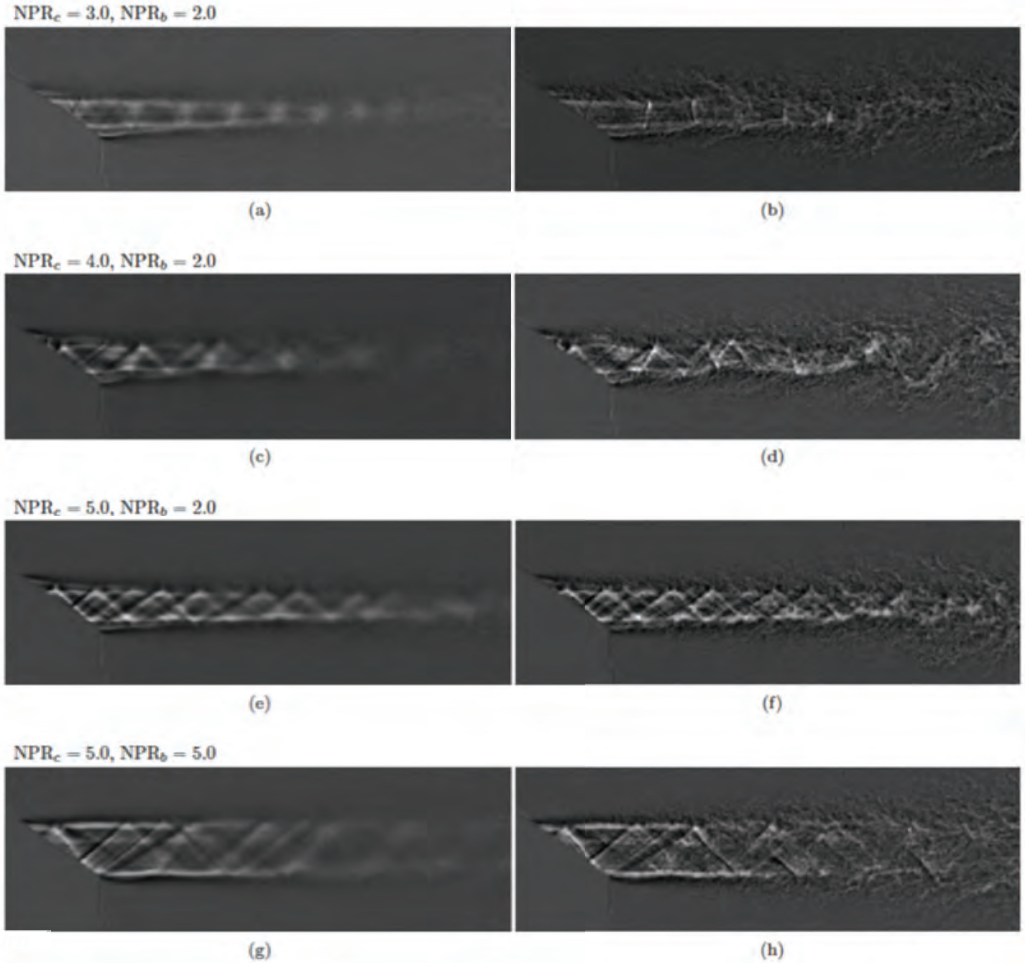
- Shock Dynamics
  - Significant hysteresis effects observed between startup and shutdown of both core and bypass flows
    - Larger hysteresis effects with changes to bypass flow
    - Pressure loads in excess of 170dB


• Tinney, Panickar, Vogel, “Effect of Aft Deck and Sidewalls on the Aeroacoustics of a Planar Multi-stream Supersonic Nozzle,” *In review with AIAA Journal*.
• Tinney, “ Wall Pressure Unsteadiness on the Aft Deck of a Planar Multi-Stream Supersonic Nozzle,” AIAA Paper 2017-0525.
• Joseph, Tinney, Murray (2017) “Ideal Gas Effects in Aeroacoustics,” *AIAA Paper 2017-0688*
• Valdez, Tinney (2016) “A New Thrust Stand for Testing Multi-Stream and Heat Simulated Supersonic Nozzles,” *AIAA Paper 2016-1890*

III. Results and Discussion

- Shadowgraphy of jet plume with ADSW

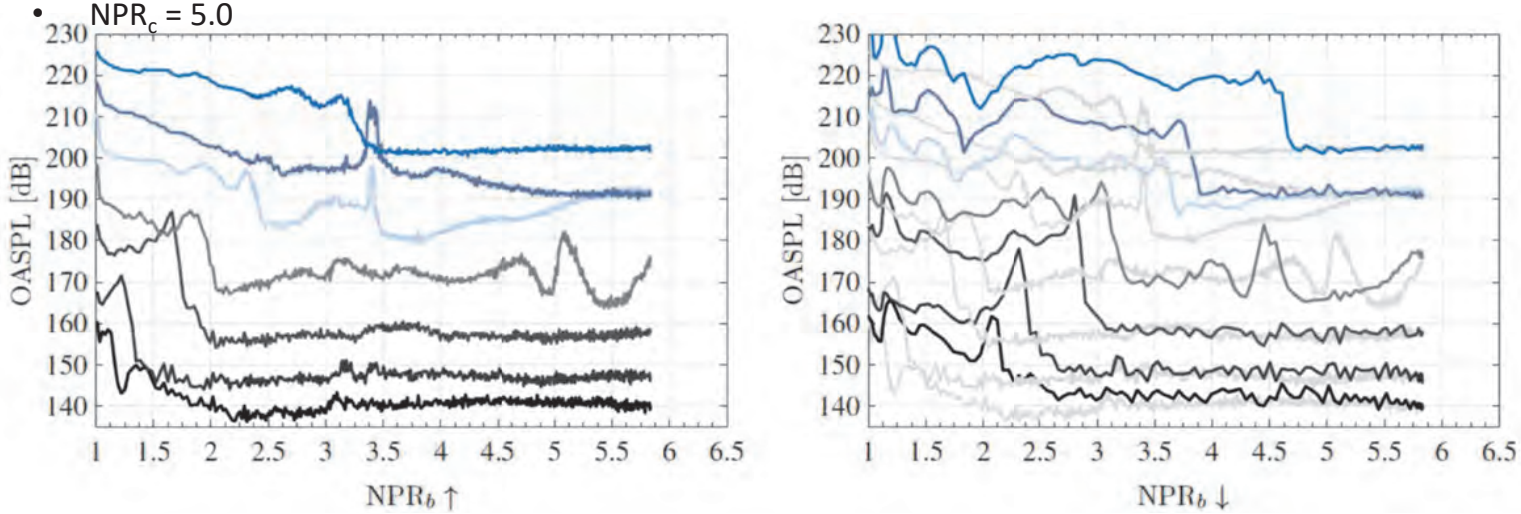
Average (100 images) Sample image



Hargathar, Settles (2009) ***Applied Optics***
Canchero, Tinney, Murray, Ruf (2016) ***AIAA Jo***

III. Dynamic Wall Pressure on Aft Deck

- OASPL [dB, ref 20μPa] of fluctuating wall pressure during startup ($NPR_b \uparrow$) and shutdown ($NPR_b \downarrow$) of the nozzle bypass flow
- $NPR_c = 5.0$



- Hysteresis effects much more pronounced with changes in the bypass NPR

NASA/CP—2018-219955

Boundary-Layer-Ingesting Inlet Flow Control

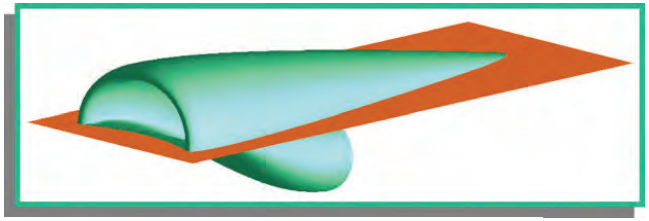
Lewis R. Owens, Brian G. Allan, and Susan A. Gorton

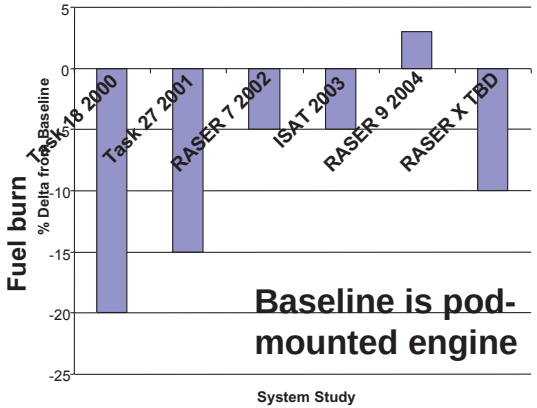
Presentation for

Propulsion Airframe Integration Technical Interchange Meeting
Cleveland, OH

30-31 May 2018

Active Flow Control Background

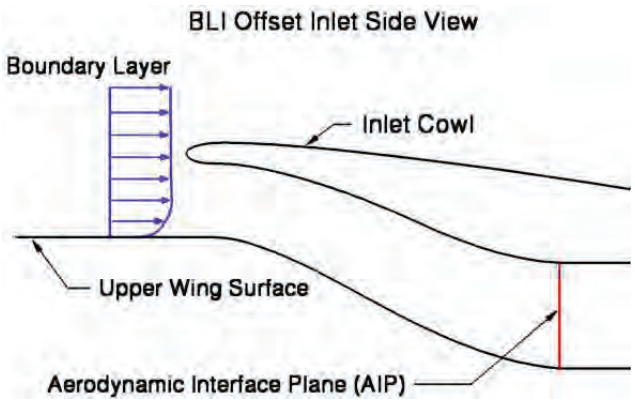


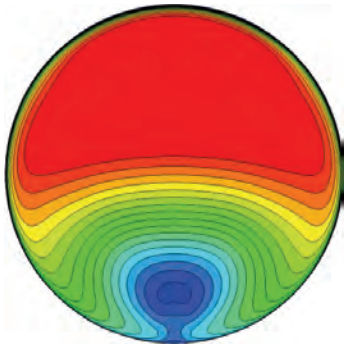


- UEET selected Boundary Layer Ingestion (BLI) for offset inlets as a commercial, revolutionary concept to achieve reduced emissions through reduced fuel burn
- Interest in BLI inlet for both commercial and military applications
- Systems studies show benefits of BLI *if* inlet distortion is controlled
- Active Flow Control (AFC) being evaluated to minimize distortion effects and enable large amounts (30%) of BLI

Inlet Flow Distortion

- Spatial variations in the total pressure at the inlet/engine interface plane
- Ingestion of a large boundary layer and the S-shaped inlet result in a high flow distortion level
- Problems with inlet distortion
  - -Increased vibration on fan blades (High Cycle Fatigue)
  - -Reduced compressor stability margin
  - -Engine stall





Total pressure ratio contours at the engine fan-face for the baseline inlet at Mach 0.85

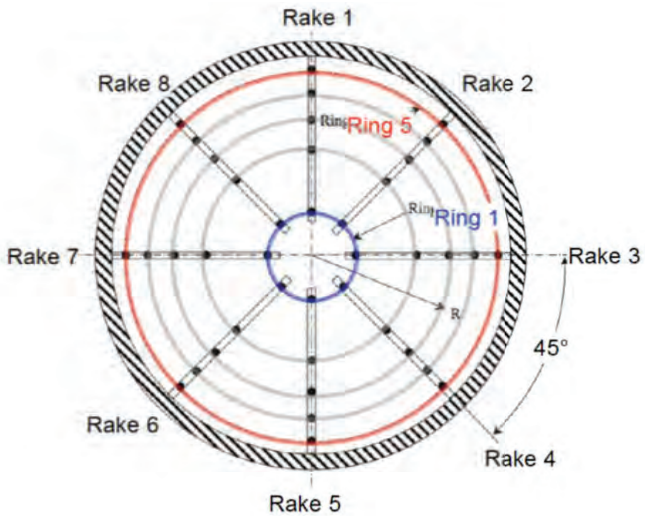
AIP Rake

SAE Standard 40-Probe Rake

(Reference: Gas Turbine Engine Inlet Flow Distortion Guidelines.

Aerospace Recommended Practice 1420B, SAE International, 2001.)

40-Probe Rake Detail

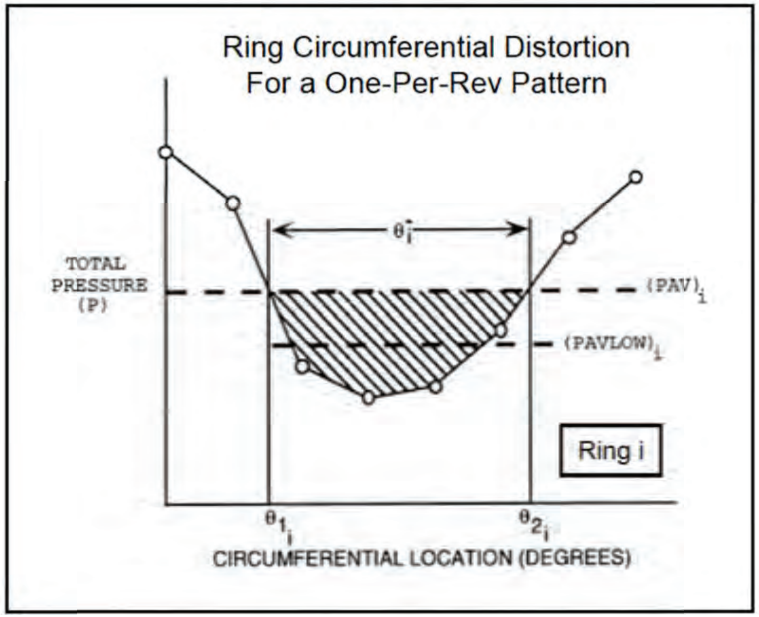


40-Probe Rake Transonic Wind Tunnel Experiment

Distortion Descriptor

SAE average circumferential distortion

Ref: SAE ARP 1420



$$DPCP_{avg} = \frac{1}{N_{rings}} \sum_{i=1}^{N_{rings}} Intensity_i$$

$$Intensity_i = \frac{PAV_i - PAVLOW_i}{PAV_i} \quad \text{for ring } i$$

$$\mathrm{PAV_i} = \frac{1}{360} \int_0^{360} P(q)_i \, dq \quad \text{(Ring Average Pressure}$$

$$\mathrm{PAVLOW_i} = \frac{1}{q_i} \int_{q_{1_i}}^{q_{2_i}} P(q)_i \, dq \quad \text{(Average Low Pressure)}$$

$$\text{where}: \quad q_i = q_{2_i} - q_{1_i} \quad \text{(Extent)}$$

Small-Scale BLI Inlet Experimental Research

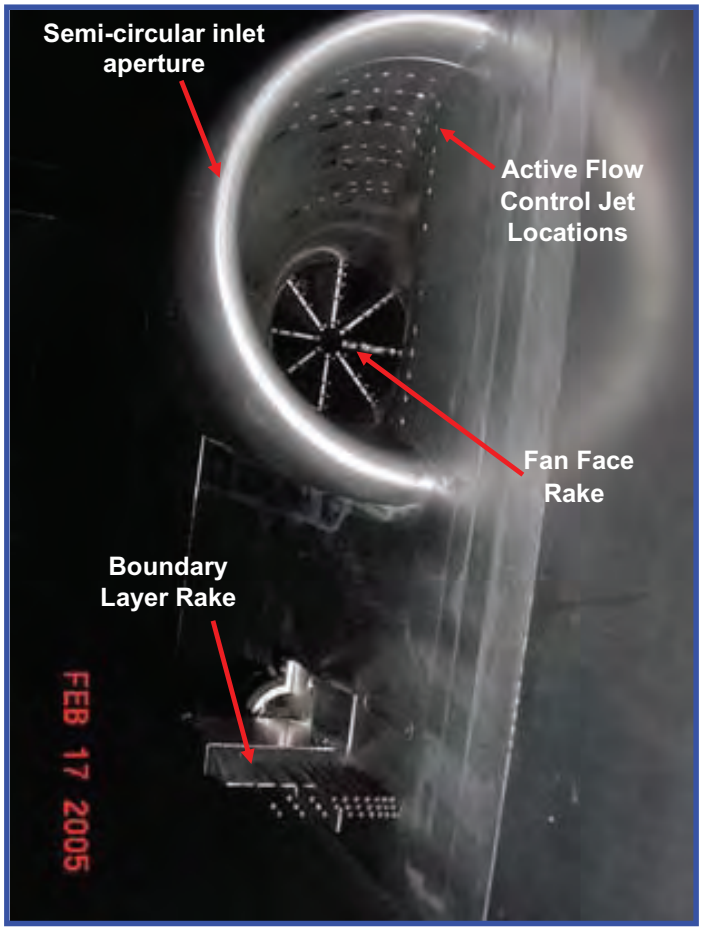
- Phase 1: Develop *flush-mounted inlet test technique* in NASA 0.3m Transonic Cryogenic Tunnel (TCT)

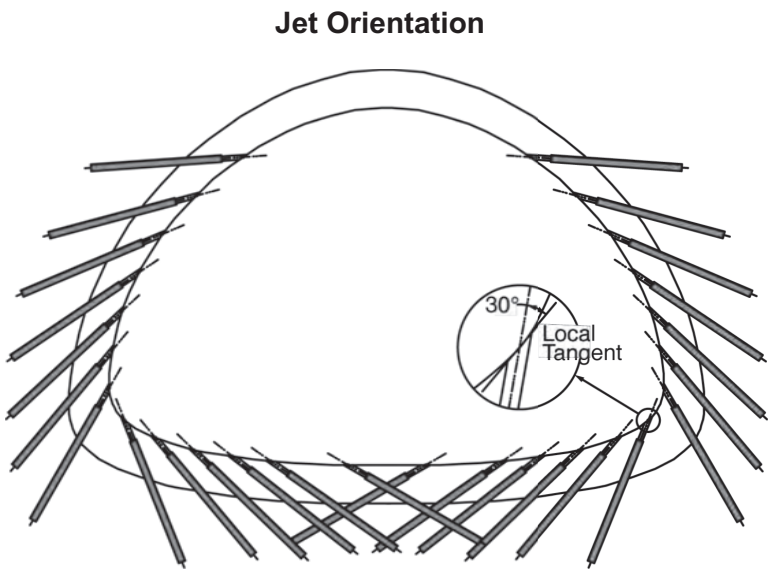
- Phase 2: Evaluate and *select control jet* actuator from simplified geometry testing (adverse pressure gradient ramp)

- Phase 3: *Low Mach number* (M=0.15) testing of control jet system with inlet geometry (6%-scale Inlet Model A - L/D=3.1)

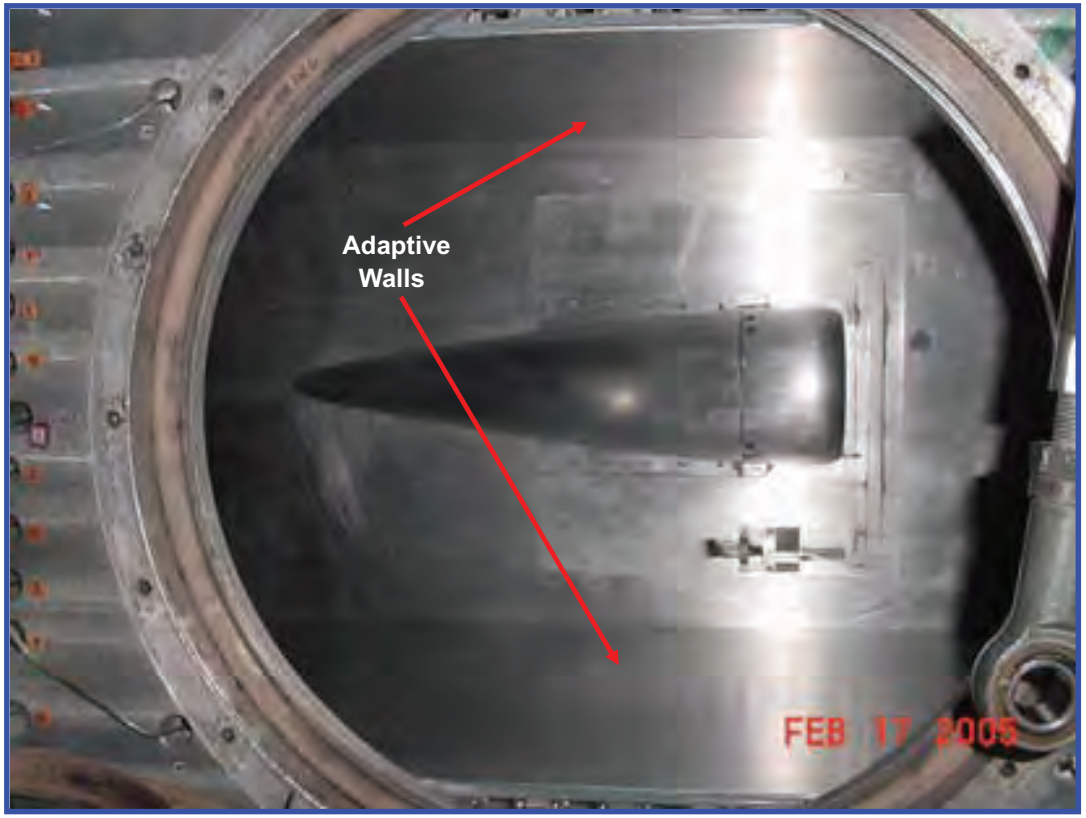
- Phase 4: *High Mach number* (M=0.85) testing of control jet system with inlet geometry (2.5%-scale Inlet Model A - L/D=3.1)

Inlet Model in NASA 0.3m TCT (Front View)

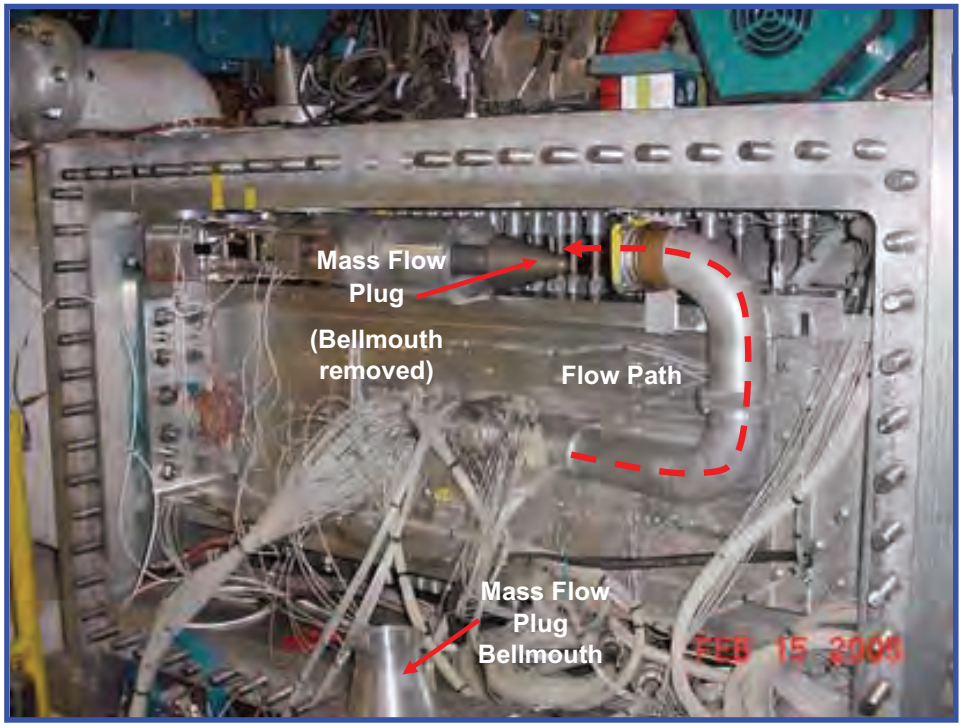




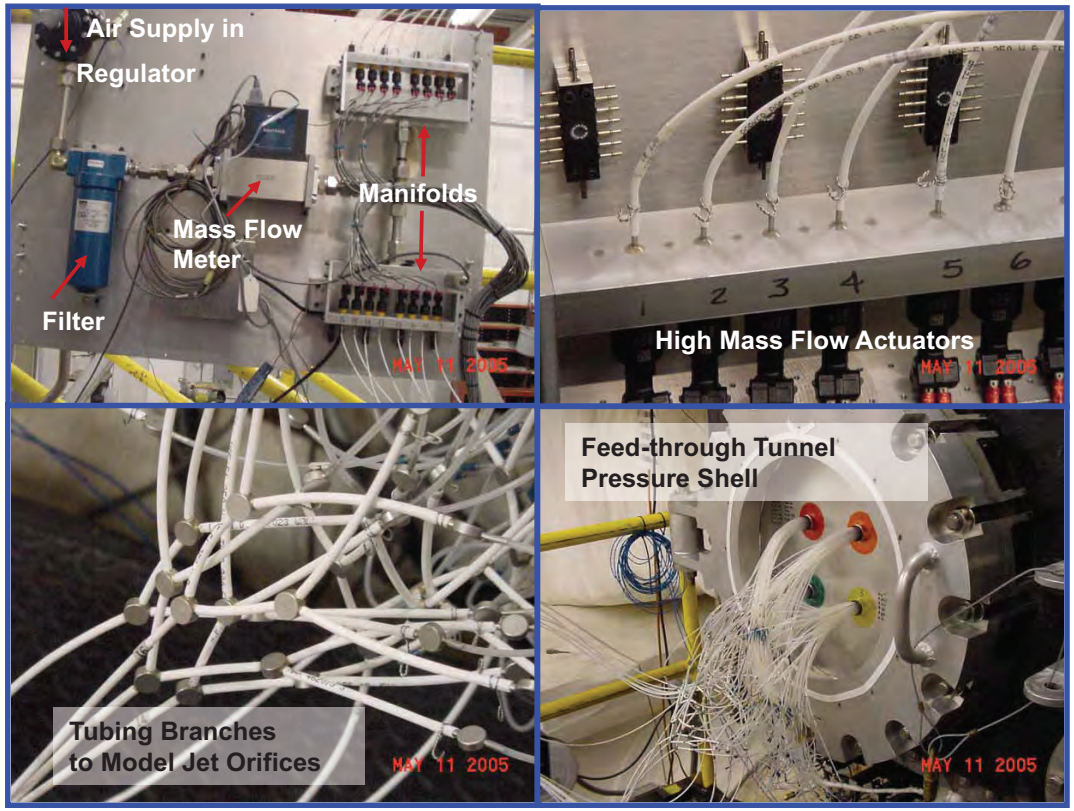
Inlet Model in NASA 0.3m TCT (Top View)



