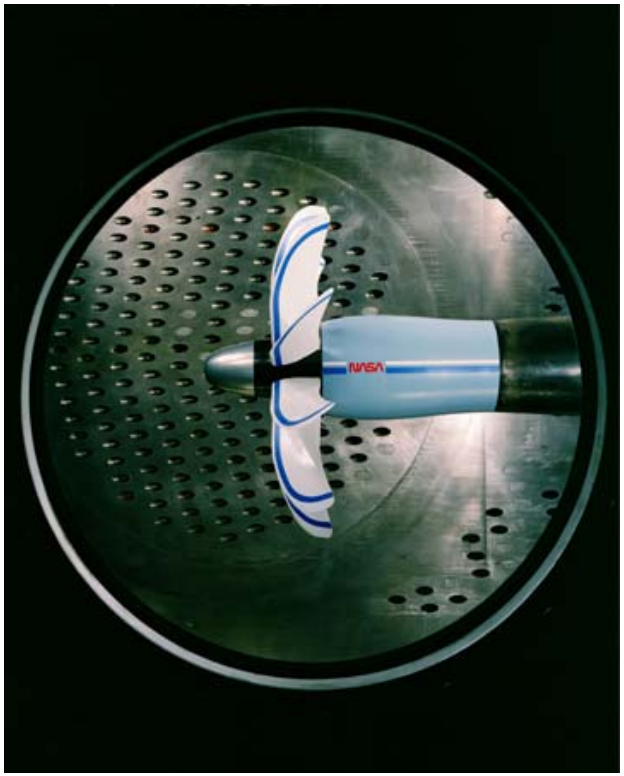
Previous Open Rotor Research in the US

Previous Open Rotor noise experience in the United States, current Open Rotor noise research in the United States and current NASA prediction methods activities were presented at a European Union (EU) X-Noise seminar. The invited attendees from EU industries, research establishments and universities discussed prospects for reducing Open Rotor noise and reviewed all technology programs, past and present, dedicated to Open Rotor engine concepts. This workshop was particularly timely because the Committee on Aviation Environmental Protection (CAEP) plans to involve Independent Experts in late 2011 in assessing the noise of future low-carbon technologies including the open rotor.

Previous Open Rotor Noise Research in the US

Dr. Dale Van Zante
Project Engineer for Propulsion
Environmentally Responsible Aviation
Integrated Systems Research Program