External Inlet Flow Ducting in NASA 0.3m TCT



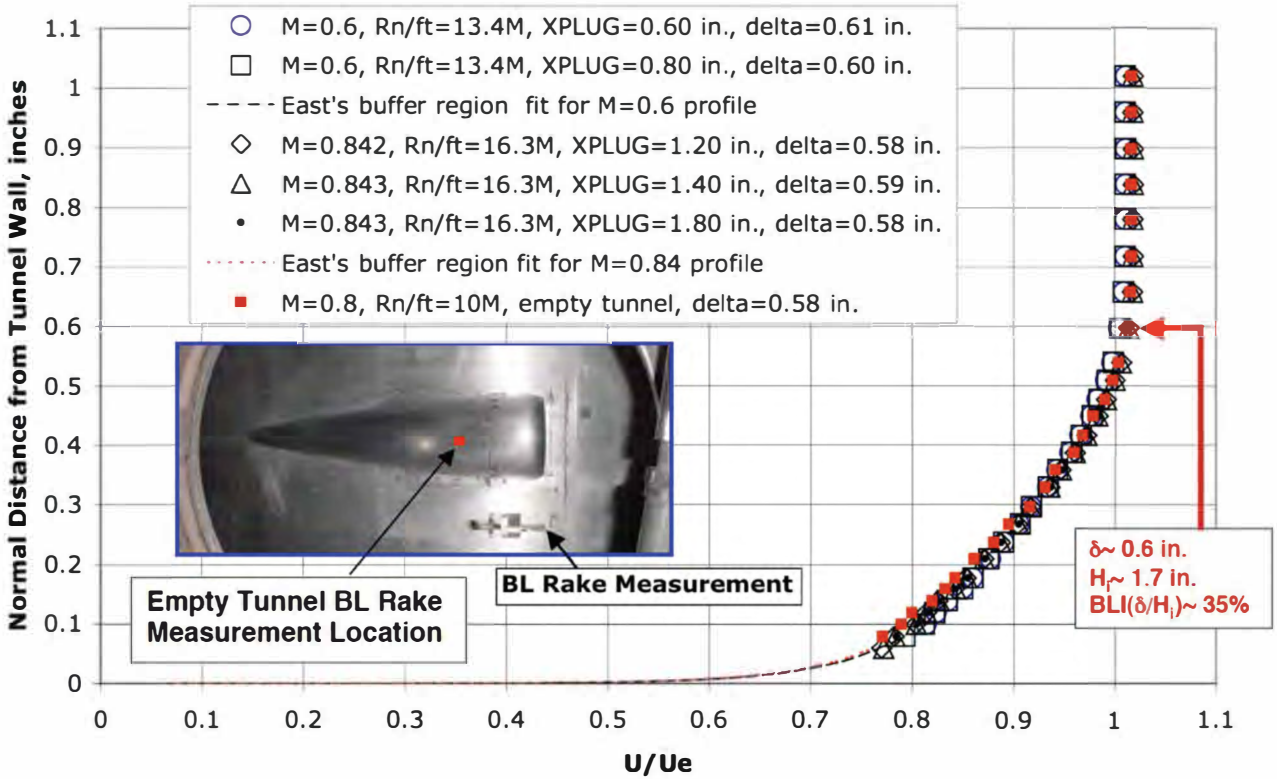
Control Jets System



Characteristics

- Input: 350 psig air supply
- Pulsed or Steady Actuators (compressed natural gas fuel injectors)
- Pulsing Range
  - -Frequency: 20 to 200 Hz
  - -Duty Cycle: 20 to 80%
- Constrictions and volume forced us to use steady jets only
- Tubing could use branching to change mass flow distribution to control jet orifices (i.e., 1 actuator to 2,4 or 6 jets)
- Jet Pressure Ratio Range: 1 to ~3

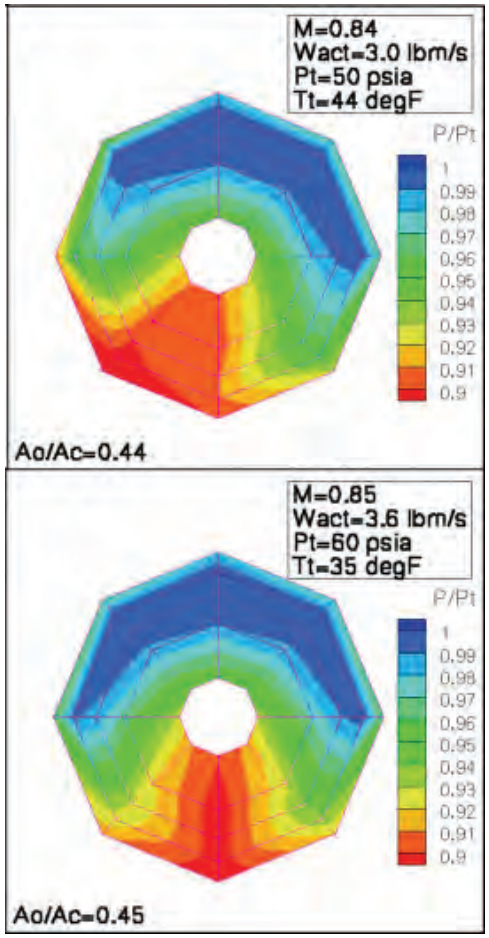
Measured Boundary Layer Profiles in BLI Inlet Test



Effect of BL Rake on AIP Pressures

BL Rake installed

BL Rake removed

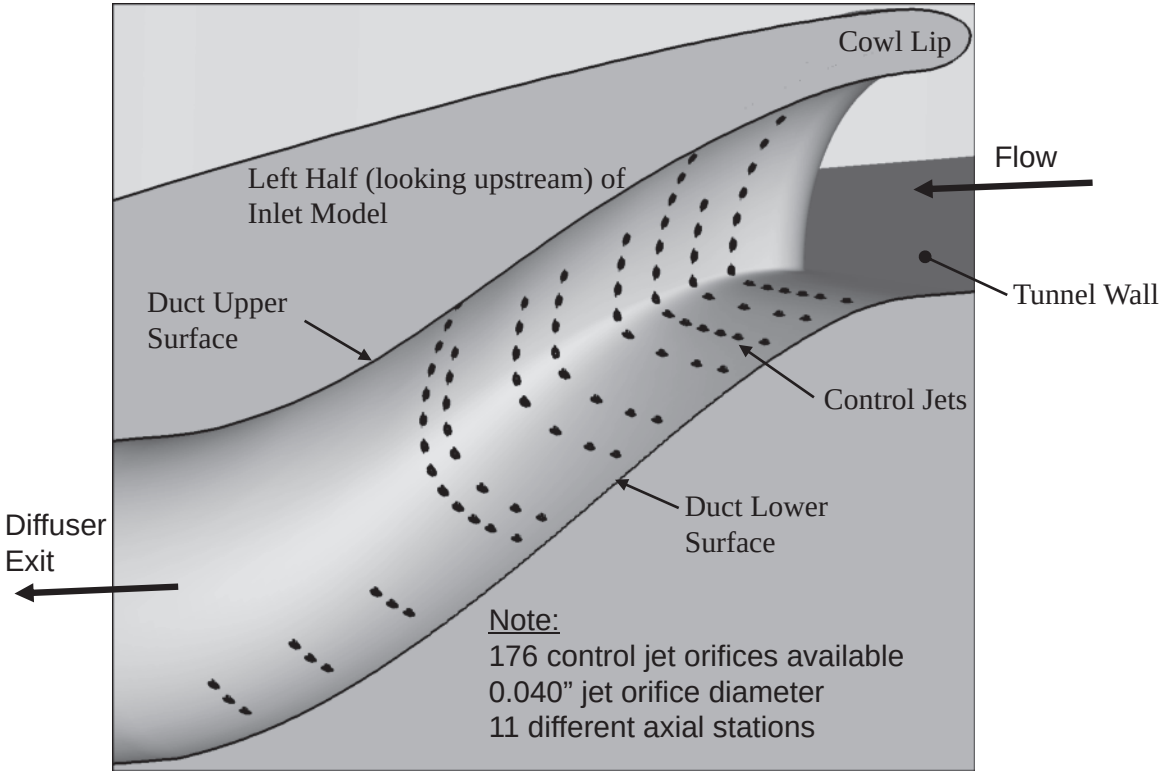


BWB Full/Model-Scale Corrected Airflow Values

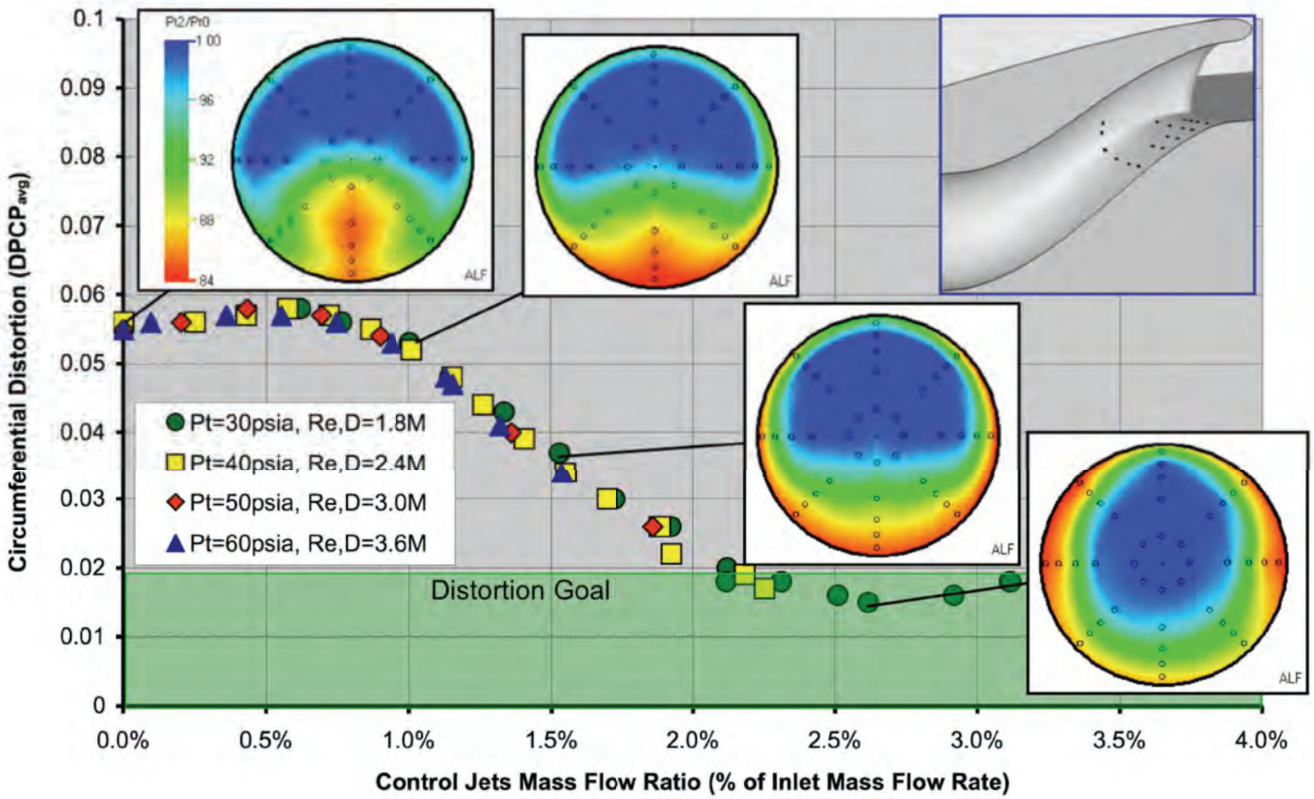
Altitude, ft	Mach	Cond.	Net thrust, lbf	Full-scale Corr. Airflow, lbm/sec	2.5%-scale Corr. Airflow, lbm/sec	Ao/Ac
20000	0.50	Max Climb	25790	2063	1.29	0.85
36089	0.85	"	14555	2081	1.30	0.65
		Max Cruise	13976	2062	1.29	0.64
		Part Power	13277	2038	1.27	0.63
			12590	2012	1.26	0.62
			11180	1950	1.22	0.60
			9784	1882	1.18	0.58
			8384	1811	1.13	0.56
			6989	1737	**1.09**	**0.54**
			5591	1659	**1.04**	**0.51**
			4193	1559	**0.97**	**0.48**
			2793	1468	**0.92**	**0.46**

Test Range

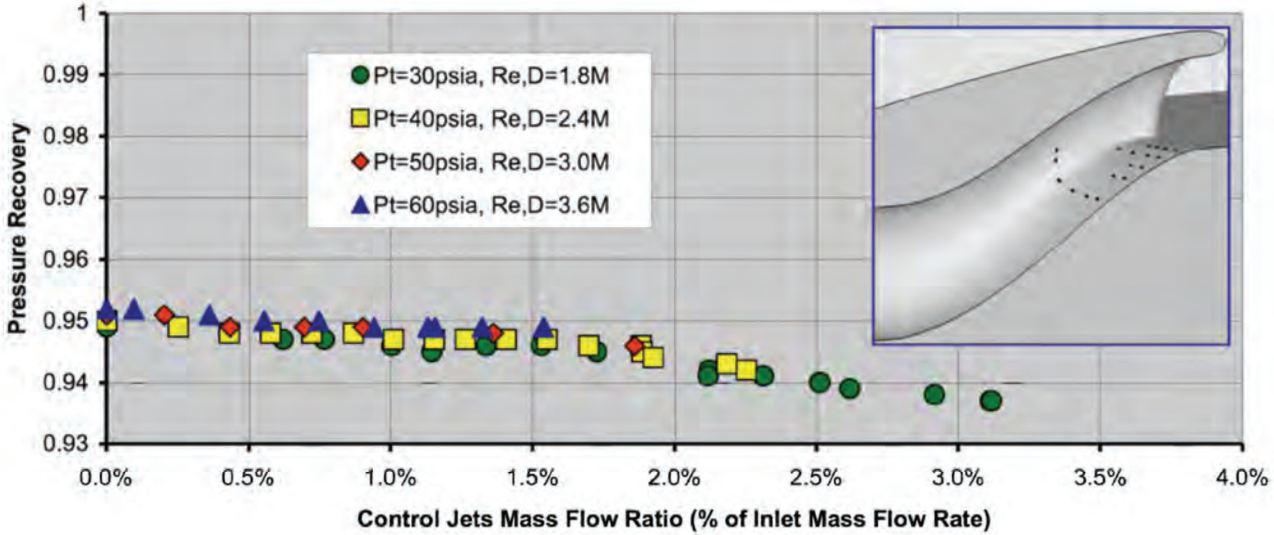
All Control Jet Locations in Left Half (Looking Upstream) of the Inlet Diffuser



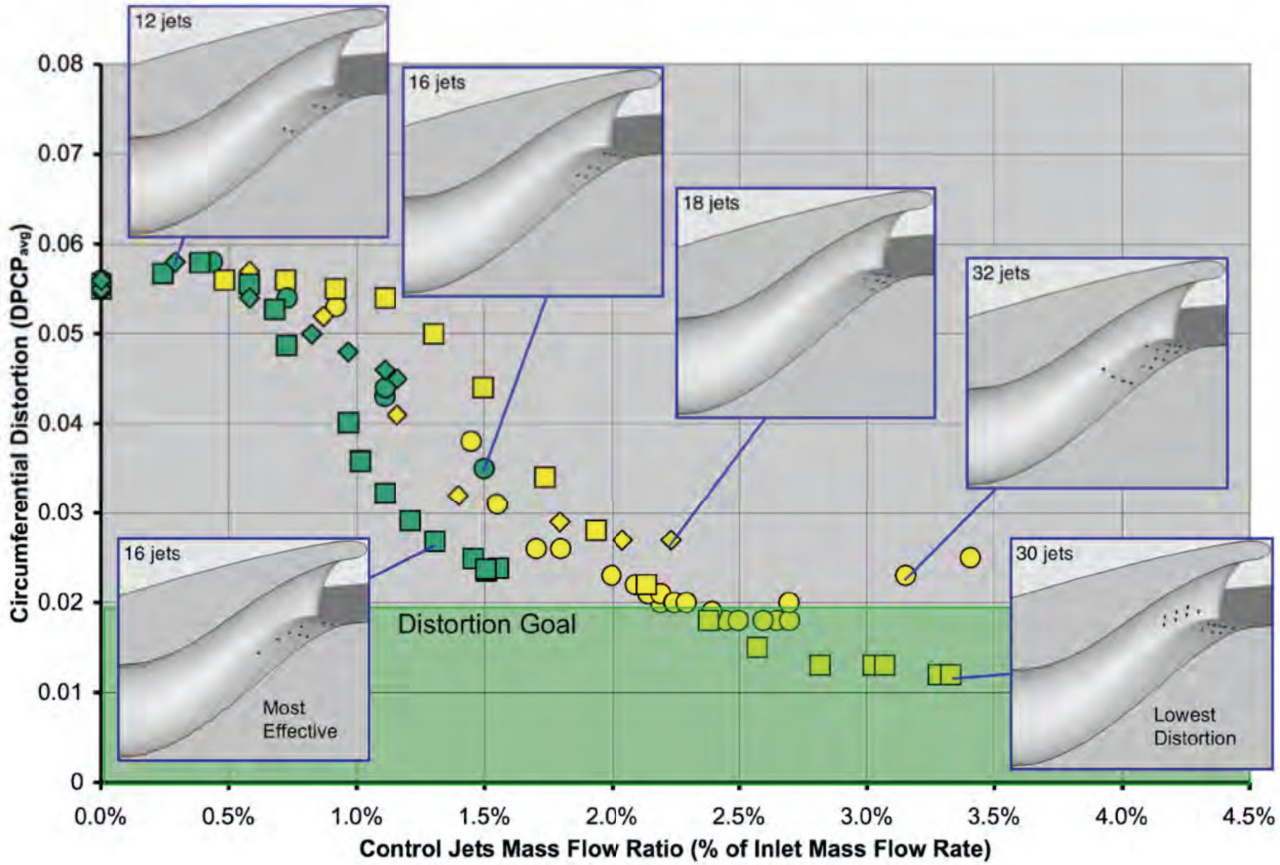
Effects of Tunnel P_t Variation (Re_D) on Distortion ($M=0.85$, $T_t=80^oF$, $A_0/A_C=0.54$, Config 10 w/36 jets)



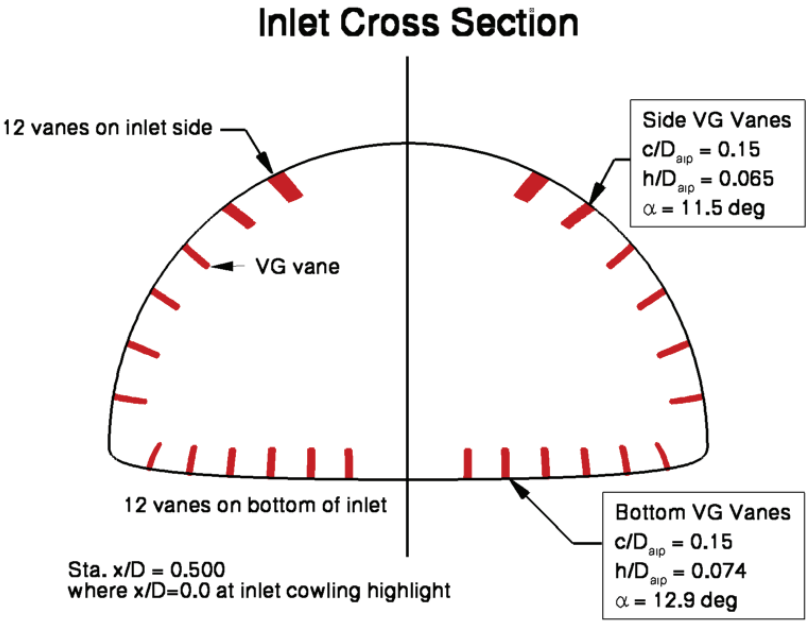
Effects of Tunnel P_t Variation (Re_D) on Pressure Recovery ($M=0.85$, $T_t=80^oF$, $A_0/A_C=0.54$, Config 10 w/36 jets)



Control Jet Momentum and Distribution Effect on Distortion
($M=0.85$, $P_t=30$ psia, $T_t=80^oF$, $A_0/A_C=0.54$)

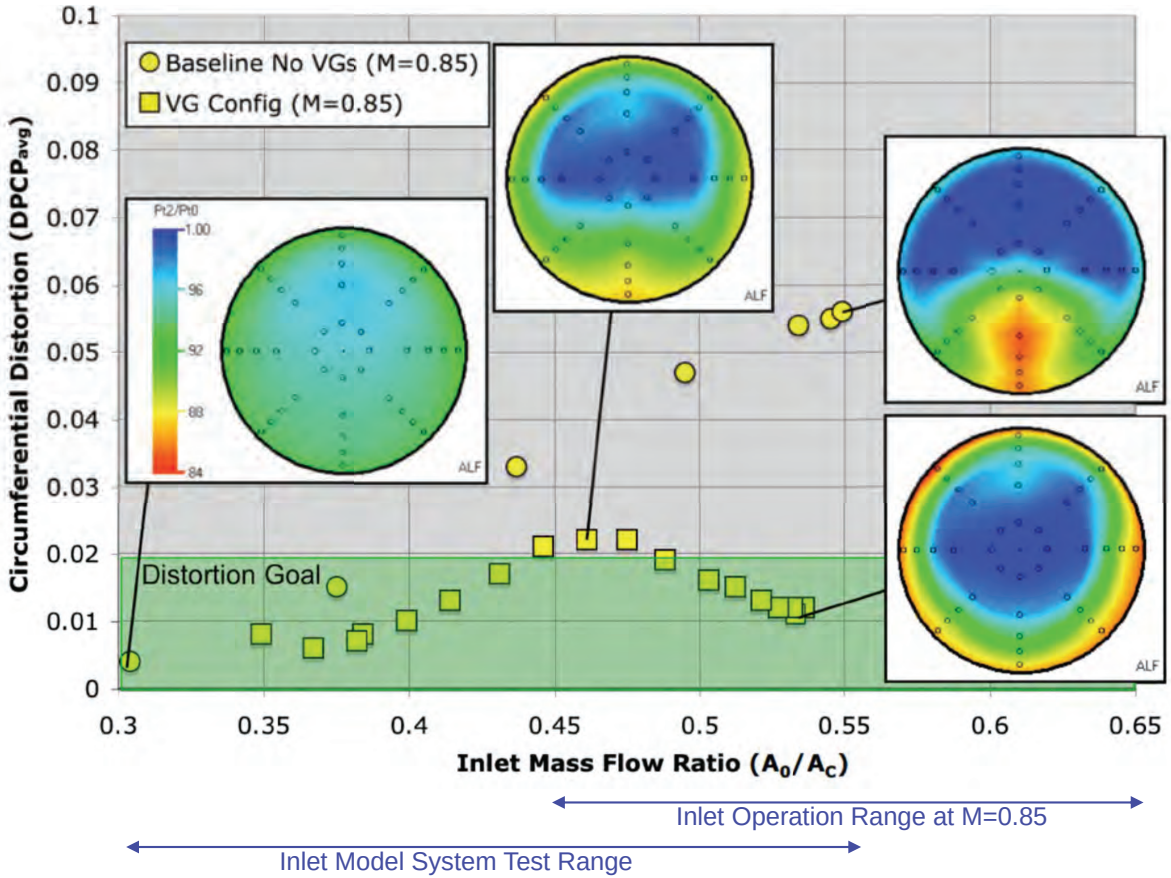


Vortex Generator (VG) Vane Installation

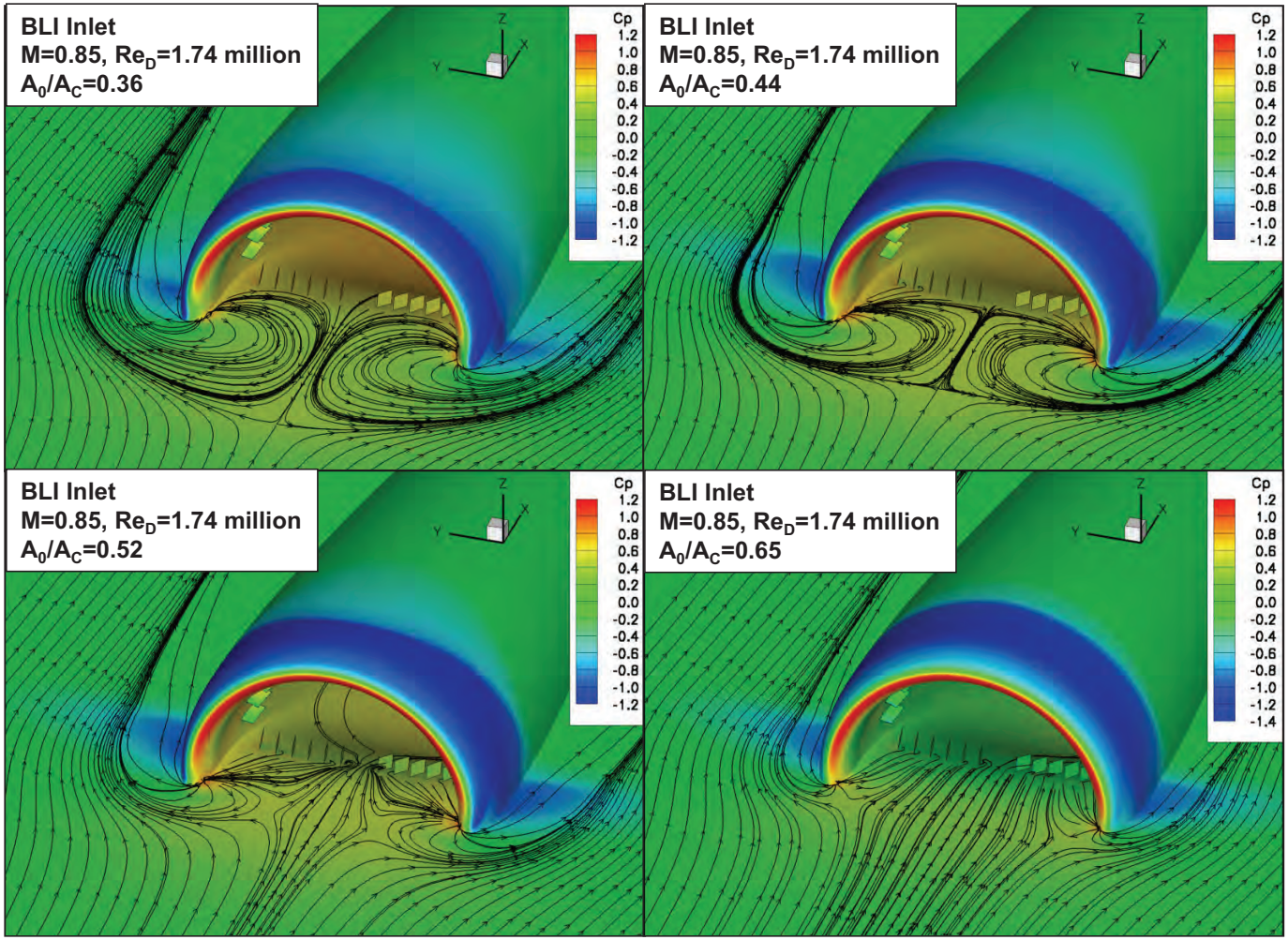


Note: D_{aip}=2.448 inches

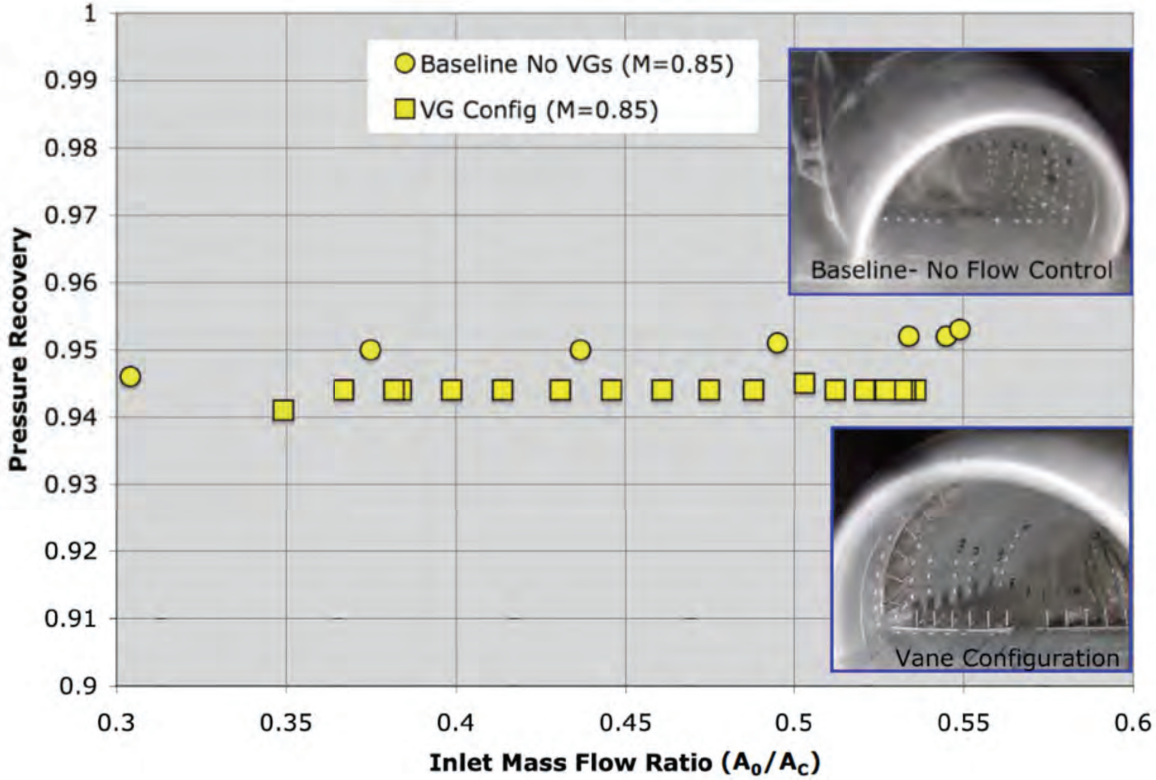
VG Vane Control Effects on Distortion
(P_t=30 psia, T_t=80ºF)



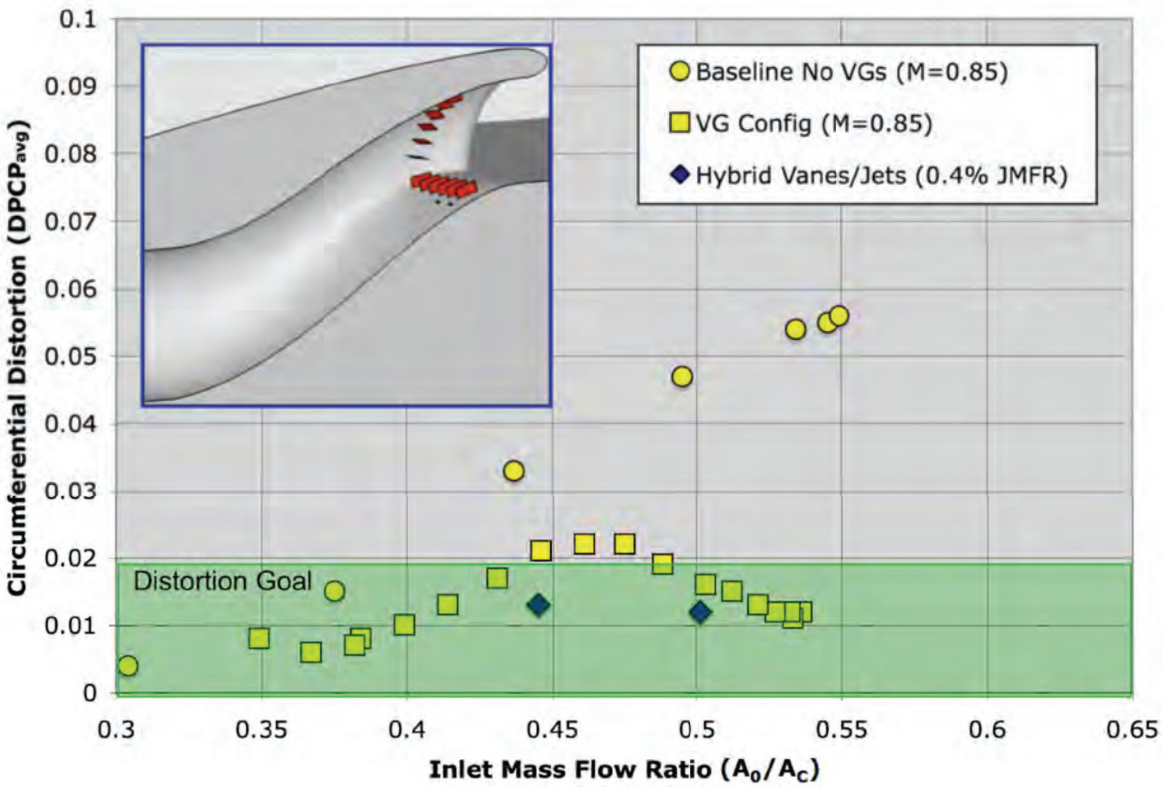
CFD Simulations for Different Inlet Mass Flow Rates



VG Control Effects on Pressure Recovery (P_t=30 psia, T_t=80ºF)



Combined VG Vane and Jet Control Effect on Distortion
(M=0.85, P_t=30 psia, T_t=80ºF, Config 11 w/4 Jets)



Conclusions (1 of 2)

- Demonstrated AFC jet system effectiveness to reduce circumferential distortion in a high Mach, significant BLI inlet flow problem

- Jet configurations were tested that lower distortion from baseline $DPCP_{avg}$ value of 0.055 to:
  - 0.025 using only 1.5% of inlet mass flow rate (most effective)
  - 0.015 using about 2.5% of inlet mass flow rate (lowest distortion)

- Balancing the control jet momentum and the jet distribution are key to effectively reducing circumferential distortion

- Measured pressure recovery decreases with significant BLI flow control

Conclusions (2 of 2)

- Point design VG vane configuration indicates reduced circumferential distortion compared to the baseline (no flow control) configuration

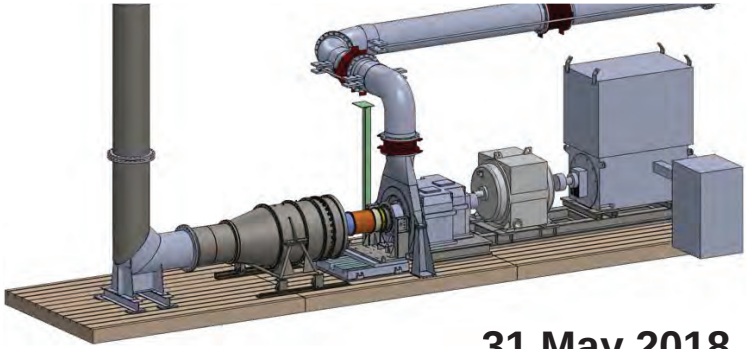
- Hybrid system configuration combined VG vanes/jets to keep the inlet distortion level low across the range of available inlet mass flow settings

References

- Owens, Allan, and Gorton, “Boundary-Layer-Ingesting Inlet Flow Control,” J. of Aircraft, vol. 45, pp. 1431-1440, 2008.

- Koklu, and Owens, “Comparison of Sweeping Jet Actuators with Different Flow-Control Techniques for Flow-Separation Control,’ AIAA Journal, vol. 55, pp. 848-860, 2017.

CARL Experimental Results and Challenges



31 May 2018

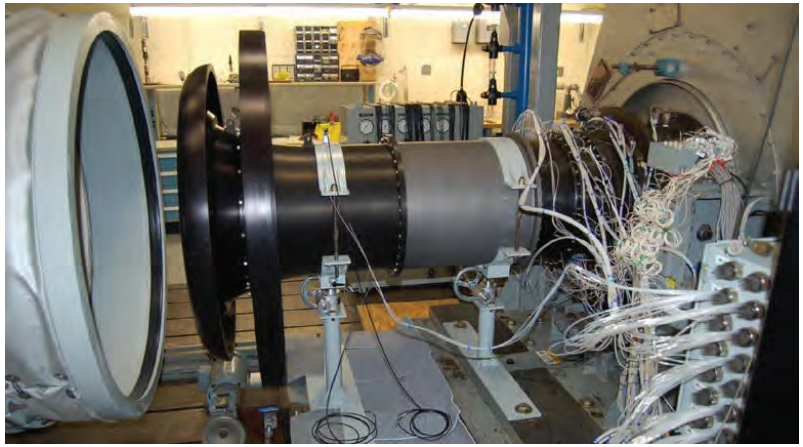
Mr. Chase Nessler
Facility Lead
Compressor Aero Research Lab
Air Force Research Laboratory

Integrity ★ Service ★ Excellence

DISTRIBUTION A. Case No. 88ABW-2018-2550. Approved for public release: distribution unlimited

Agenda

- Introduction
- Instrumentation Challenges
- Aeromechanic Characterization Challenges
- Swirl Generator Challenges
- Conclusions



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Introduction

❑ The CARL mission

- Enhance the understanding of complex internal flow physics within fans and compressors through analytical, computational, and experimental methods

❑ How do we do this?

- Database of validation-quality experimental results that are used to enhance numerical methods and design tools
- Annular Cascade Facility for isolated distortion generators and non-rotating flow physics
- Compressor Facility for fan rig testing and coupled configurations

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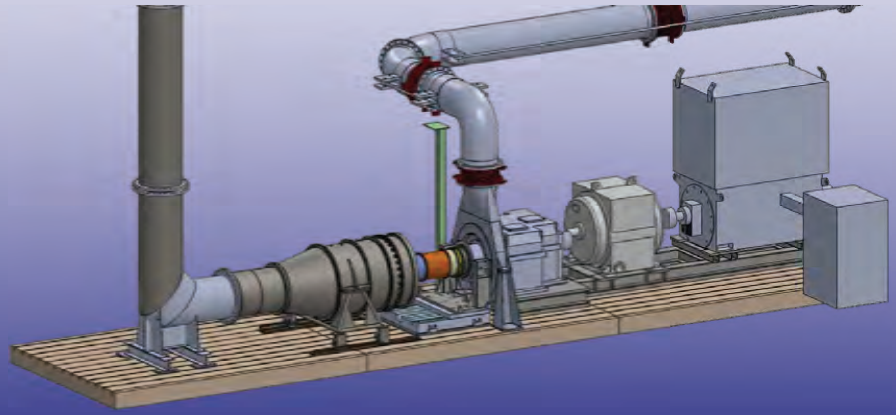
CARL Compressor Facility Overview



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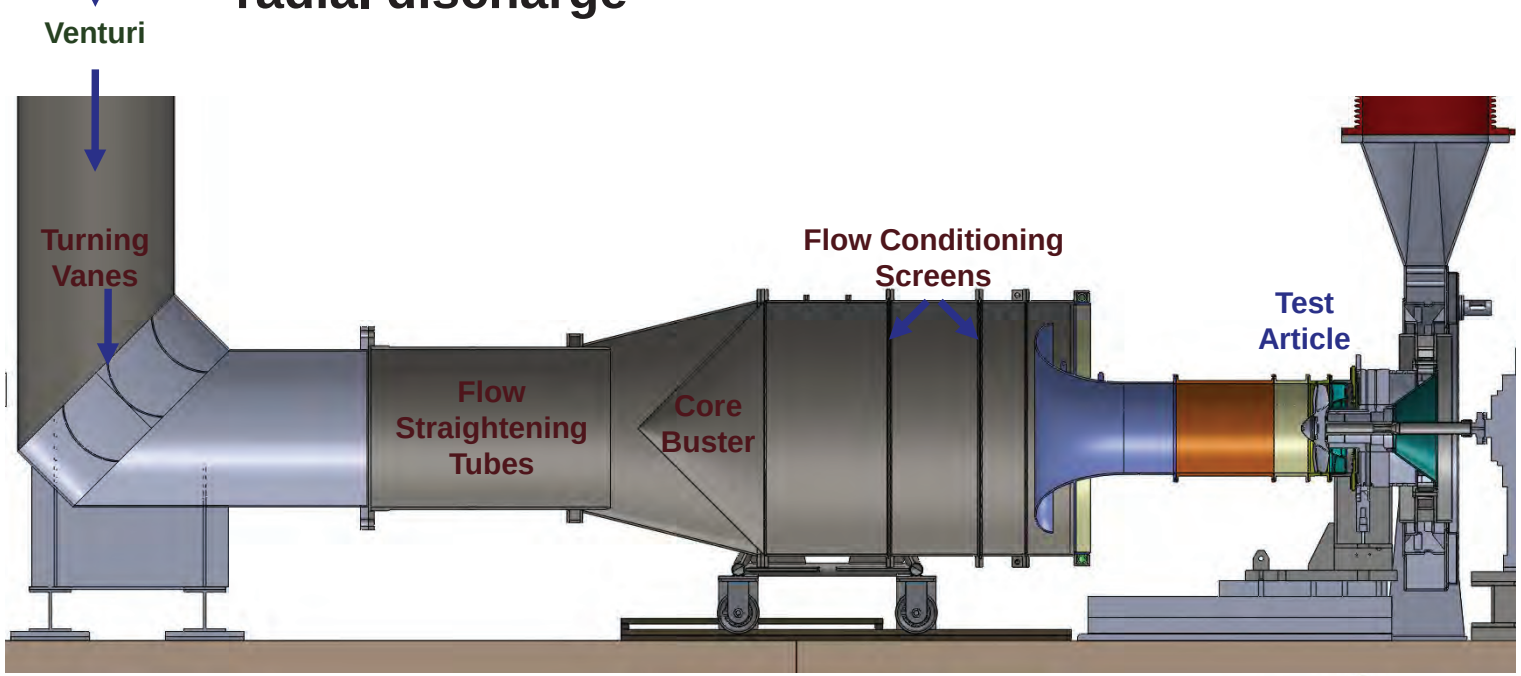
Introduction: Compressor Facility

- 6,000 hp drive train with 22,000 RPM output
- Flowpath with axial conditioning and inflow and radial discharge



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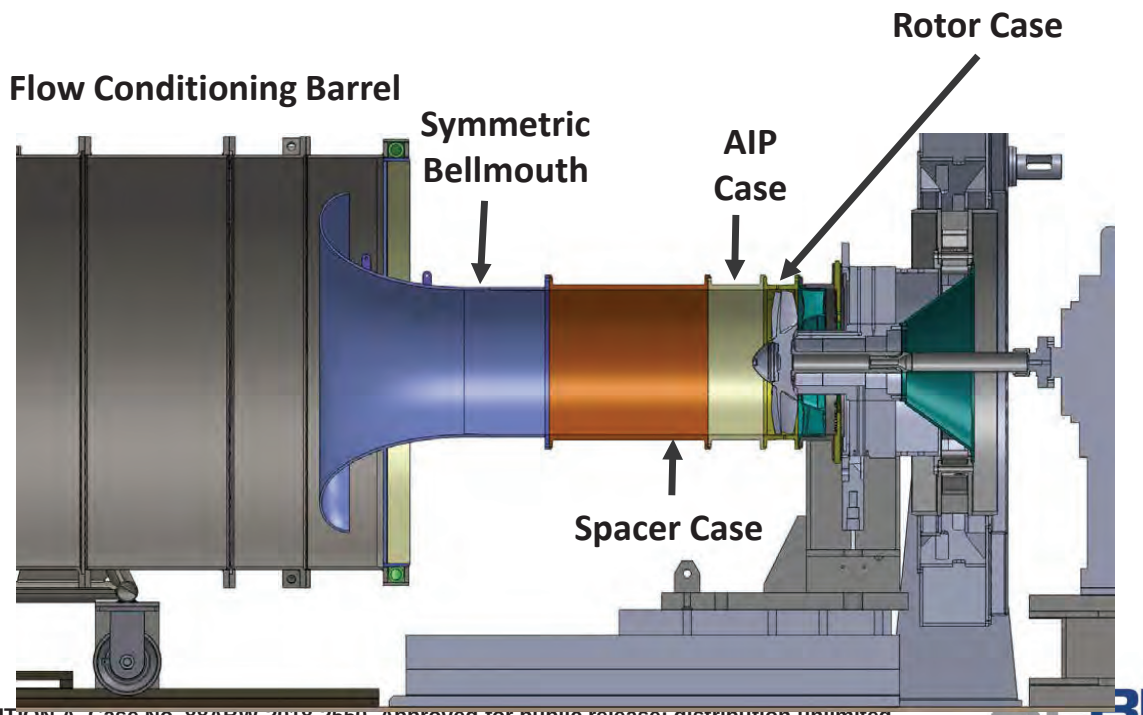
Introduction: Compressor Facility

❑ Reconfigurable Flowpath

- Developed flowpath appropriate for clean inlet and distorted inflow testing through reconfigurable upstream ducting and rotators



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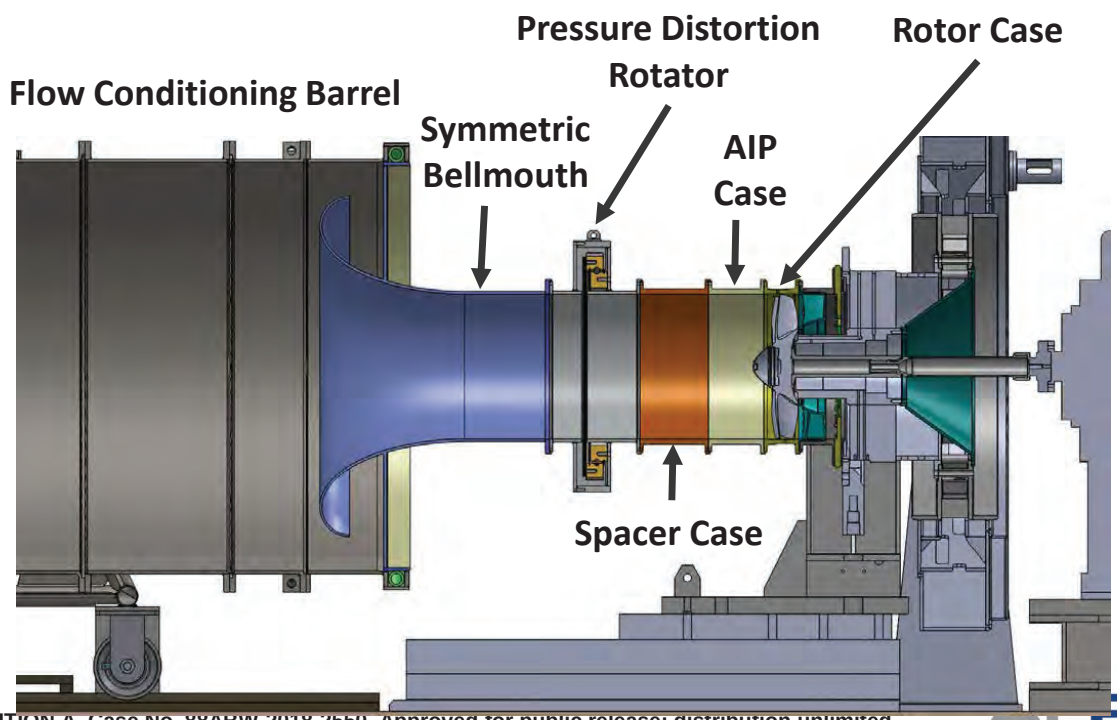