X-Noise Workshop, Lausanne, Switzerland
March 18, 2011

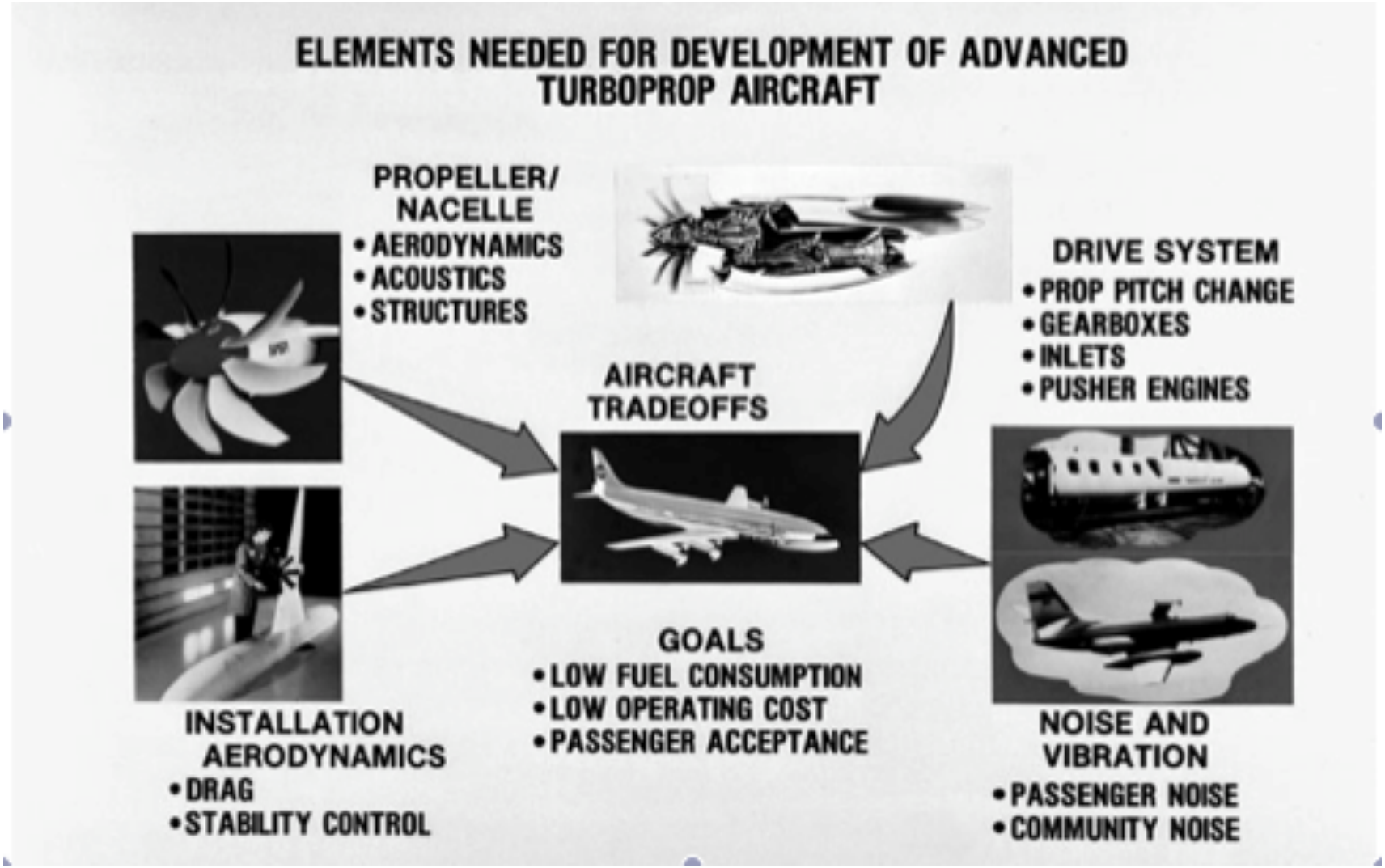
Outline

NASA Advanced Turboprop Program (1975 – 1989)

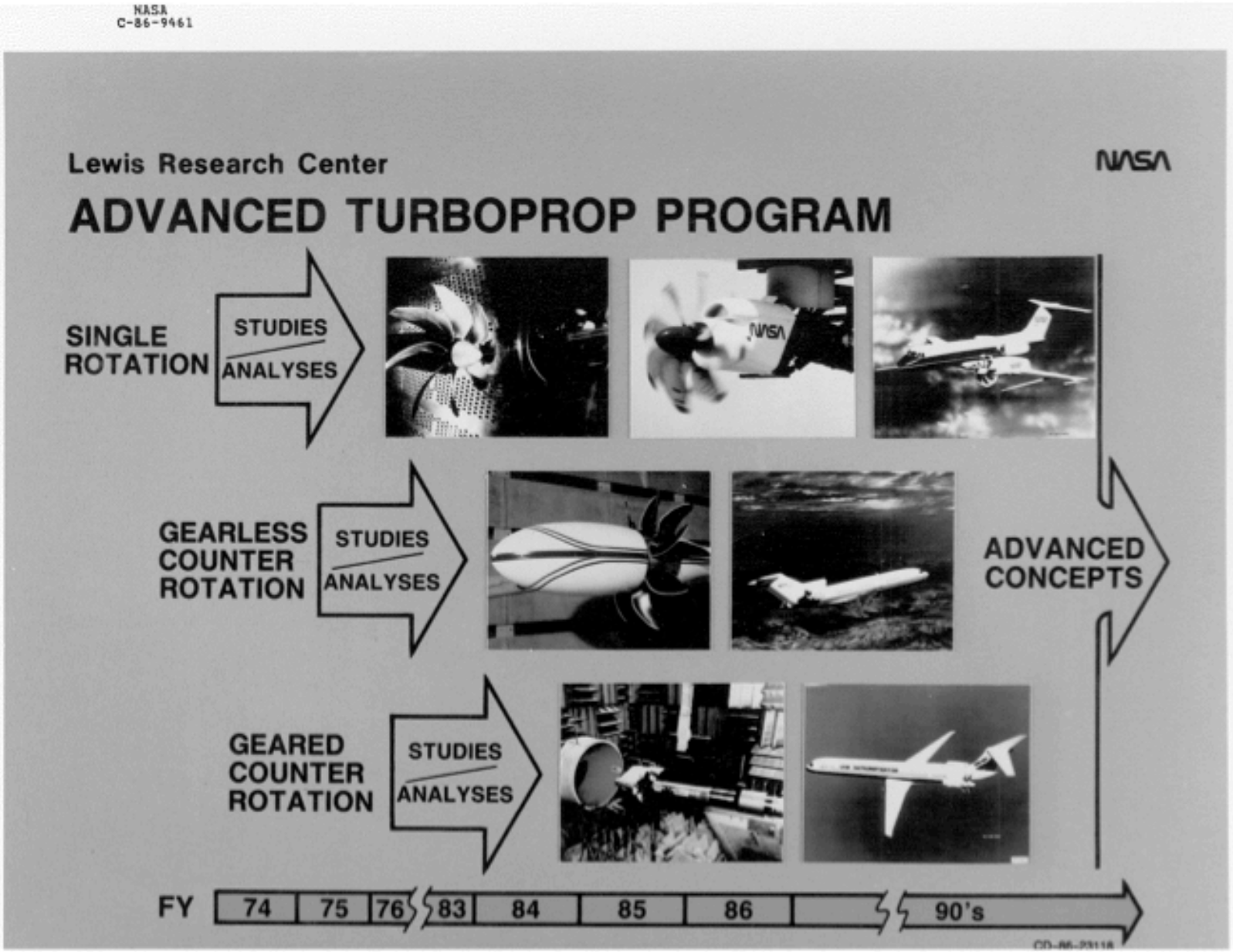
- **Overview/Objectives**
- **Wind tunnel tests**
- **Ground tests**
- **Flight tests**
- **Results**

Objectives

- **Reduce Fuel Consumption**
- **Lower Operating Cost**
- **Passenger Acceptance**



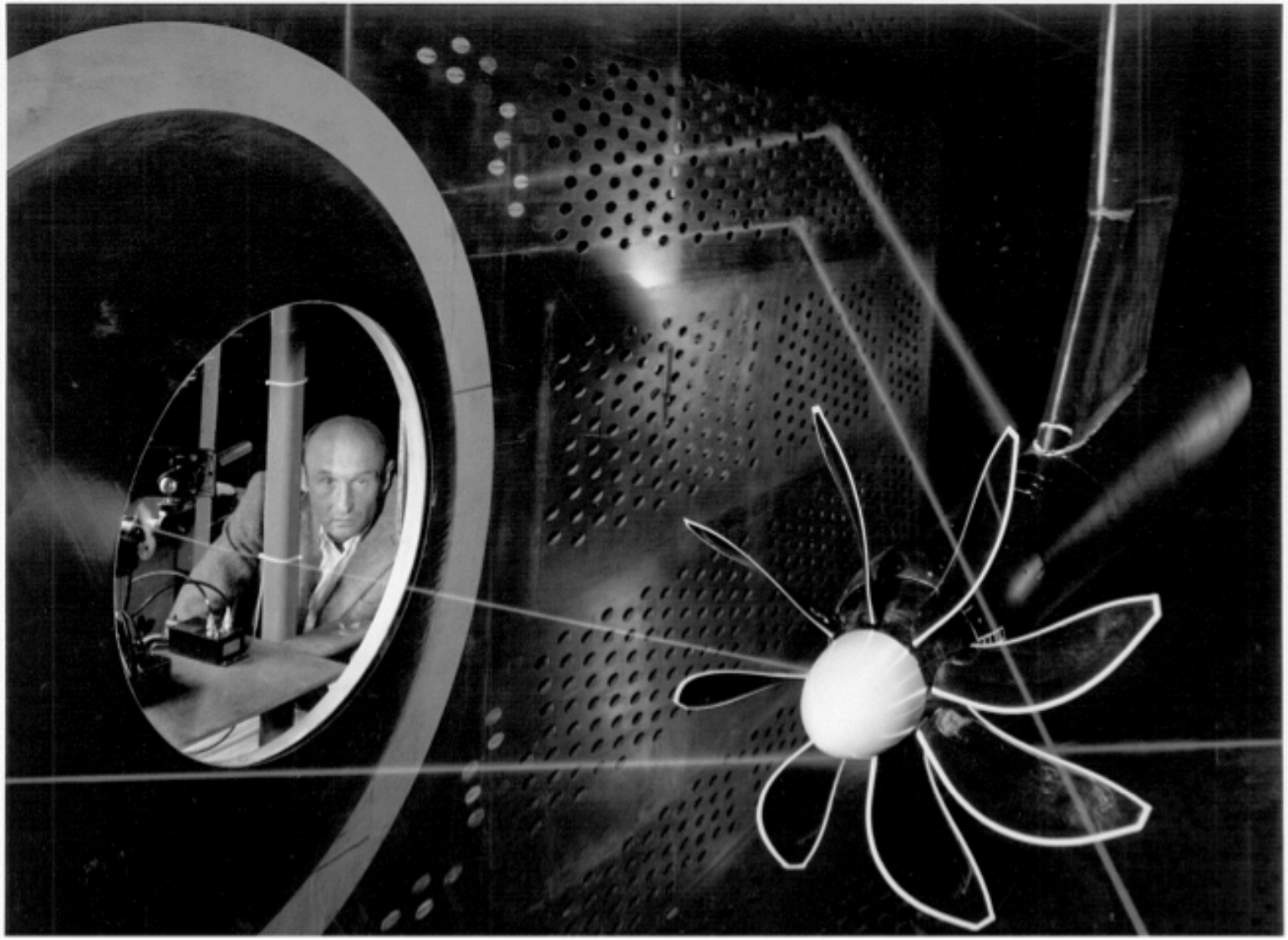
Single Rotation and Counter Rotation Propfans