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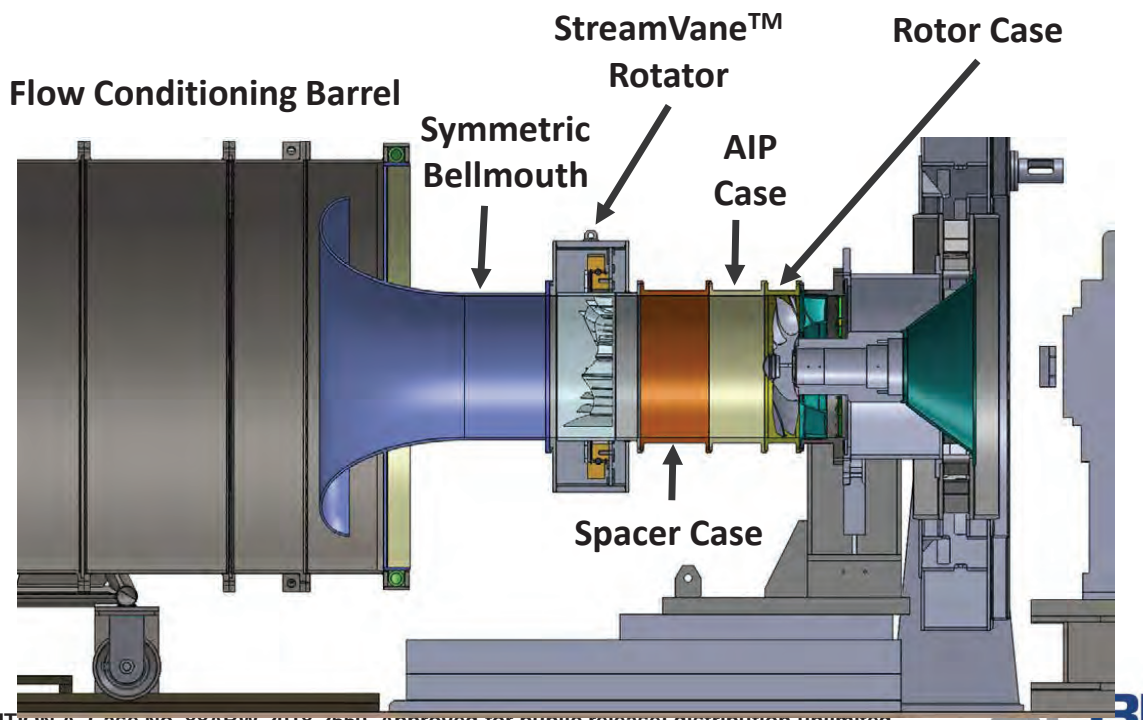

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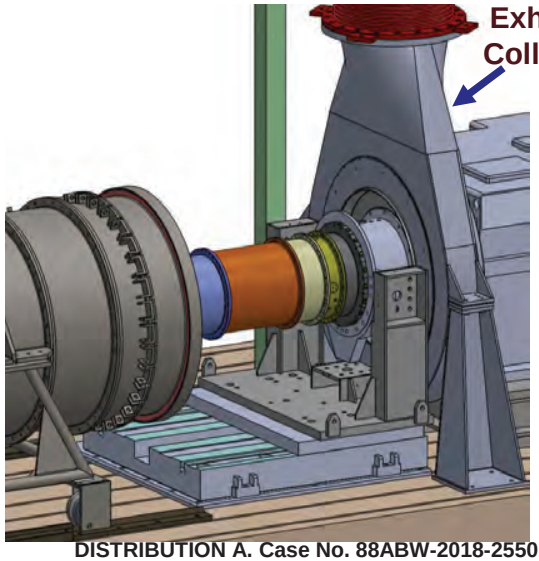
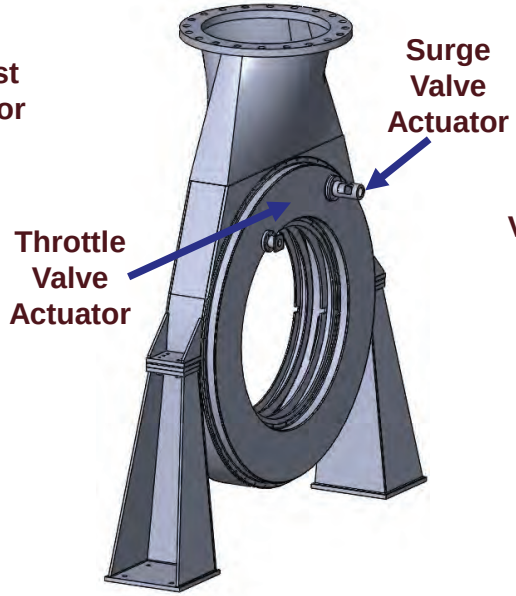
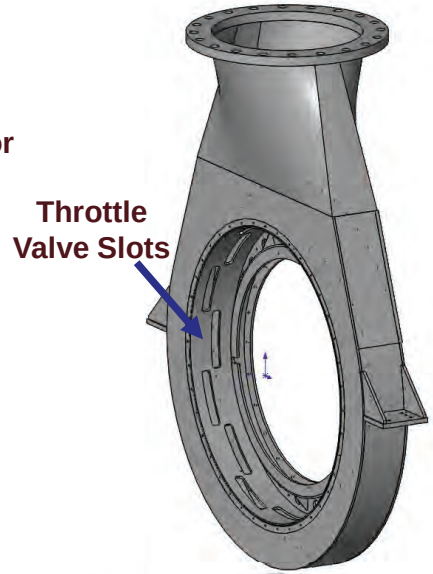
Introduction: Compressor Facility

❑ Radial Exhaust Collector with Fan Throttle

- Throttle valve with slotted fixed circular plate and concentric circular plate with identical slots that rides on top of the fixed plate
- Test article is throttled by rotating the mating circular plate so that the slots become covered
- Accurate identification of stall is a challenge







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Challenges: Instrumentation

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Challenges: Instrumentation

- **Non-uniform flowfields in fans require denser measurements than traditional rigs**
  - Inlet Distortion Measurement
  - Exit Plane Total Pressures and Total Temperatures
  - Over-the-Rotor Kulites
- **Specific Challenges**
  - Rotate instrumentation vs. Rotate distortion?
  - Simultaneous time synced measurement vs. Resolution?
  - Non-interference with flowfield
  - Miniaturization to decrease influence
  - Capturing the correct quantities (e.g., flow angle on stage exit rakes)

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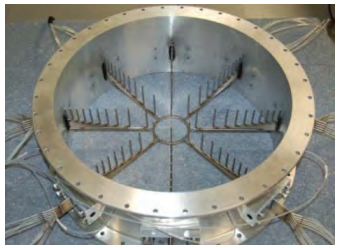
Inlet Distortion Measurement

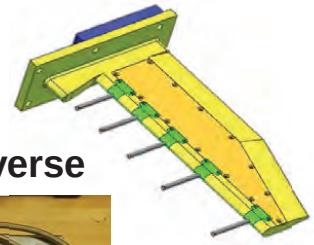
❑ Rakes versus PIV Measurements

- Rakes increase failure risk, generate blockage and wakes, and straighten streamlines but can provide total pressure and even velocities
- PIV enables capture of 2 or 3 components of unsteady velocity without dramatically impacting the flow

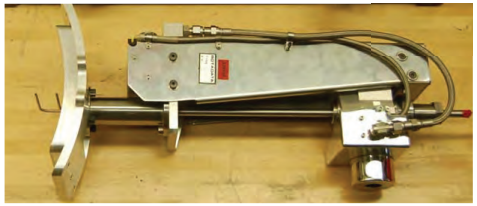
Steady 8x10 Rake Case



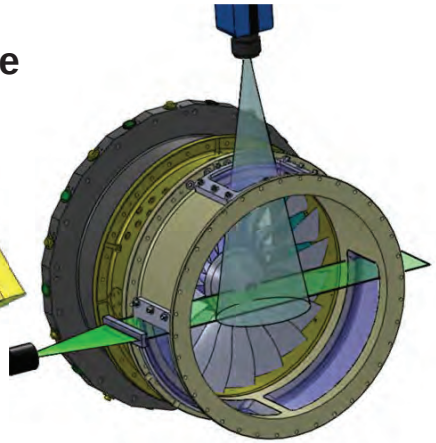
Prati Probe Rake

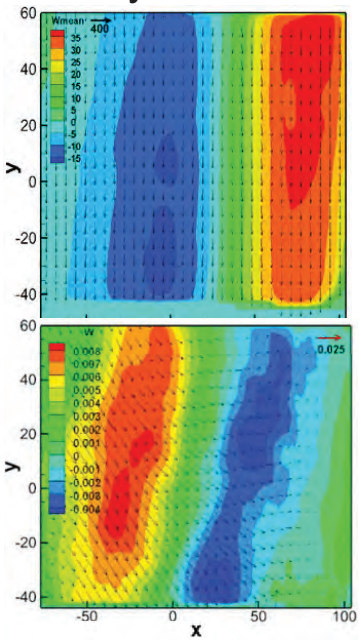


5-Hole Probe Traverse



PIV Configuration, Mean Flow, and Dominant Mode





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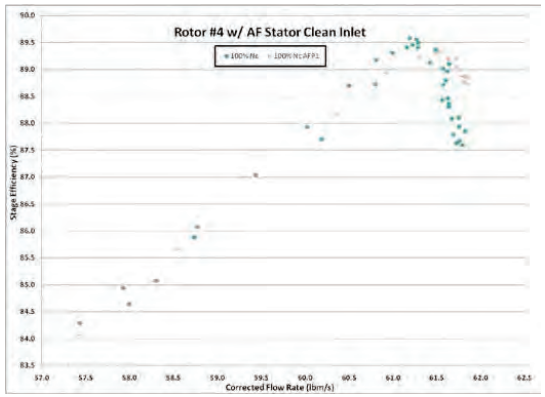
Exit Plane Instrumentation

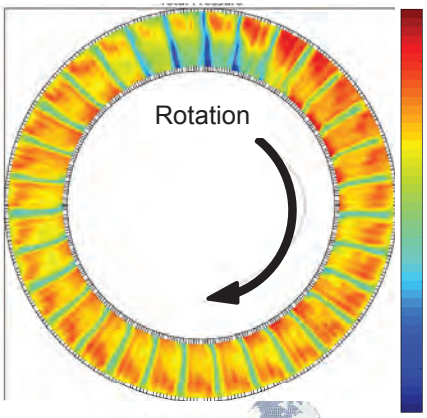
- **Performance Measurement and Exit Plane Reconstruction**
  - Steady instrumentation positioned to recreate a stator passage in clean inflow and allow area averaging (centers of equal area, equal percent pitch)
  - Rotation of distortion to match appropriate clocking intervals based on stator pitch allows reconstruction

Exit Rake Case

Area-averaged Performance



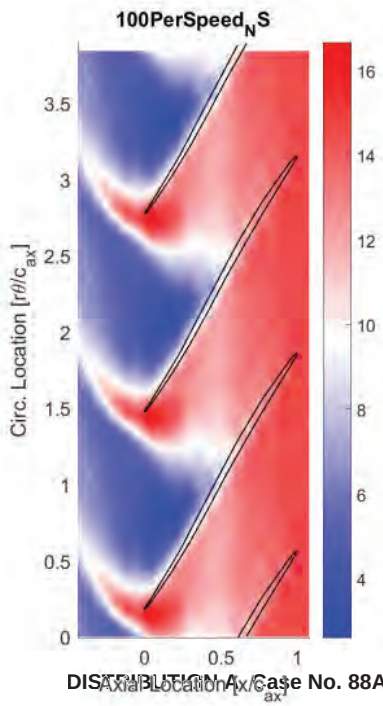
Reconstructed Distortion Flowfield



ON A. Case No. 88ABW-2018-2550. Approved for public release: distribution unlimited

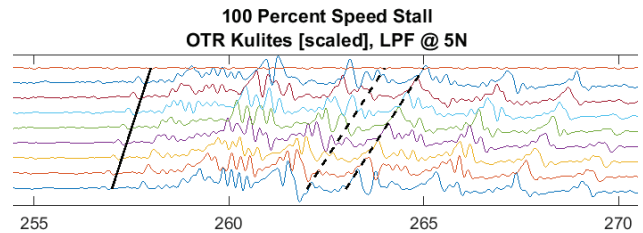
Over-the-Rotor Kulites

- **Unsteady data acquisition: Wall Static Kulites**
  - Total of 28 Kulites placed at two different measurement planes
  - Not able to extract specific unsteady events spatially unless phase-locked to rotor



Reconstructed Time-mean Flowfield

Simultaneous Upstream Kulite Circumferential Trace



XTEL-140 (M) Series Kulite

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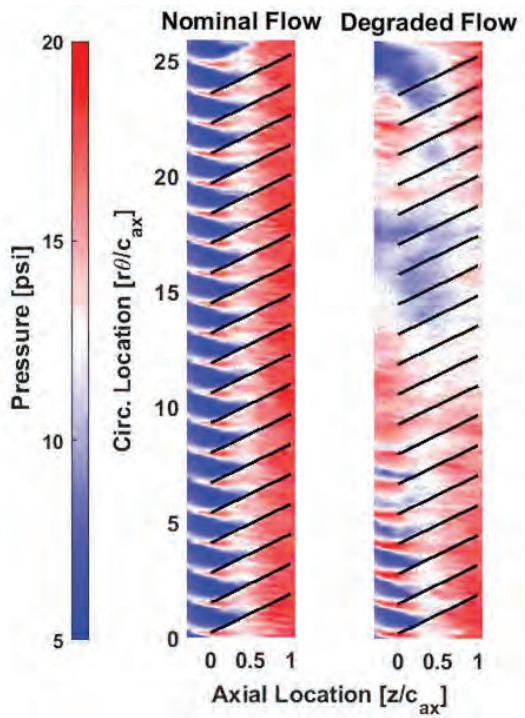
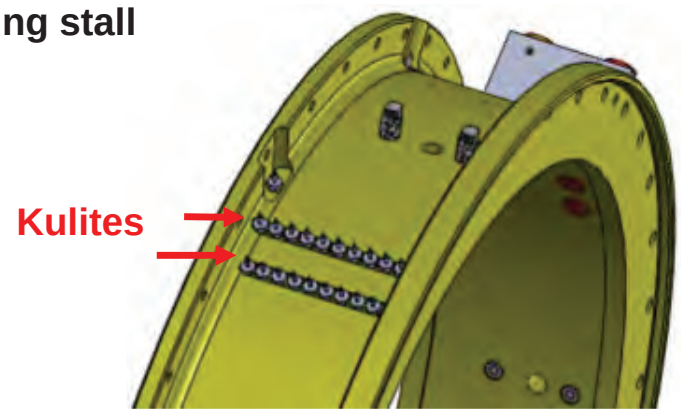
Over-the-Rotor Kulites

- **Unsteady data acquisition: Wall Static Kulites**
  - Kulite ensemble averaging and spatial reconstruction allows capture of rotating stall



Measure degraded aero flowfield due to rotating stall

Rotor Case



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Challenges: Aeromechanic Characterization

DISTRIBUTION A. Case No. 88ABW-2016-6059. Approved for public release; distribution unlimited.

Challenges: Aeromechanic Characterization

- **Fan Response Prediction and Measurement is Critical**
  - Accurate Geometry and Structural Response characteristics
  - Strain gage and NSMS for Health Monitoring and Data
- **Specific Challenges**
  - Use of Non-Contact stress measurement and identification of significant events
  - Strain Gage Placement and amount of Rotating Instrumentation
  - Validation for Fluid-Structure Interaction simulations

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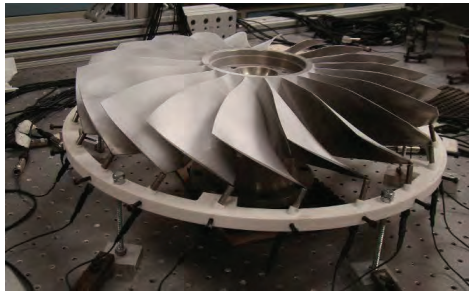
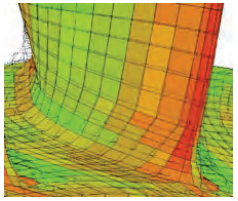
Accurate Structural Characterization

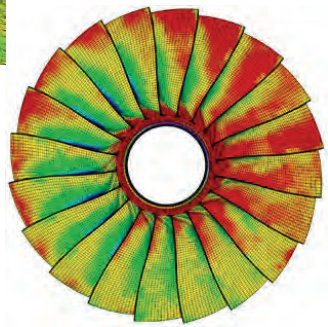
- **Unsteady data acquisition: Strain Gages**
  - Placement selected based on FEA of real geometry
- **Unsteady data acquisition: NSMS Light Probes**
  - Rotor arrival time indicates modes, amplitudes, interactions
  - Can be combined with Kulite & PIV measurements to form multivariable dataset to identify coherent physics events

Traveling Wave Experiment

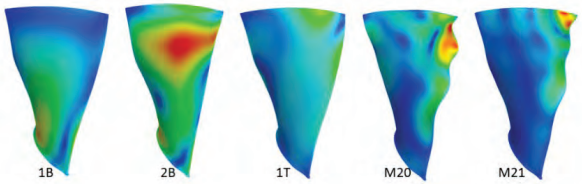




ATOS Scan Data



Modal Analyses



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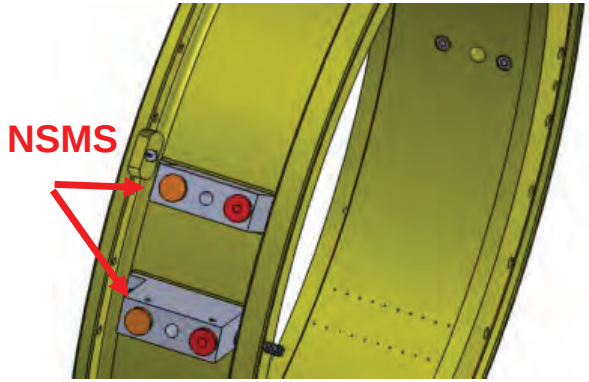
Strain Gage and NSMS Measurements

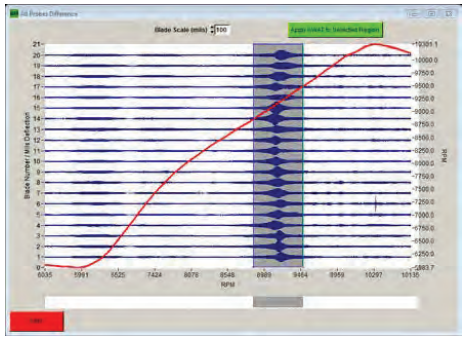
- **Unsteady data acquisition: Strain Gages**
  - 12 on-rotor strain gages
  - Live stress monitoring with comparisons to 60% of Goodman limits
- **Unsteady data acquisition: NSMS Light Probes**
  - 12 leading edge and 12 trailing edge spot probes
  - Displayed events, arrival time, and stress amplitudes

Strain Gage Placement

Rotor Case



NSMS Output



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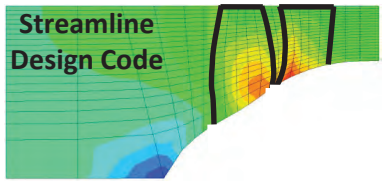
Challenges: Swirl Distortion Generator

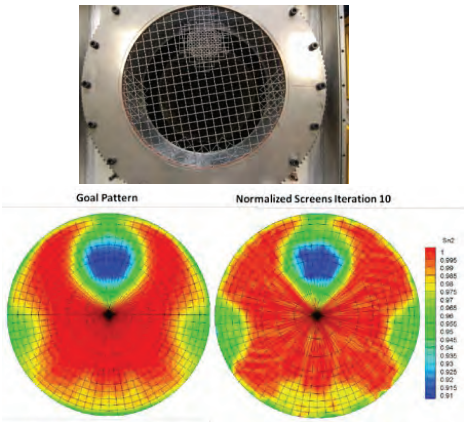
DISTRIBUTION A. Case No. 88ABW-2016-6059. Approved for public release; distribution unlimited.

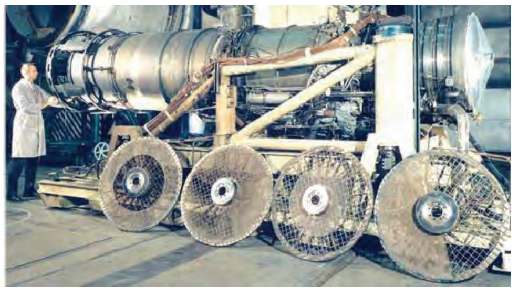
Challenges: Swirl Distortion Generators

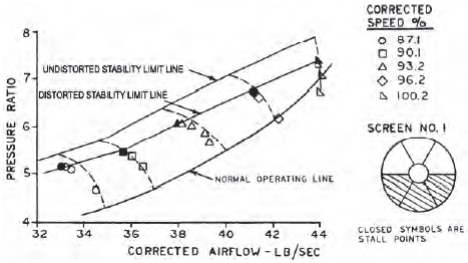
- Typical compression system design practices rely on 1D-meanline codes that assume uniform inlet conditions
  - Further research is necessary to define key design parameters of interest



- Similar to the methods of evaluating pressure distortion
  - broad spectrum of velocity fields needs to be processed through a compression system and evaluated







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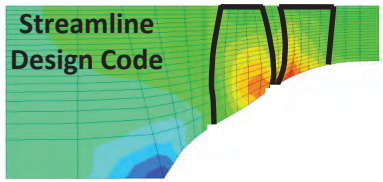

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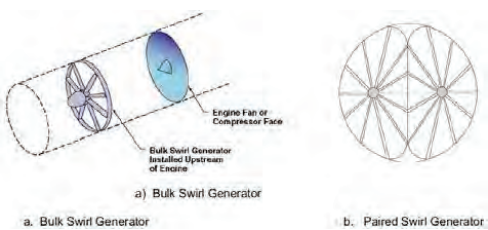

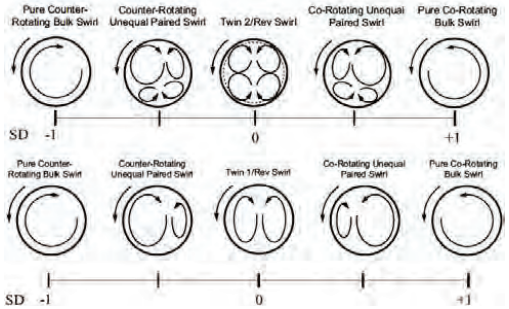

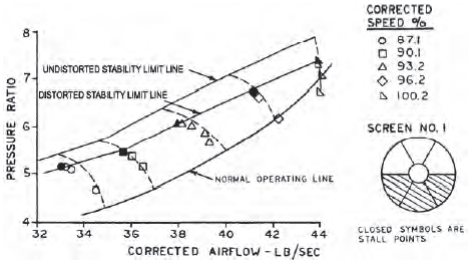

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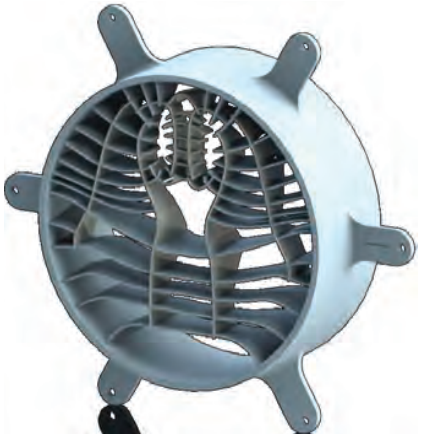
Challenges: Swirl Distortion Generators

- StreamVane™ swirl generator
  - Patented by Virginia Tech
  - Generates user defined swirl patterns from a 2D vector field
  - Able to produce bulk flow features as well as complex localized features
  - Generates a specified swirl pattern through a continuous series of changing vane profiles stacked along a number of predefined vane paths
  - Vane profile shapes are based on six-percent-thick NACA 63-series blade sections

- Developmental Challenges
  - Mach number dependence on secondary flow field
  - Validation of the CFD computational model
  - Validation of low speed wind tunnel tests used for the development process
  - Validation of material properties and structural characterization



AFS1 StreamVane™

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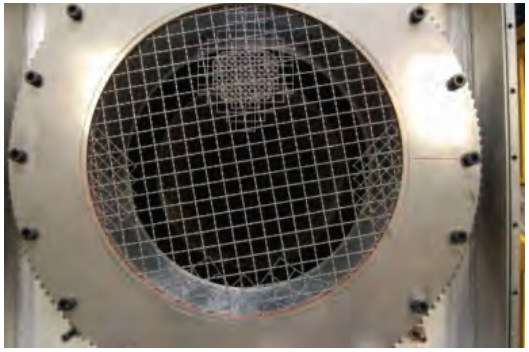
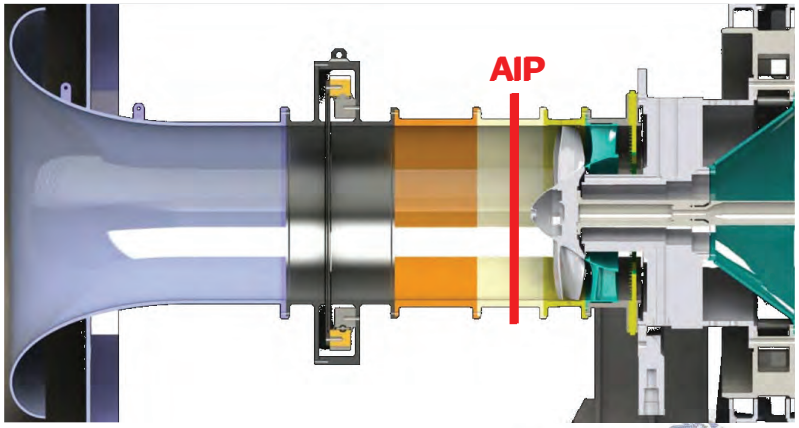
Challenges: Swirl Distortion Generators

- The objective of this study was an evaluation of the flowfield as it varies axially from the exit of the StreamVane
  - Motivated by the recommendations by the SAE for how to define and take flow measurements at an AIP
  - Unlike pressure distortion screens, there is currently no standard for specifying a distance between a swirl generator and an AIP
  - Through the analysis of the axial extent of both pressure distortion and swirl distortion, an axial spacing related to duct size can be determined





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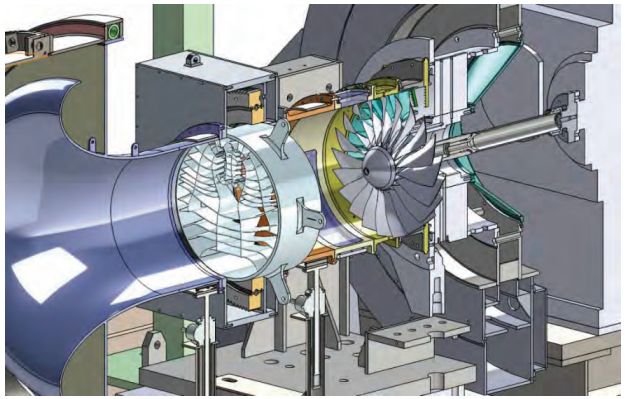
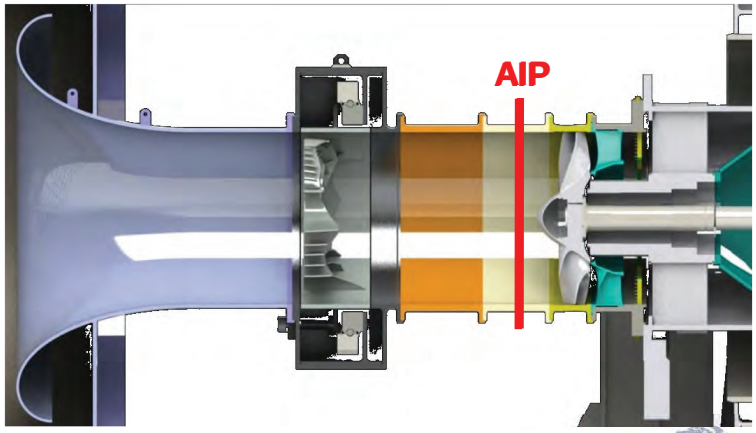
Challenges: Swirl Distortion Generators

- The objective of this study was an evaluation of the flowfield as it varies axially from the exit of the StreamVane
  - The desired axial spacing is based on the following criteria:
    - Minimizing the pressure distortion at the AIP
    - Ability to generate a specified secondary flowfield at the proposed spacing
    - Minimizing the potential effect between the swirl generator and the compression system



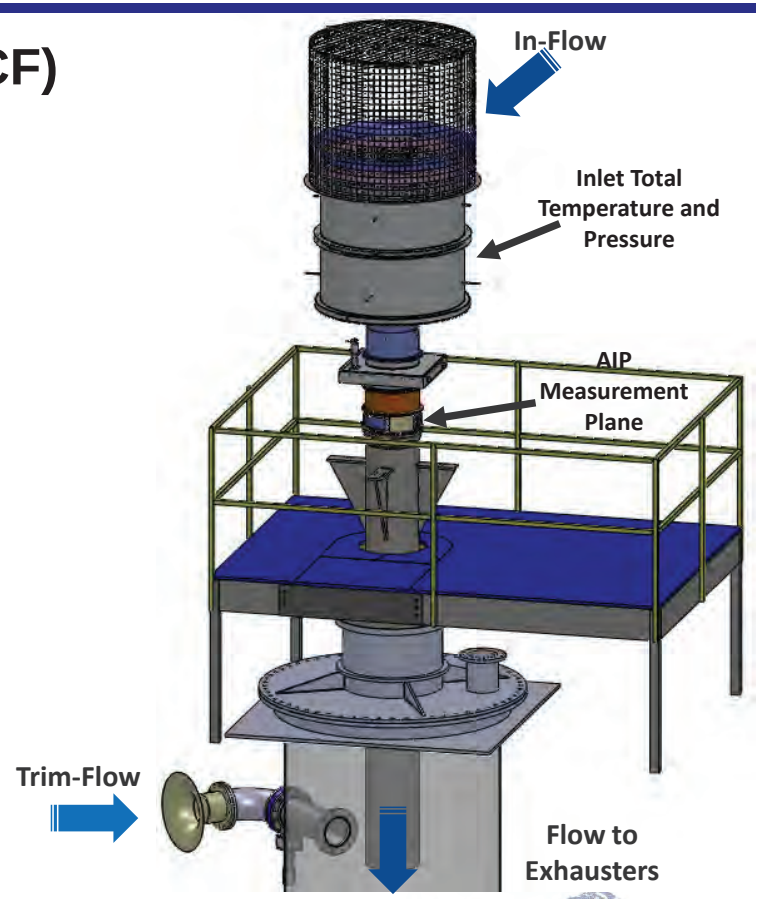


DISTRIBUTION A. Case No. 88ABW-2018-2550. Approved for public release: distribution unlimited

Challenges: Swirl Distortion Generators

❑ Annular Cascade Facility (ACF)

- Vertical test configuration
- 17 inch diameter test section
- Utilizes two gas turbo exhauster to pull up to 70lbm/s
- Closed-loop feedback control of Mach number to within ±0.5%
- 10 duct diameters in length before flowpath change
- Various stages of Flow conditioning
- AIP location is fixed



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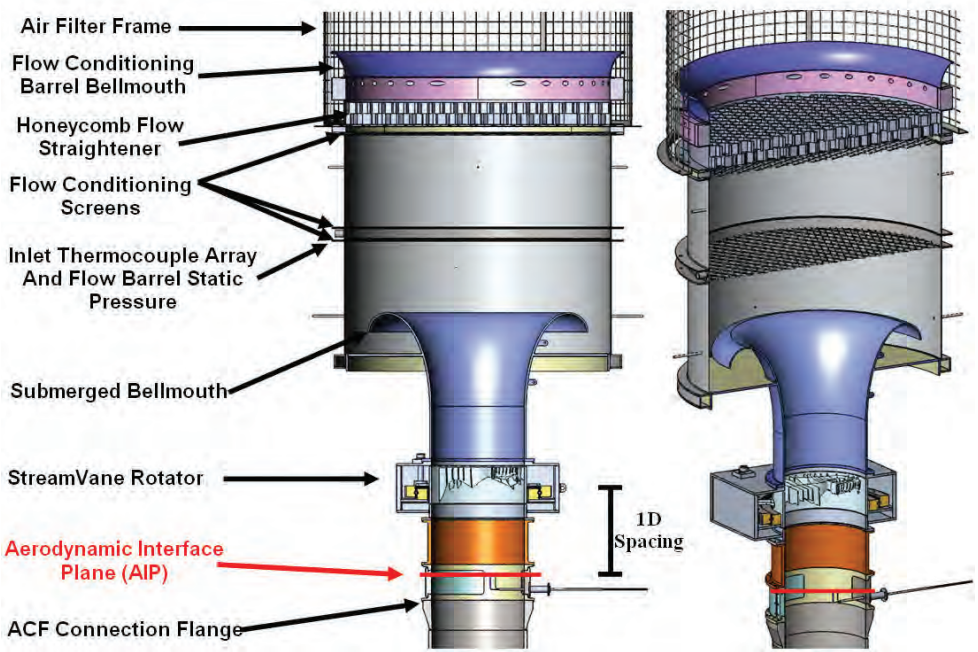

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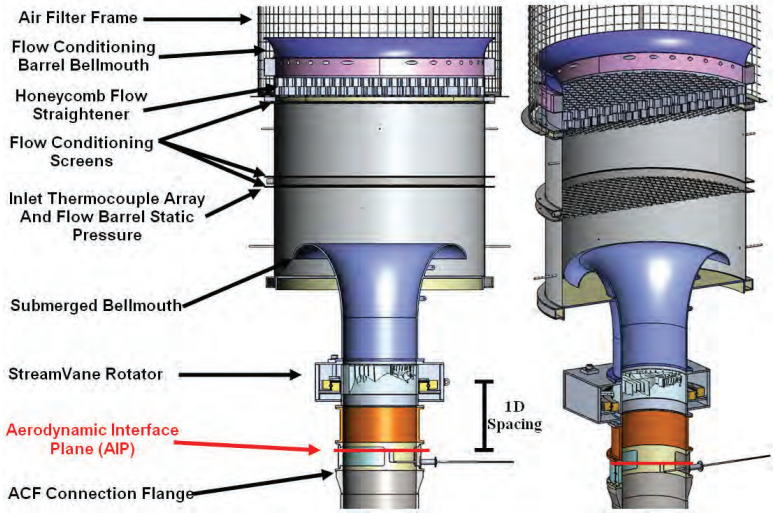
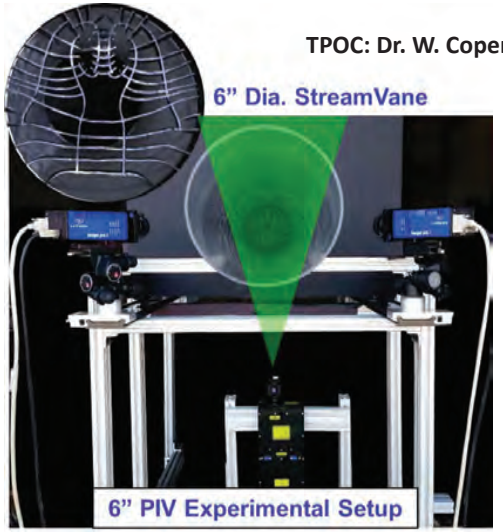
Challenges: Swirl Distortion Generators

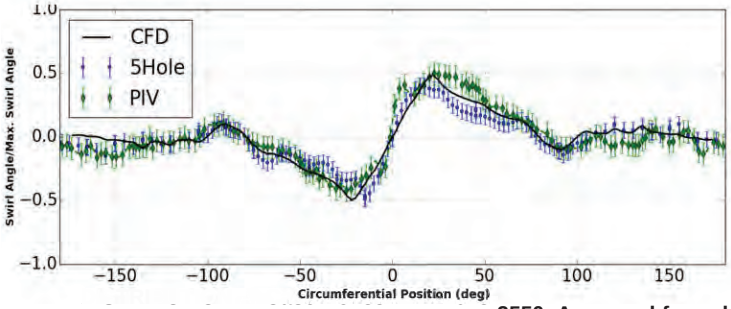
- AFRL Experimental Evaluation and Feedback to Virginia Tech

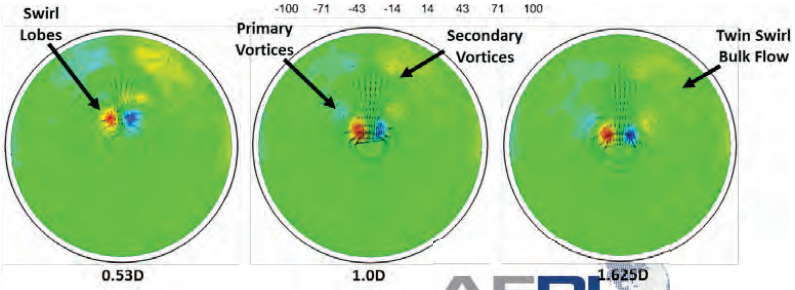


TPOC: Mr. C. Nessler



TPOC: Dr. W. Copenhaver



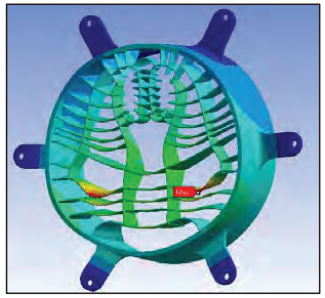


2550. Approved for public release: distribution unlimited

Challenges: Swirl Distortion Generators

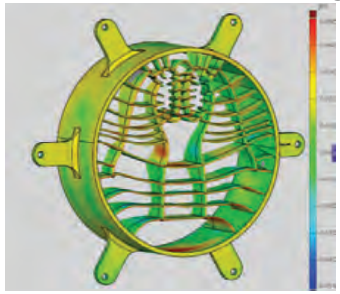
- AFRL Structural Evaluation and Feedback to Virginia Tech

CFD Surface Static Pressure Extracted and Used as Applied Load in FEA

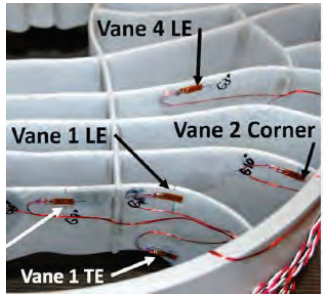


FEA Stress Prediction

RQTI/TEFF

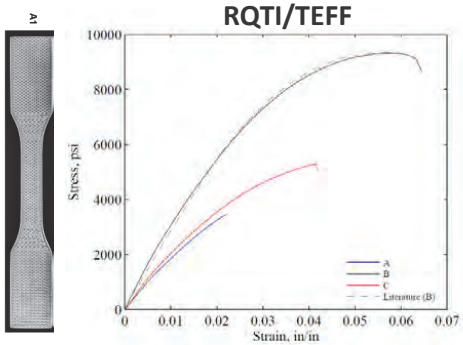


ATOS Scanned Geometry vs Design



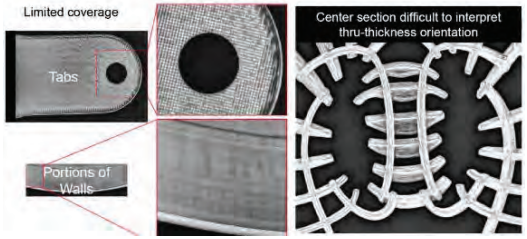
Strain Gage Test with Applied Aero Loading

RQTI/TEFF



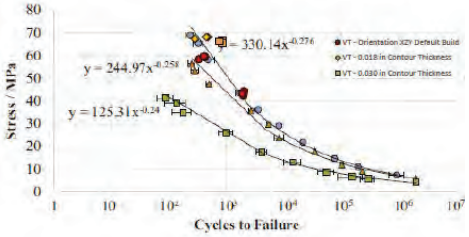
Quantified "As Built" Mechanical Properties

RX Collaboration



Computed Tomography (CT) Scan and X-Ray

Virginia Tech



Characterization of Fatigue Properties

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Summary

- Key Results
  - High fidelity inflow and outflow quantification
  - Over-the-rotor Kulite reconstruction of rotating stall and circumferential variations
  - Aeromechanic quantification of rotor, including NSMS

- Key Challenges
  - Controlling fan operating point with configuration change
  - Accurate identification of stall point
  - Data organization and processing for large, unsteady multi-variable datasets
  - Aeromechanic characterization

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Questions?

POC: Chase Nessler
Email: chase.nessler.1@us.af.mil

National Aeronautics and Space Administration

W8 Test Plans With StreamVanes

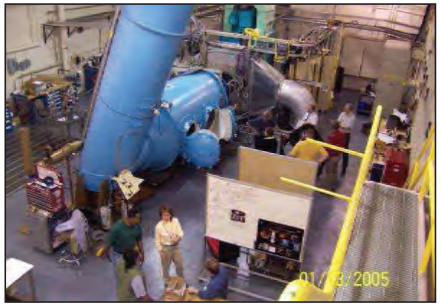
Julia Stephens

Chris Hughes

Mark Celestina

NASA Glenn Research Center

May 31, 2018



www.nasa.gov

Advanced Air Transport Technology

https://www1.grc.nasa.gov/aeronautics/bli/
NASA GRC, Dave Arend

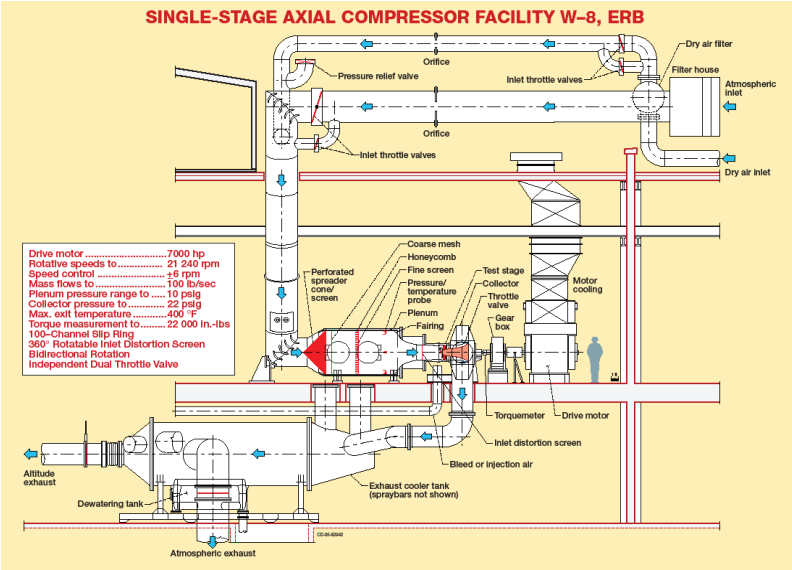
W8 Facility

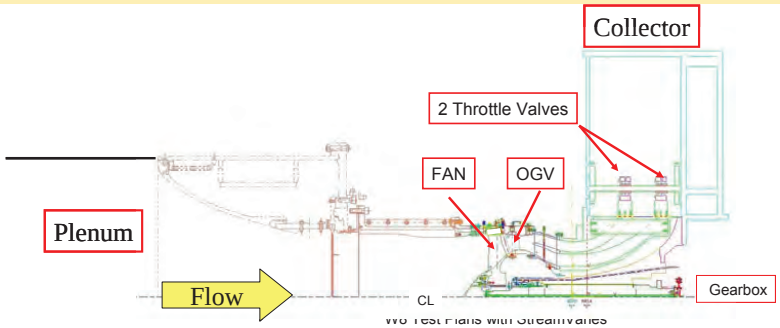
- A single axial stage facility designed to:
  - Acquire detailed data for model development as well as to validate CFD codes
  - Investigate innovative flow control strategies for improving and/or controlling compressor performance and operability
  - Study the effects of inlet distortion on fans
  - Investigate the aerodynamic performance and operability of fans and compressors

W8 Overview

Unique Capabilities

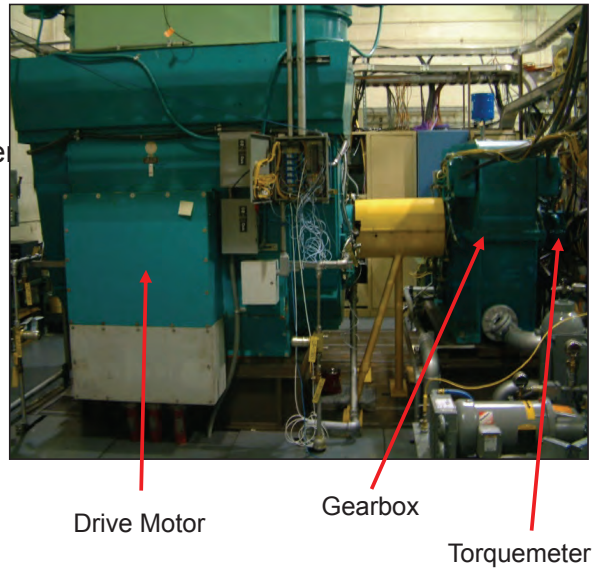
- Compatibility with both 20.2" and 22.0" dia. fans/compressors which provides compatibility with AFRL, NASA, and industry
- Bi-directional bearings which provides compatibility with 9x15 LSWT drive system as well as compatibility with industry rotation conventions.
- Common shaft attachment scheme with W-7 Multistage Facility & the 9X15 LSWT
- Inlet Bleed system - modifies inlet boundary layer thickness to simulate various inlet installations.





Drive System

- Electric Drive Motor
  - 7000hp,3600 rpm
  - Powered by the ERB Variable Frequency Syste
- Gear Box
  - 7000hp
  - 5.9:1 gear ratio
- Compressor Bearing Housing
  - Speed: 1,860 rpm to 20,300 rpm
  - Tilting pad journal bearings and thrust bearing
- In-line torquemeter rated for 22,000 in-lbs
- Separate lube modules for motor, gearbox, torquemeter, and compressor bearing housing.
- Slip ring installed on the high speed shaft of the gearbox.