Low Speed Wind Tunnel tests

High Speed Wind Tunnel tests

One of the first applications of Laser Doppler Velocimetry (LDV) and blade deflection measurement methods



Verified Scalability

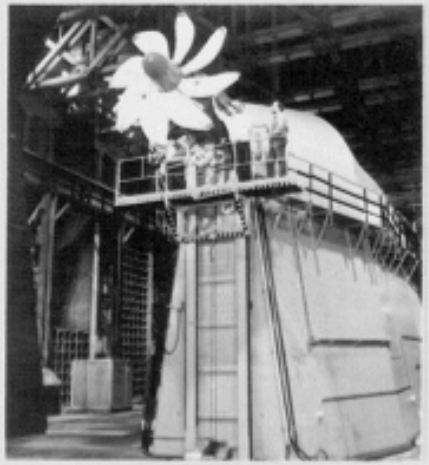
Ground and Integrated system tests

NASA C-86-8426

NASA ATP LeRC

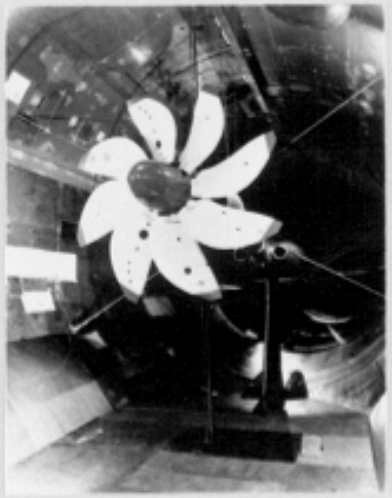
FY86 SIGNIFICANT ACCOMPLISHMENTS—LARGE-SCALE SYSTEMS

LARGE-SCALE PROPFAN RIG AND PTA AIRPLANE MODEL TESTING ACCOMPLISHED TO VERIFY PERFORMANCE PRIOR TO FLIGHT TEST



STATIC TEST AT WPAFB

- FIRST LARGE-SCALE PROPFAN TEST
- ACCEPTABLE BLADE STRESSES
- NO STALL FLUTTER
- STALL BUFFET REGION DEFINED



MODANE HIGH-SPEED TUNNEL TEST

- TESTED LARGE-SCALE 8-, 4-, AND 2-WAY BLADE CONFIGS. AT TUNNEL SPEEDS UP TO MACH 0.83
- ACCEPTABLE BLADE STRESSES
- NO CLASSICAL FLUTTER