Capabilities

- **W-8 Facility Capabilities**

Parameter	Operating value
Inlet air pressure	5-20 psia
Inlet air temperature	Ambient
Inlet airflow	100 lb/s max
Atmospheric exhaust	0.8 psid blowers
Altitude exhaust	26 in. Hg vacuum max
Rotor speed	20,600 rpm max
Rotor size	22 in. max
Drive motor	7,000 hp max

Inlet Characteristics

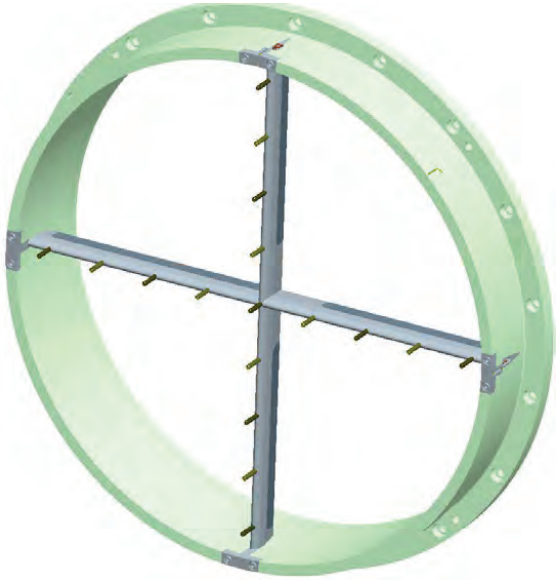
- 8 total Pressure

  Calibrated for total pressure recover

- 9 total temperature

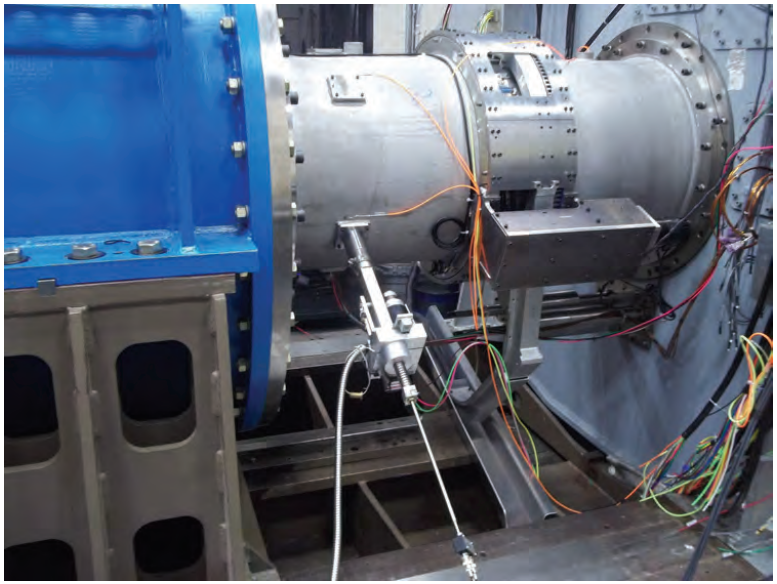
  Calibrated for total temperature recovery, density sensitivity, and angle sensitivity

- 8 static Pressures

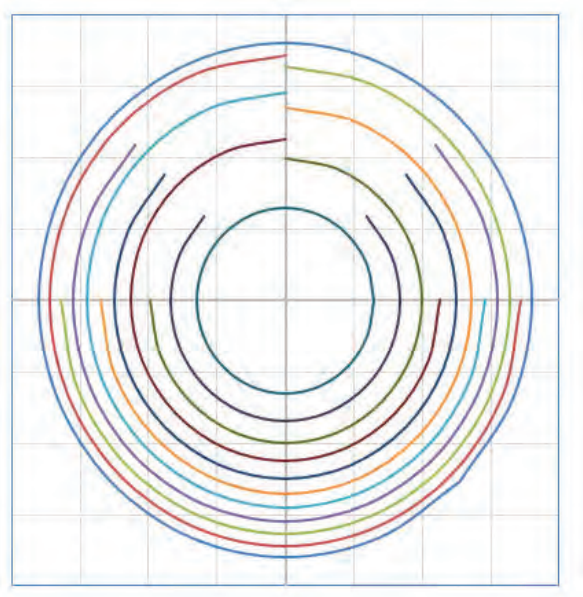


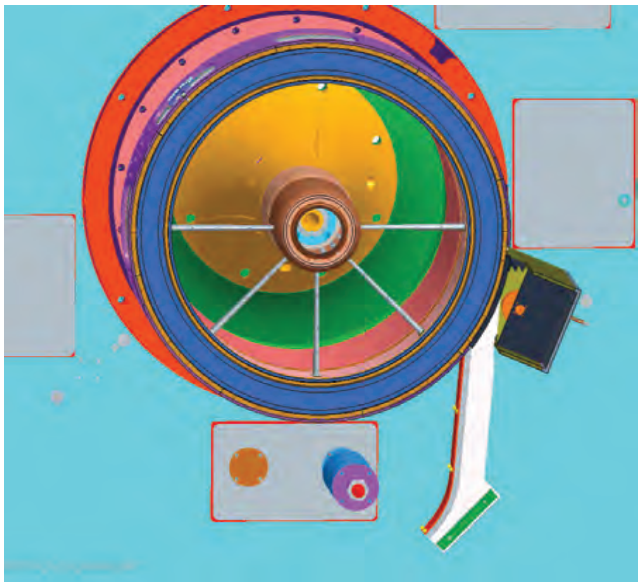
Characterize Baseline Facility

- Turbulence intensity has been shown to be < 1% at the fan entrance (Van Zante 2007, Bozak 2017)
- Desire to show circumferential uniformity
- Need to know at StreamVane Location upstream of fan



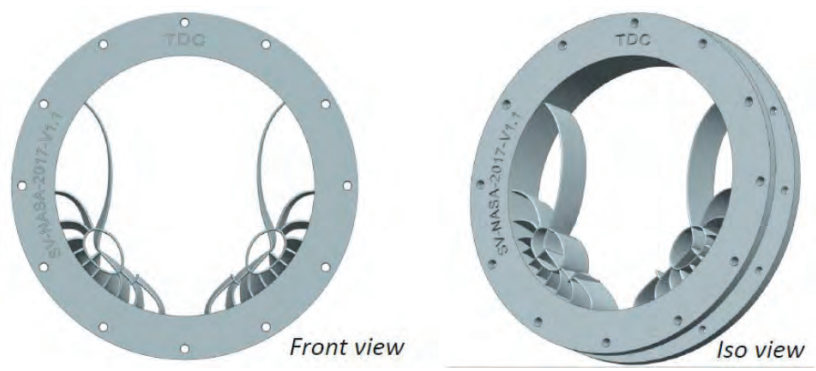
Empty Section Swirl



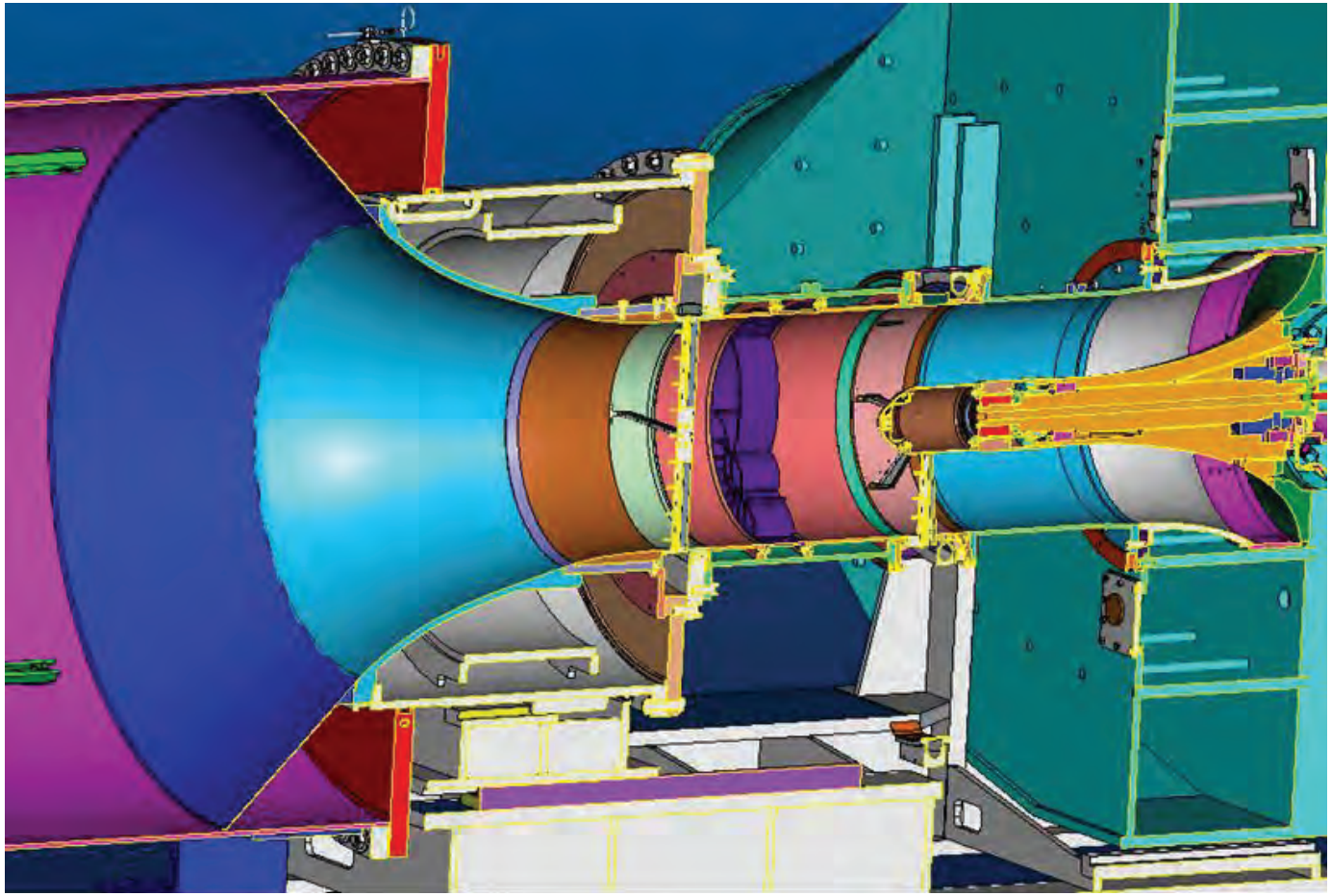


StreamVane™ Method (AIAA 2016-0534)

- Patented Virginia Tech Technology process
- Generates user defined swirl patterns from a 2-D vector field



- NASA is working with Virginia Tech University to develop StreamVanes for testing with 22” diameter fans
- Can be upgraded with screens to include total pressure distortion



National Aeronautics and Space Administration

W8 Test Plans with StreamVanes

Piping Upgrades

- Increase test section length to allow for entire fan system with upstream and downstream measurements
- Turbulence under 1%
- No swirl

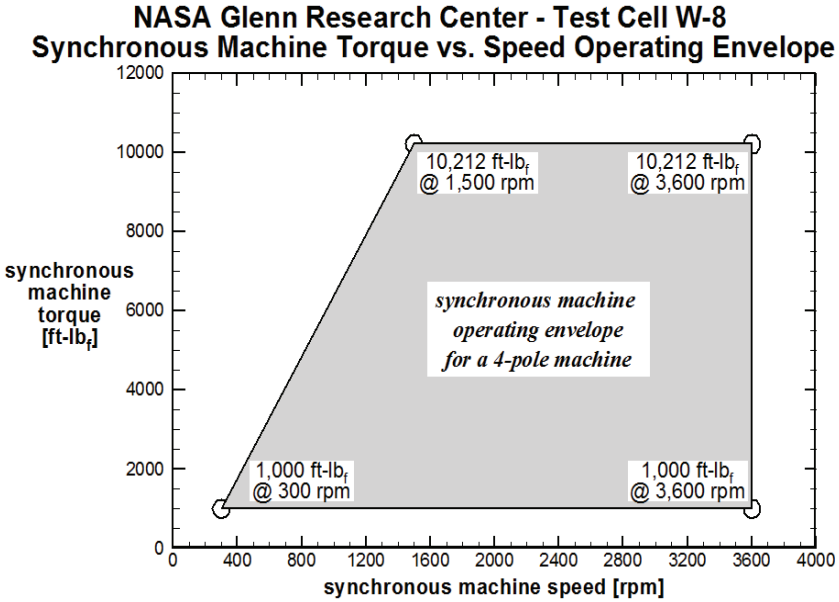
Driveline Upgrades

Fall 2018

- New Motor

FY 2019

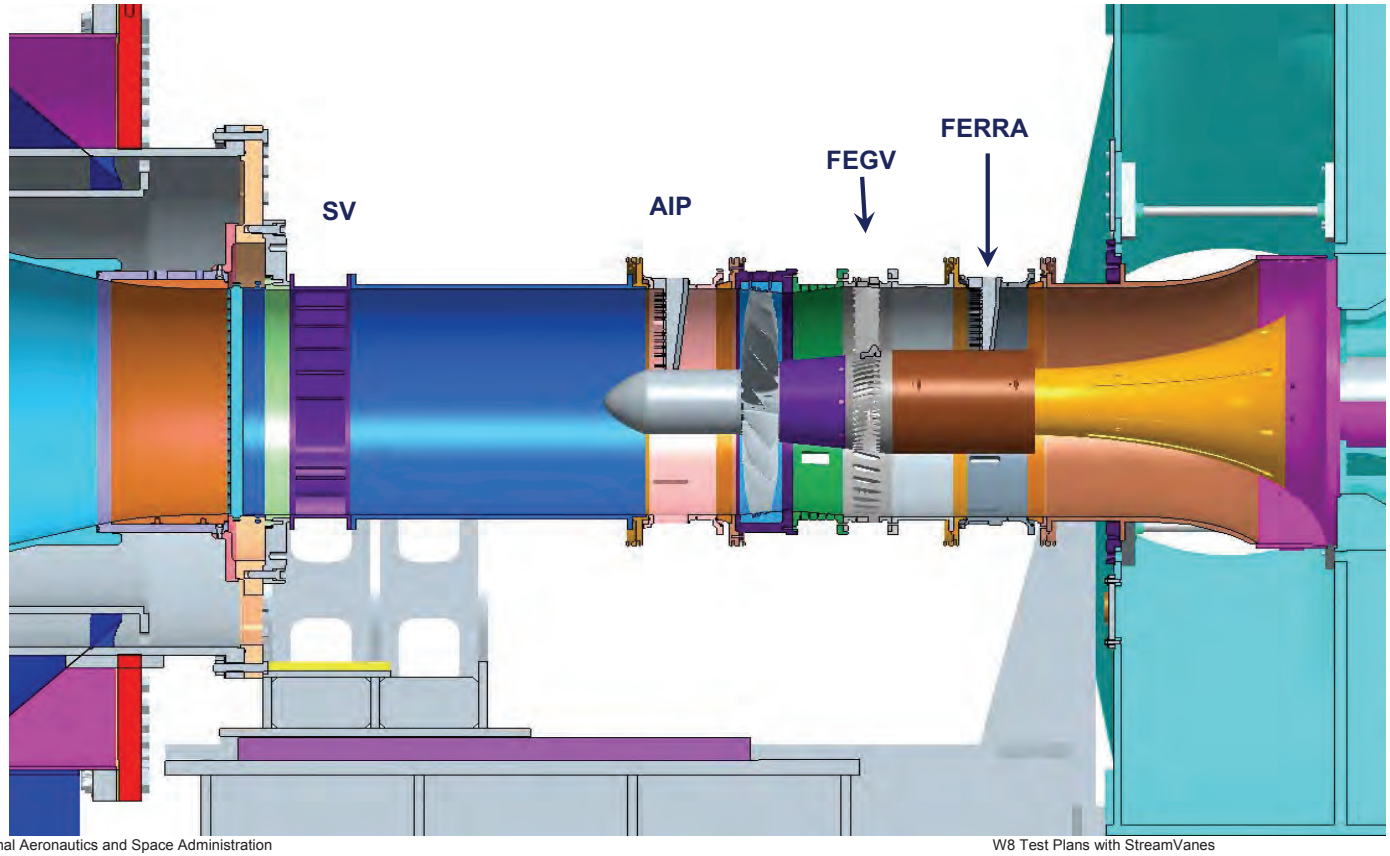
- New Shaft with Balance capability
- New Bearings



Data Upgrades

- Netscanner Pressure Measurement
- Cobra Data Acquisition
- New Shaft with balance capability
- Upgrade the on board data system and slip ring

Testing With the BLI Fan



National Aeronautics and Space Administration
NASA
Advanced Air Transport Technology Project
Acoustic Considerations for PAI
(formerly: Ultimate Performance for Podded Propulsors UP3)
Dr. Dale Van Zante, Senior Advisor for Propulsion
Acknowledgement to Dr. Russ Thomas and team
www.nasa.gov

The Premise:

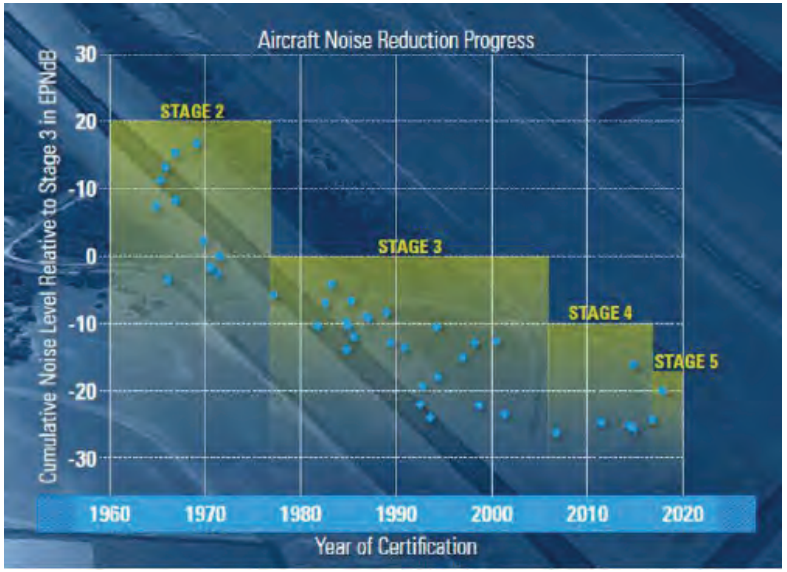
Noise is an aircraft system level issue.

> **The propulsion system noise is influenced by the local aerodynamic environment. (it's easy to make a quiet propulsor noisy with a bad installation)**
>
> **The presence of aircraft structures near the propulsion system will impact the noise produced and how it radiates to observers (you have to understand the aerodynamics first before you can understand the acoustics)**

Ergo, propulsion airframe integration will have significant influence on the acoustics of the final aircraft system design.

Background

- FAA current noise certification standards for airplanes certificated in the US (known as Stage 5) entered into effect in January 2018 and represents an increase in stringency of 7 EPNdB (cumulative) relative to Stage 4 levels.

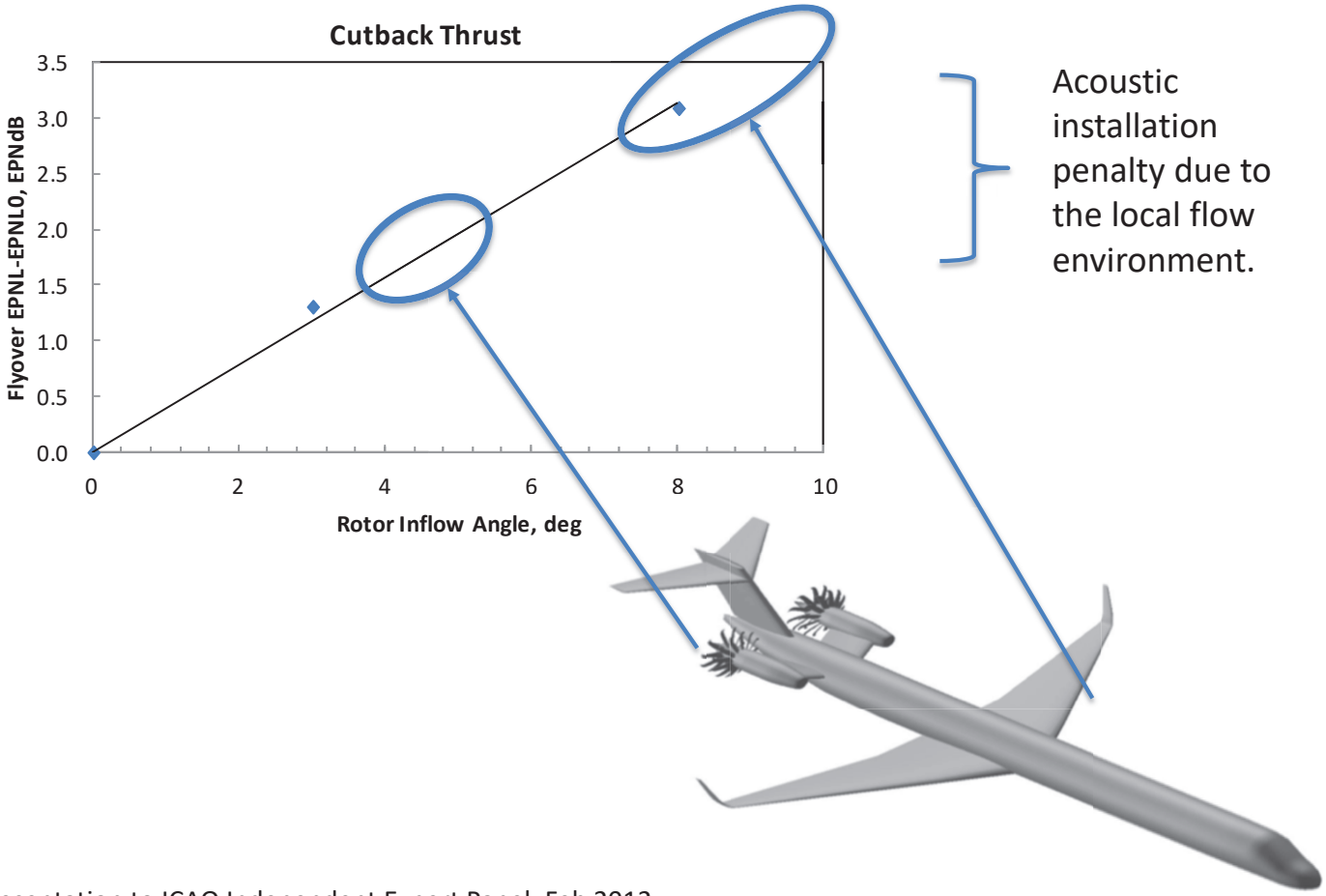


"Despite advances in noise reduction technologies, aviation noise is still the greatest constraint to capacity/growth at airports."

-- Sandy Lancaster, Environmental Program Manager at Dallas-Fort Worth International Airport, during the Acoustics Technical Working Group held at LaRC on April 10, 2018

- **By 2030 it is expected that regulations for noise will be much stricter than current Stage 5. At least 2 new stages for regulations might be expected.**

Example: PAI impact on noise for Open Rotors



Acoustic installation penalty due to the local flow environment.

Presentation to ICAO Independent Expert Panel, Feb 2012.

Engine noise source character

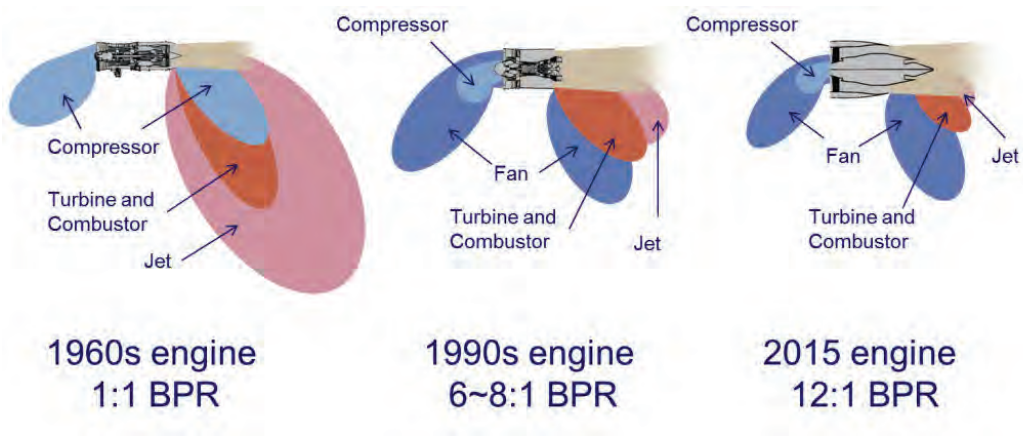


Image: Epstein, 2015

The configuration and cycle characteristics of the new engines will influence the effect of the propulsion system installation on total system noise.

Noise challenges with low FPR engine configurations

Slim/low drag nacelle
Short inlet – large diameter fan
Close rotor-OGV spacing
High PR core with lean-lean combustor

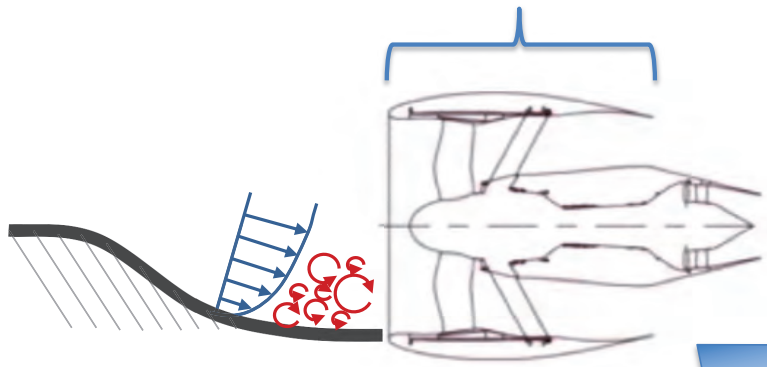
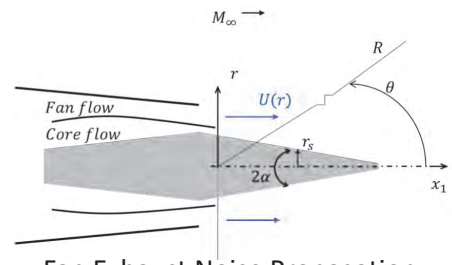


Image: Epstein, 2015



Fan Exhaust Noise Propagation

Distortion Induced Noise

Jet-Surface Interaction
Trailing Edge Noise

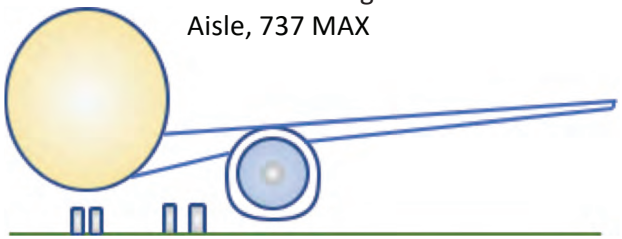
Low FPR engine configuration changes are beneficial, and necessary, for reducing fuel burn, however, but may be detrimental for noise. The inlet and outlet ‘boundary conditions’ for the engine will influence the overall system noise.

Potential Future Airframes:

What are the acoustics considerations of engine installation on these configurations?

Images: NASA

Installation effects: Reflection and Shielding

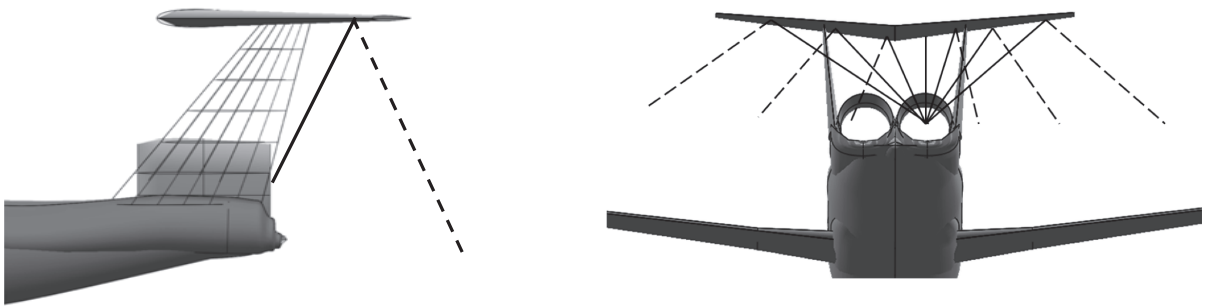


NASA Boeing PAA Chevron Nozzle in 2005

Large diameter engines must be ‘tucked in’ tighter to the wing underside leading to increased scrubbing noise and reflection.

Installation effects: Reflection and Shielding

The NASA D8 engine and tail configuration

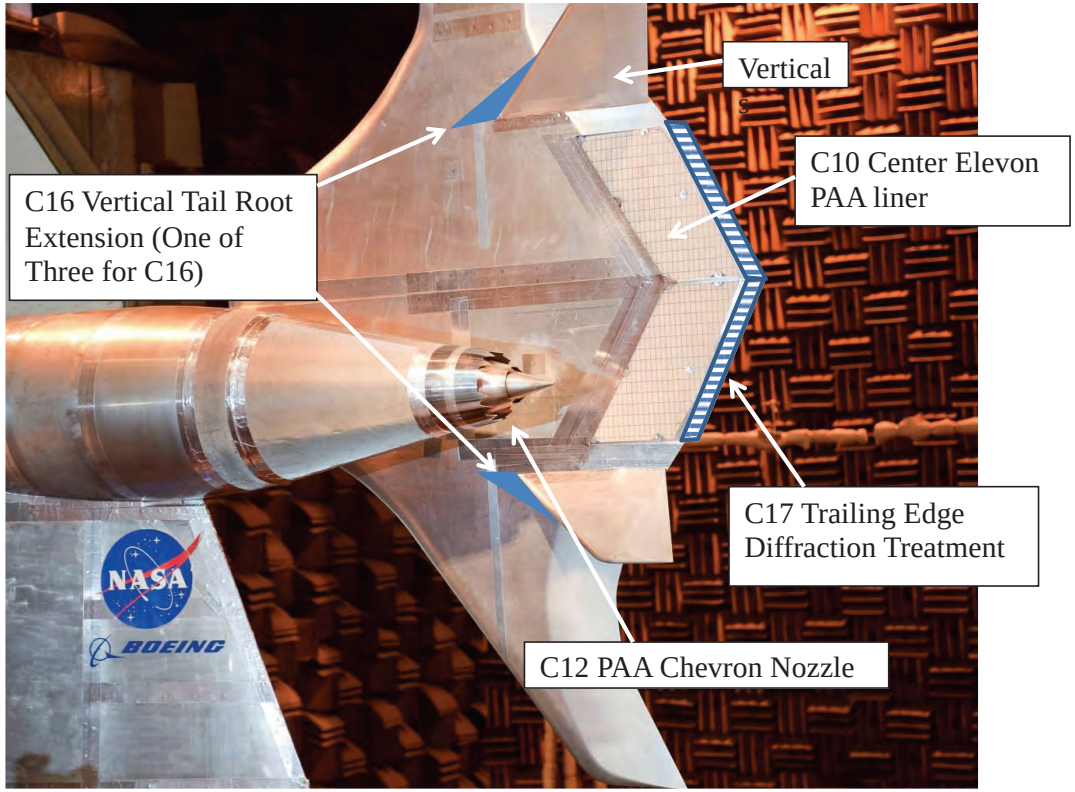


Accurate noise estimates for the D8 will require validated distortion induced propulsion noise models as well as trailing edge, reflection and shielding models.

From: Clark, I. A., Thomas, R. H., and Guo, Y., "Aircraft System Noise Assessment of the NASA D8 Subsonic Transport Concept," 24th AIAA/CEAS Aeroacoustics Conference, Atlanta, Georgia, 2018.

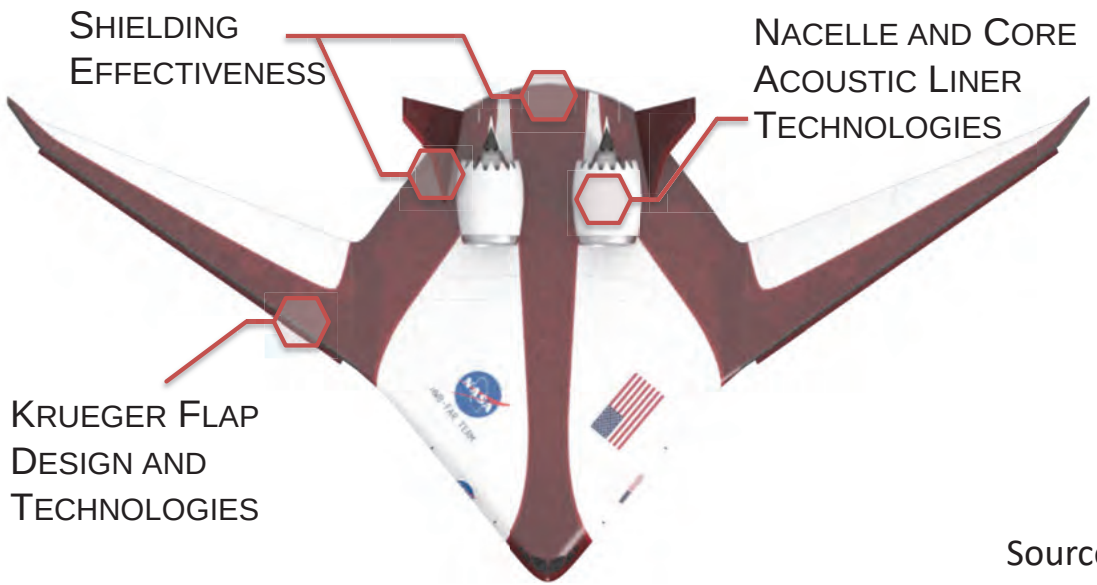
Non-traditional use of acoustic liners

NASA / Boeing Series of PAA Experiments 2004-2012
(image from AIAA-2013-0541)



Application of external liners might be possible for under wing mounted engines also.

What if noise regulations force a configuration change?



Source: NASA image
AIAA-2017-3193

An aircraft configuration change is necessary to achieve the long term NASA noise goal. Engine placement is one of the factors in producing ultra quiet configurations.

Summary

Noise regulations for future transport aircraft may require greater attention to the engine installation impact on the aircraft acoustic signature.

New engine cycles/configurations and aircraft configurations will require validation data to support accurate noise estimates in the design process:

For example:
distortion induced noise
surfaces near the propulsion system

Airframe and engine development have often progressed as parallel but separate activities. Going forward, PAI/PAA specific tests (with accurate propulsion simulation) may be necessary, therefore, test methods for airframes and propulsors must be harmonized.

Calibration of a Flow Angularity Probe With a Real-time Pressure Sensor

Brock Pleiman

Public Release #: 88ABW-2018-0663

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Table of Contents

- Background Instrumentation, New Probe Inspiration, Design and Goals
- Multi-hole Calibration Methodology Evolution
- Test Planning
- Data Acquisition
- Data Processing
- Conclusions
- Questions

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Background Instrumentation, New Probe Inspiration, Design and Goals

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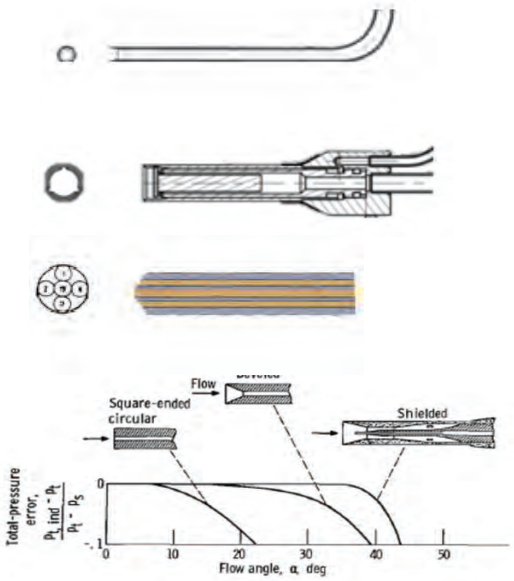
Background Instrumentation, New Probe Inspiration, Design and Goals

- Inlet pressure recovery serves as a top level performance indicator
  - Pressure recovery = $\frac{P_{T_2}}{P_{T_0}}$

Probe Design	Figure	Total Pressure	Total Pressure @ Angle	High Frequency Total Pressure	Angle of Flow
Pitot-Static	1	✓	✗	✗	✗
Co-axial	2	✓	✗	✓	✗
Multi-Hole	3	✓	✓	✗	✓
New Design		✓	✓	✓	✓

Multiple probe types required for total understanding of flow



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Inspiration for new probe design

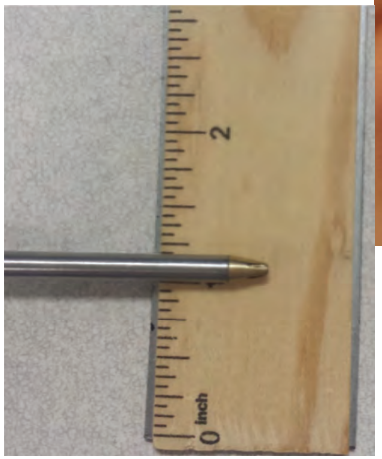
- Goals:
  - Similar accuracy as historical probe designs

$$\sigma(\alpha \,\&\, \beta) = \pm 1.1°$$

$$\sigma\left(P_0 \,\&P_{\{Static\}}\right) = \pm 0.035$$

$$\sigma(Mach) = \pm 0.05$$

  - Diameter smaller than 1/8”
  - Cheaper to manufacture/calibrate than combined recent co-axial and 5-hole manufacture/calibration costs



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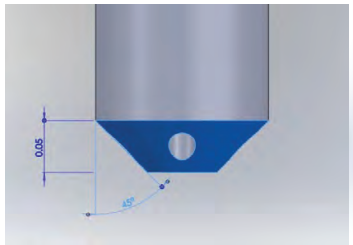
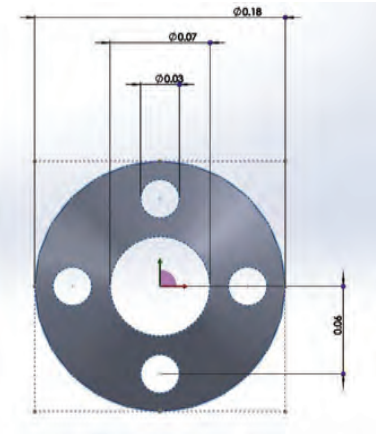
Probe Design

- **<u>Hole size discrepancy is not common for multi-hole probes</u>**
- 1 Kulite 0.055” diameter 25 PSIA sensor in center port
- Four 0.028” steady state ports
  - Located at 0º, 90º,180º and 270º
- 45 degree included angle
  - 35º-45º common for 5 hole probes
  - 45º was chosen for accuracy purposes

Section	Inner Diameter	Outer Diameter
Time-Dependent	0.058”	0.072”
Steady State	0.017”	0.028”
Total Probe	0.165”	0.180”





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Multi-hole Calibration Methodology Evolution

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Comparing Uncertainties

- Paul showed the how probe uncertainties change with calibration technique
  - Results show Paul's angle prediction was slightly better than Gallington's
  - Using Paul's change to include the center port pressure, Gallington's Coefficient of Mach was also updated

Pressure Normalization Techniques	Pitch Uncertainty [Degrees]	Yaw Uncertainty [Degrees]	Total Pressure Uncertainty [PSI]	Static Pressure Uncertainty [PSI]
Treaster & Yocum (1979)	±1.22	±2.07	±0.0003	±0.0001
Gallington (1980)	±0.40	±0.61	±0.0003	±0.0001
Pisasale & Ahmed (2002)	±3.05	±6.28	±0.0001	±0.0003
Paul (2011)	±0.38	±0.61	±0.0003	±0.0001

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Test Planning

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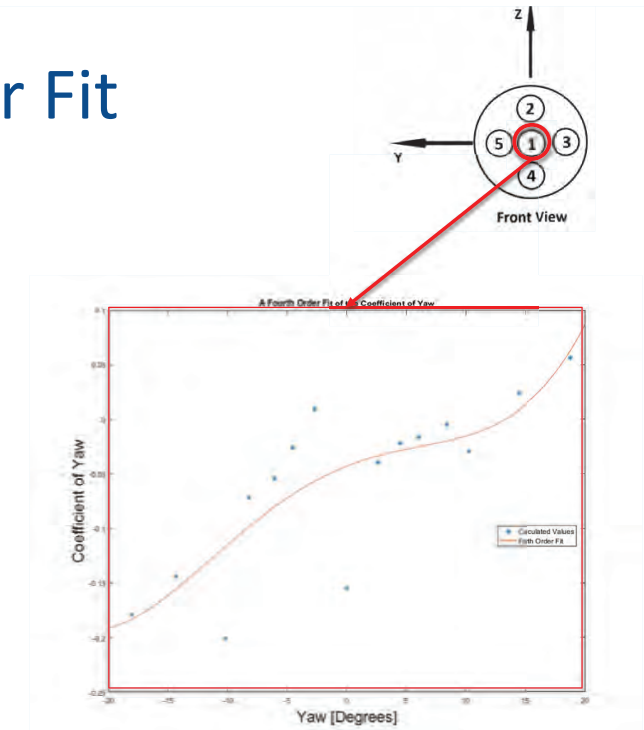
Fourth Order Fit

"Experience has shown that a fourth-order curve fit [from coefficient to actual value] is necessary to calibrate five-hole probes"

- 95% confidence interval requires 66 points in each zone
  - ≥ 330 for fourth order (66/zone)
  - ≥ 255 for third order (51/zone)
- 397 points per Mach number
  - 4th order fit for each Mach number
  - Allows for some calibration unpredictability
    - 54 in each zone worst case



Pitch angle	0°	2°	4°	6°	8°	10°	14°	18°	22°	26°	30°	34°	38°	42°
# roll angles	1	8	12	16	24	32	24	28	36	40	48	56	60	12

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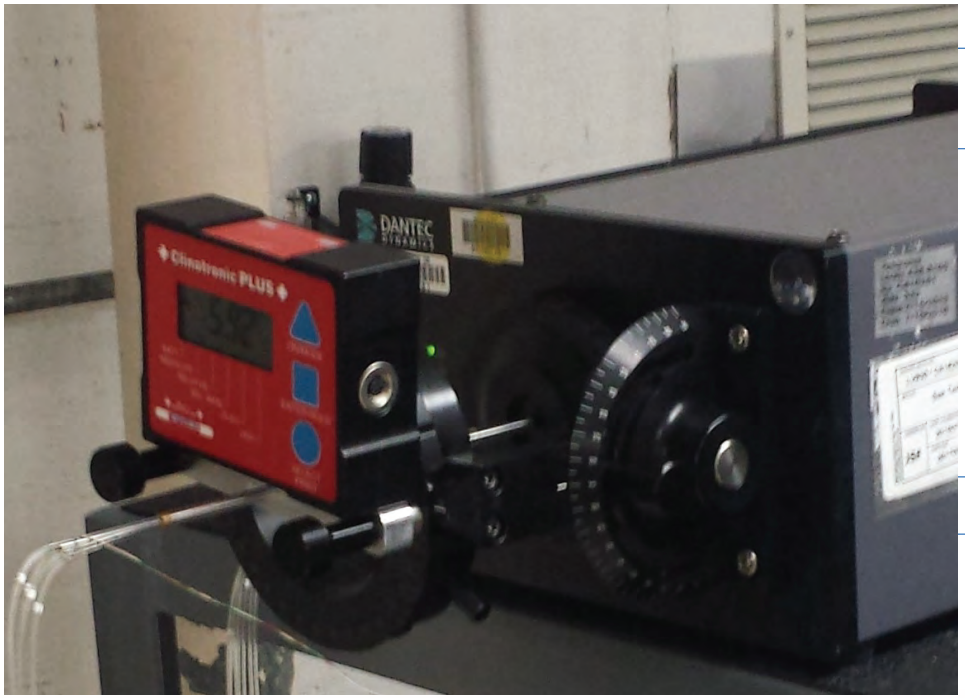
Experimental Set-up

- Multi-hole probe was calibrated in the hot wire calibrator jet
  - Probe was located where the hot wire would normally be placed



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Data Acquisition

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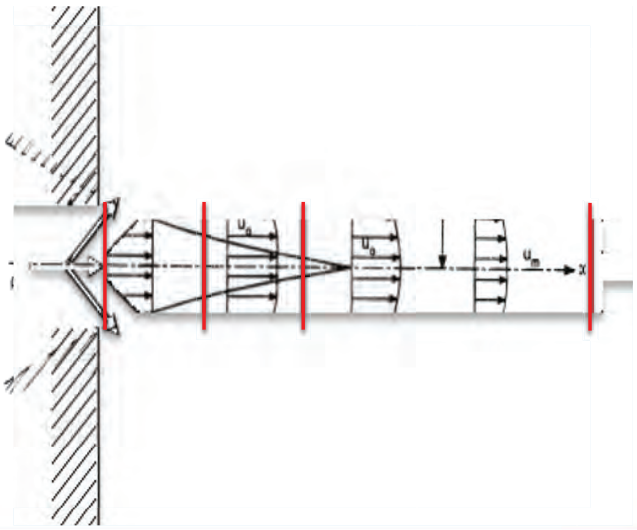
Time-Dependent Baseline Testing

- Performed to determine frequency amplitude and pressure loss of the free jet at:
  - Various downstream locations
  - Various sampling intervals
  - Various sampling rates



Sampling Rate [kHz]	Data Sampling Interval [Seconds]	X-Location	Mach Numbers
2	5, 10, 20, 60	1, 2, 3, 4	0.2, 0.31, 0.4, 0.5, 0.6, 0.7
15	1, 5, 10	1, 2, 3, 4	0.2, 0.31, 0.4, 0.5, 0.6, 0.7
75	1, 5, 10	1, 2, 3, 4	0.31, 0.7

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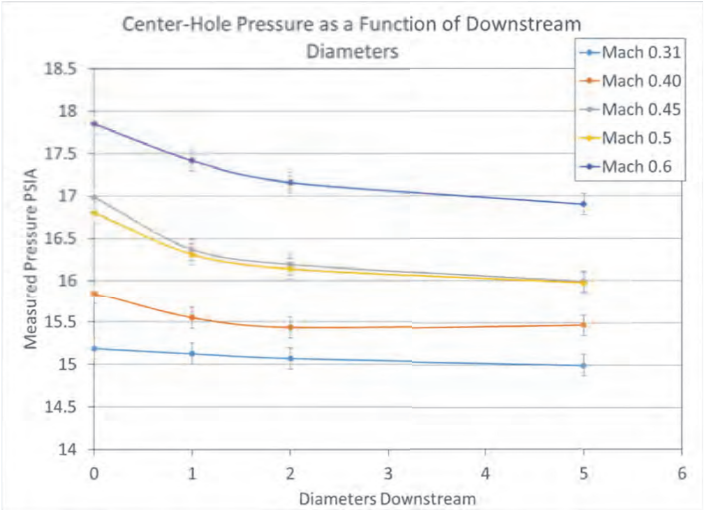
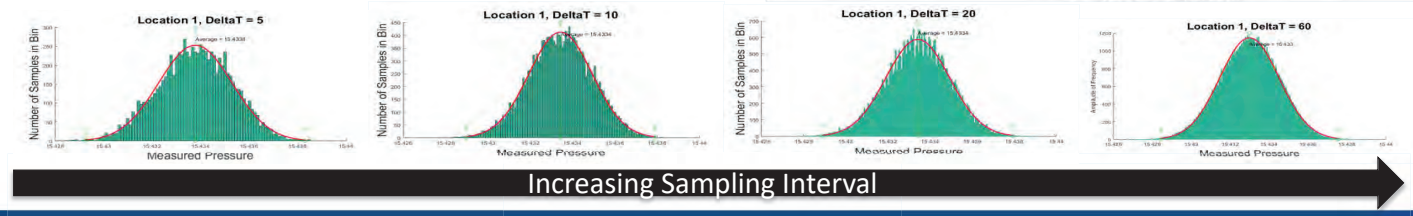
Dynamic Content Baseline Measurement

- The hot-wire calibrator outputs minimal high frequency output (<0.001)
- Pressure decreases with distance from jet orifice
- Gaussian distributions improve with increasing sampling interval





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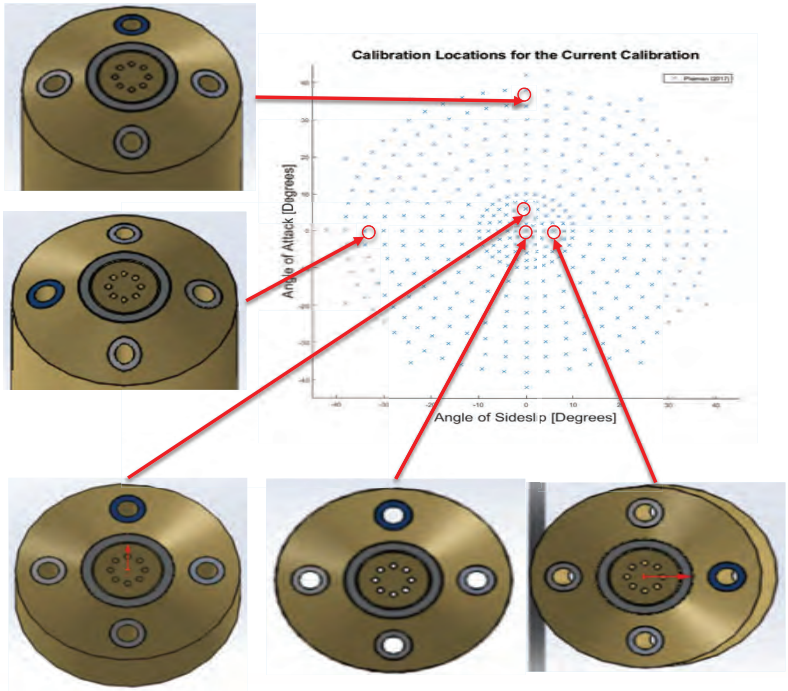
Calibration & Validation Acquisition

Calibration Acquisition

- Each calibration point set in order by:
  - Mach number
  - Roll
  - Alpha
- Each calibration point was sampled at:
  - Ports 2-5 collected 10 Hz average for 10 seconds (Steady State)
  - Port 1 collected at 15Khz for 5 seconds



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Goals of project

- Recall 3 primary goals of probe design
  - Similar accuracy as historical probe designs

$$\sigma(\alpha \,\&\, \beta) = \pm 1.1°$$
$$\sigma\left(P_0 \,\&P_{\{Static\}}\right) = \pm 0.035$$
$$\sigma(Mach) = \pm 0.05$$

  - Diameter smaller than 1/8”
  - Cheaper to manufacture/calibrate than combined recent co-axial and 5-hole manufacture/calibration costs

Data Processing

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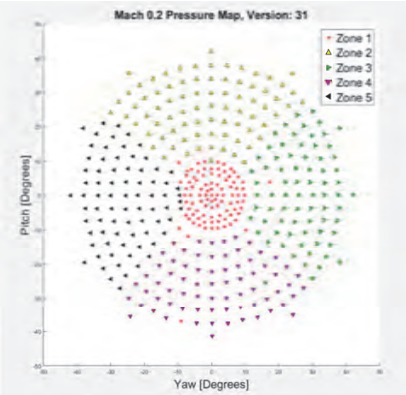
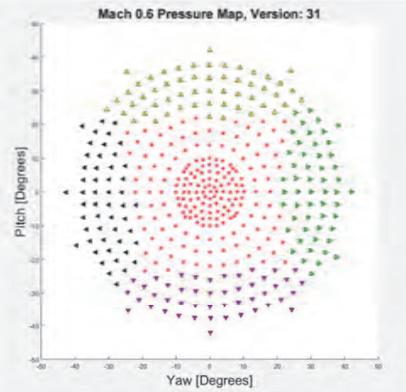
Zone Maps

- Zone determined largest measured pressure
- New design shows large increase in range of center port
  - 10° at Mach 0.2
  - 22° at Mach 0.6
- Increase requires additional calibration points in outer regions for future testing meaning >400 points per Mach number





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Standard Deviation is a function of Speed

Mach Number	Pitch (°)	Yaw (°)	P_0 (PSIA)	P_{static} (PSIA)	Mach Number
±0.2	±2.51	±2.03	±0.096	±0.052	±0.007
±0.31	±0.80	±0.86	±0.046	±0.027	±0.004
±0.45	±0.39	±0.44	±0.015	±0.012	±0.002
±0.5	±0.69	±0.54	±0.028	±0.021	±0.006
±0.6	±0.20	±0.15	±0.028	±0.115	±0.110

- Generally as speed increases, the uncertainty decreases
  - Exceptions at Mach 0.5 & 0.6, where flow quality is questionable
- Results show that lower limit to capabilities may be between Mach 0.2 to 0.31
  - Future testing will be used to verify limits

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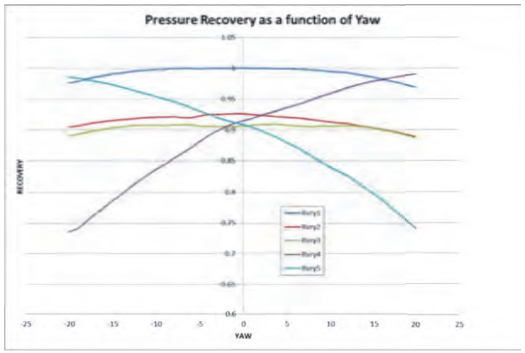
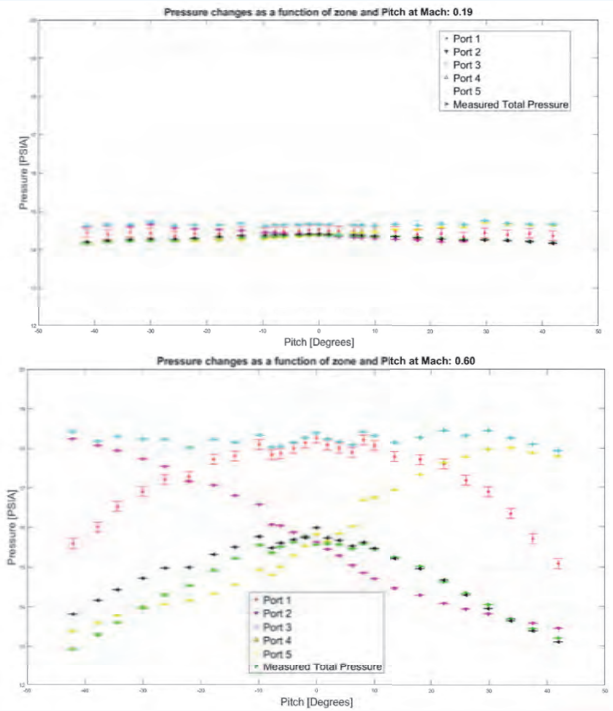
Accuracy Limitations Due to Pressure Differential

- Increase standard deviations due to pressure differences between ports
  - Difference between highest pressure port and lowest varies by 2 PSIA

Mach Number	ΔP (PSIA)
0.2	0.5
0.31	1
0.45	1.25
0.5	1.5
0.6	2.5



Pressure Recovery as function of Yaw from a previous 5-hole probe calibration



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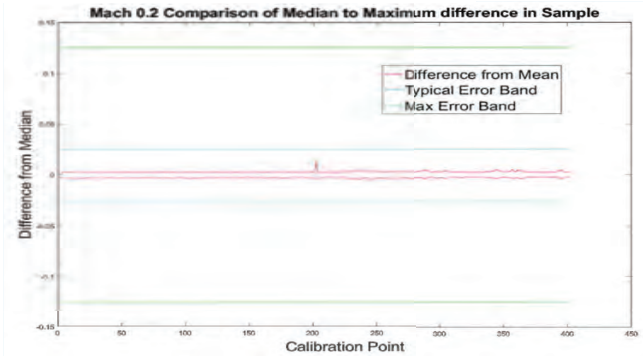
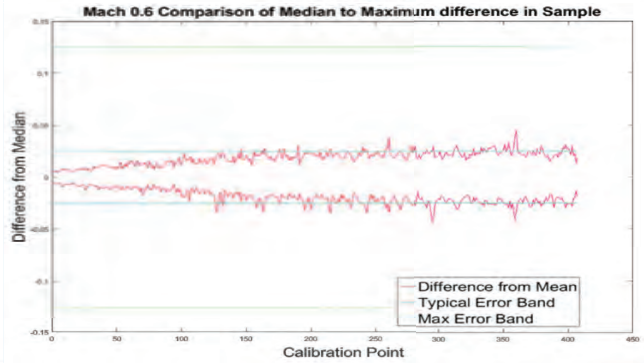
Time-dependent Pressure Fluctuations

- Desired to know flow aligned high frequency total pressure at non-zero angles
  - Original plan: calibrate the fluctuations about mean of center probe and add them to calculated total pressure
    - Assumption: Roll should not increase pressure fluctuation amplitude
      - Due to symmetry
  - However, FFT amplitude was not consistent with changes in roll

Time-dependent Pressure Fluctuations

- Plotted pressure fluctuation RMS as a function of calibration point
  - Should be step function
- Relationship existed between time-dependent pressure RMS increase
  - Relationship generally depends on:
    - Mach number
    - Alpha
    - Beta
    - Isentropic total pressure





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Conclusions

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Conclusions

- Testing shows that large scale testing of new probe design is warranted
  - Steady-state calibration results show general agreement with historical/recent data
  - RMS calibration results show general trend; however, 2 sigma deviations in pressure are less than steady state uncertainty
- AFRL is looking for potential test processes on how to dynamically calibrate high frequency pressure response for comparisons between historical instrumentation and new design

Acknowledgements & Questions

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Propulsion-Airframe Integration Flight Test Instrumentation

Stephen Cumming
Hyun Dae Kim, presenting
NASA Armstrong Fight Research Center

Propulsion-Airframe Integration Technical Interchange Meeting
May 30 & 31, 2018

Outline

- Introduction
- Current Capabilities
  - On- and off-surface flow measurements
  - On- and off-surface flow visualization
  - Thrust estimation
- Capabilities in Development
- Needed Capabilities
- Concluding Thoughts

Introduction

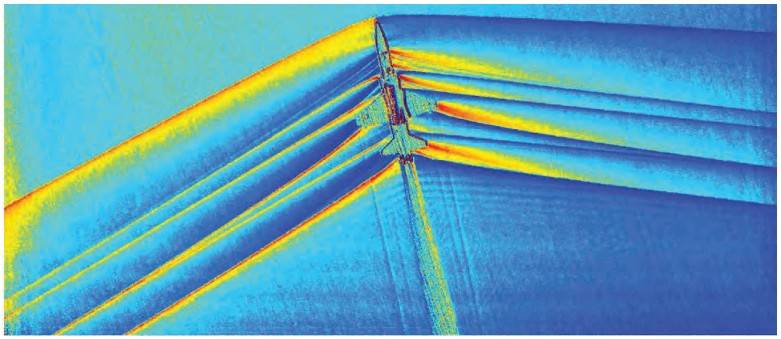
- This presentation focuses on flight test instrumentation for flow measurements applicable to PAI
  - Since internal engine instrumentation is not substantially different for in-flight measurements, this area isn't covered in detail
  - There are some technologies for strain measurement, e.g. Fiber Optic Strain Sensing (FOSS), that have applications for PAI, but they are not covered in detail
  - Not intended to cover everything currently used in the flight test environment
- Current and potential future measurement technologies at NASA Armstrong Flight Research Center are discussed

NASA Armstrong Flight Research Center

- Mission: Advancing technology and science through flight
- Vision: To fly what others only imagine
- 70+ years of flight test and flight research history and experience
- Located on Edwards Air Force Base
- Some of the aircraft tested and flown at AFRC:
  - X-15
  - F-8 Digital Fly-By-Wire
  - F-8 Supercritical Wing
  - HL-10 Lifting Body
  - X-29
  - X-31
  - F-18 HARV
  - F-16XL
  - X-43A
  - SOFIA
  - X-56

Aerodynamics and Propulsion Branch

- Competencies include:
  - Aerodynamics
  - Propulsion and Performance
  - Flow Physics
  - Aerospace Meteorology
- Responsibilities include both research and airworthiness support

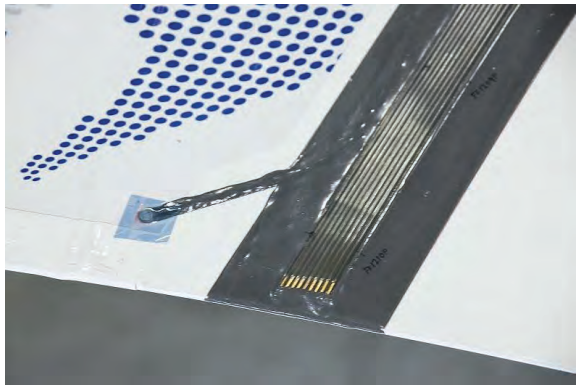


Current Capabilities

- A wide variety of flight test instrumentation exists to characterize the flow in and around a propulsion system
- Capabilities exist to provide flow measurements on and off of surfaces and to provide flow visualization on and off surfaces
- Techniques exist to estimate as-installed thrust during flight

On-Surface Flow Measurements

- Electronic Scanned Pressure Sensors
  - Are used to measure a large number of relatively steady pressures
  - Generally installed via drilled ports or surface-mounted strip-a-tube
  - Due to tubing, difficult to use for dynamic pressure environments
  - Requires temperature control of measurement unit for reasonable accuracy in-flight



- Absolute pressure sensors
  - Are used to measure absolute pressure at a single location
  - Variety of form factors and sizes provide options for drilled ports or surface mounting
  - Wide range of potential response rates
  - Temperature sensitivity can be problematic in-flight

On-Surface Flow Measurements

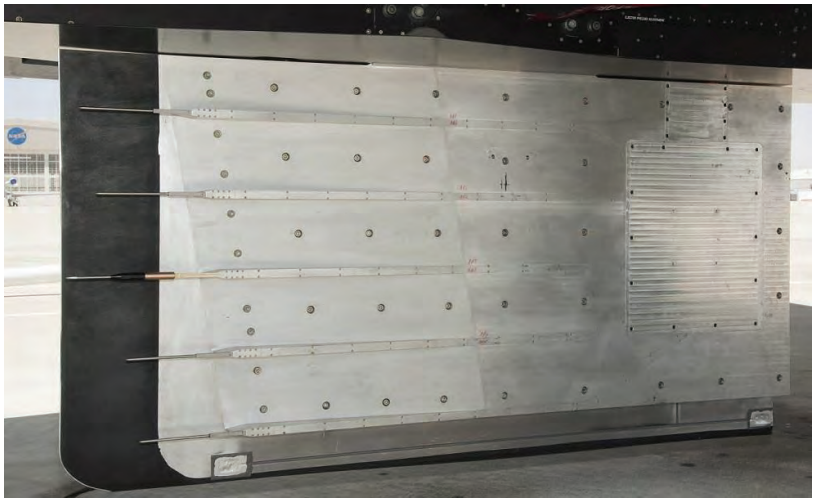
- Differential pressure sensors/microphones
  - Are used to measure differential pressure at a single location
  - Variety of form factors and sizes provide options for drilled ports or surface mounting
  - Wide range of potential response rates
  - Some temperature sensitivity, but not as large a concern as for absolute sensors
  - Location of reference pressure measurement is critical to understanding the results
- Thermocouples
  - Provide a surface temperature when mounted on a surface
  - Established technology, but it can be difficult to install such that the air temperature at the surface is measured instead of the structural temperature

Off-Surface Flow Measurements

- Flow rakes
  - Are used to provide off-surface flow properties for a variety of geometries, including pressure, temperature, flow velocity and direction (calibration required for flow velocity and direction)
  - Can be designed to provide steady or dynamic measurements
  - Hardware must be designed for flight environment
  - Calibration often needed
  - Measured flow is affected (to various degrees) by the rake itself

Off-Surface Flow Measurements

- Multi-hole probes
  - Are used to provide pressure, flow velocity and direction, and sometimes temperature at a specific off-surface location
  - A large variety exist, ready to purchase off-the-shelf
  - Calibration is required
  - Measured flow is affected (to various degrees) by the probe itself



Inlet Rake

- Typically used for new design long inlets to characterize inlet flow characteristics. Industry standard is a 40 probe rake (8 rakes with 5 probes each)

- total pressure distortion (transient and steady state)
- acoustic phenomenon (inlet buzz)
- flow angularity
- average total recovery (P2ave/P0)
- stall margin
- thermal distortion
- Inlet mass flow
- vibration
- shock wake determination

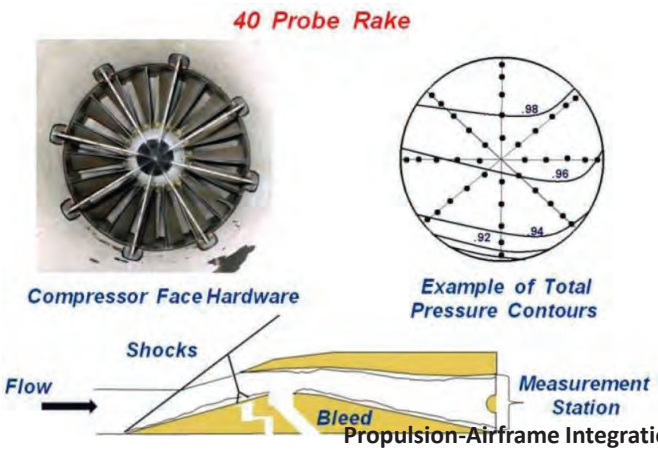
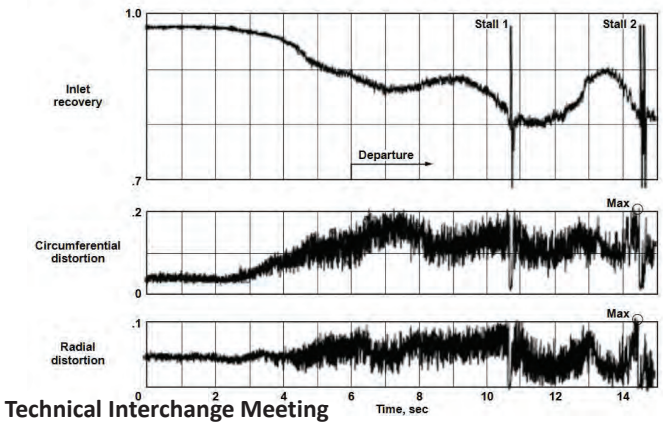


Figure 3. Measured time histories of inlet and engine entry descriptors for airflow quality and performance for a stall event.



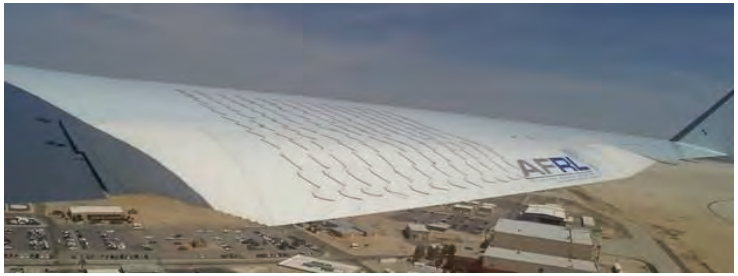
On-Surface Flow Visualization

- Oil Flow/Liquid crystal
  - Can identify flow direction, transition, shock locations
  - Minimal recent use
  - Techniques are messy and material can be hazardous

- Sublimation chemicals/ Emitted dyes or glycol
  - Can identify turbulence and separated flow
  - Minimal recent use
  - Only one test point per flight
  - Techniques are messy

On-Surface Flow Visualization

- Tufts
  - Can identify flow direction and separated flow
  - Easy and cheap to install
  - Careful consideration of installation required to avoid influencing the flow
  - Variety of types of materials used
    (flow cones, parachute cord, wool yarn, etc.)



- Infrared imaging
  - Can be used to detect laminar, transition, and turbulent flow and shocks
  - Most easily used at supersonic flight conditions
  - Requires temperature difference
  - Requires specialized viewing system

Off-Surface Flow Visualization

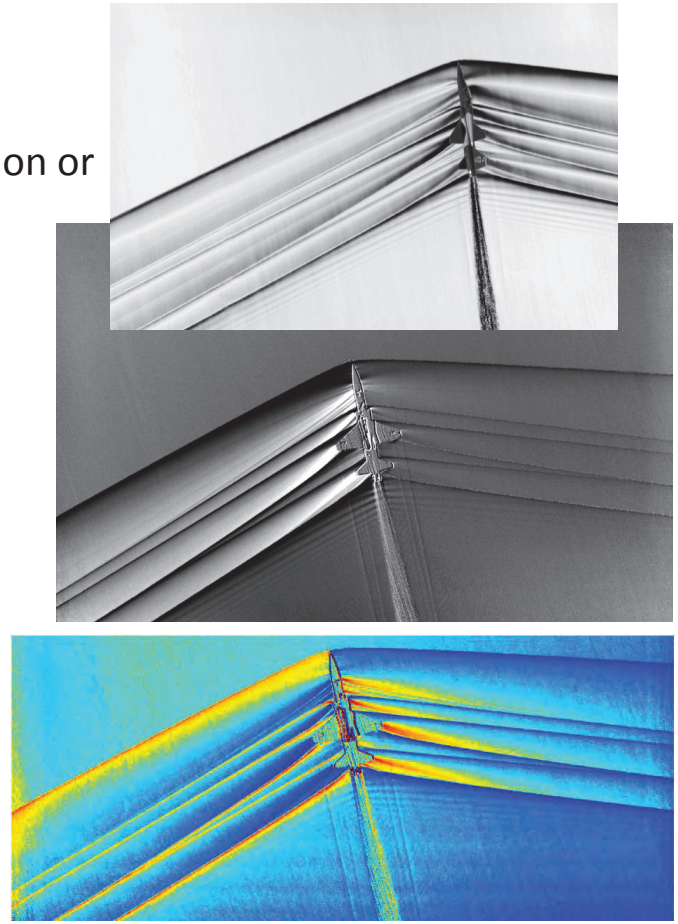
- Smoke
  - Can be used to visualize vortical flow, separated flow, and streamlines
  - Minimal recent use
  - Requires substantial modifications to aircraft to use
  - Substantial fire hazard

- Natural Condensation
  - Can be used to visualize vortical flow, shocks, shear layer instabilities
  - Minimal recent use
  - No modifications required to aircraft, but not reliable and difficult to repeat

- Schlieren
  - Can be used to visualize density changes from shock structures from supersonic shocks, subsonic and supersonic vortices
  - Two methods currently used for flight: AirBOS and BOSCO

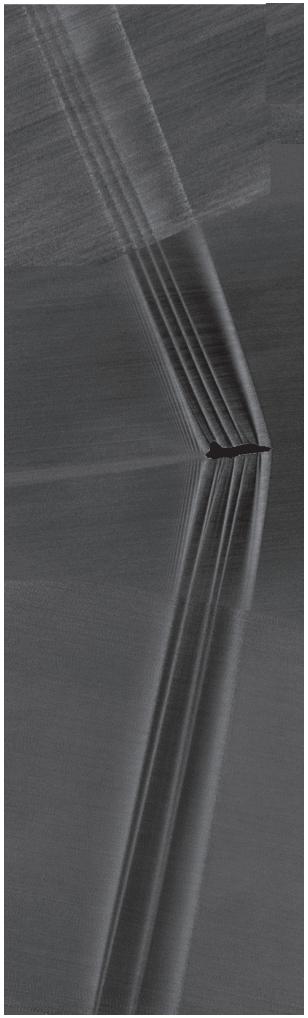
AirBOS

- Airborne Background Oriented Schlieren
  - Downward looking at desert vegetation or ocean speckles
  - Wide field of view, very detailed
  - Currently using KingAir to look down on target
  - Imaged F-18, F-15, and T-38
  - Only T-38 releasable currently



BOSCO

- Background Oriented Schlieren using Celestial Objects
  - Ground based (upward) or air-to-air (side view) looking at Sun/Moon
  - 0.5 deg field of view
  - Working toward air-to-air capability



Thrust Estimation

- Extremely difficult to directly measure thrust
  - Previous efforts involved strain gauges on thrust links or string pots that require installed thrust stand run to calibrate
- Engine model is used in conjunction with instrumentation and other information from engine to estimate thrust
  - **Bill of Material engine sensors:** N1, N2, fuel flow, pressures, temperatures, nozzle area, guide vane positions
  - **Engine/Airframe communication**: All buss communication between engine and airframe
  - **Performance testing requirements**: Flight test quality fuel flow, fuel sample lab testing for all flights
- Technique is highly reliant on accurate modeling
  - Generic models can have errors as large as 20%
  - OEM models are an improvement (errors as small as 2%), but uncertainties due instrumentation and fuel are still present

Capabilities in Development

- Low-profile conformal pressure sensors
- Low-profile conformal shock and transition detection sensors
- Carbon-based heating layer for laminar/turbulent flow visualization
- Pressure sensitive paint (PSP) for in-flight use
- Wireless sensor and instrumentation sensor technologies

Needed Capabilities

- Improved off-surface flow measurements and visualization
  - In-flight Particle image velocimetry (PIV) has been targeted for future efforts, but currently unfunded
- Improved flight-capable pressure sensors
  - Less intrusive, less temperature dependence, cost effective
- Less intrusive sensors and visualization techniques
- Improved engine modeling for flight test

Concluding Thoughts

- Current flight test instrumentation capabilities have been adequate for conventional aircraft configurations but have limitations, including potential for affecting flow
- New and improved instrumentation may be needed to properly evaluate future configurations
- NASA AFRC is continually looking for opportunities to take new flight test instrumentation to flight

Questions?

Thanks:
Mark Davis
James Faber
Mike Frederick
Daniel Jones