PTA MODEL TESTING

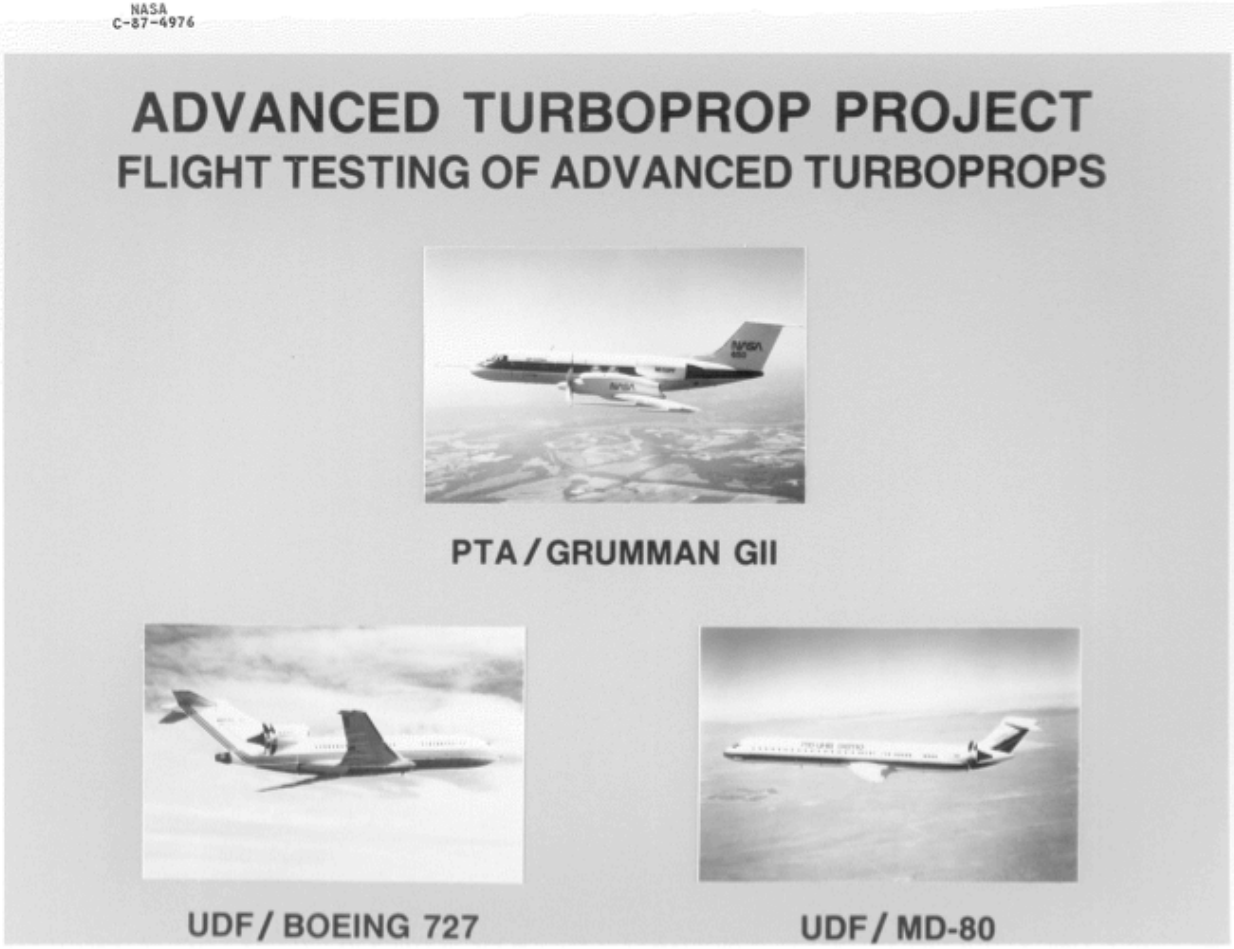
- COMPLETED HIGH- & LOW-SPEED TESTING IN LaRC TUNNELS
- CONFIRMED PREDICTED PTA S&C/HANDLING
- VERIFIED PTA CAPABILITY TO FLY TO MACH 0.8/35,000 FT. PROPFAN DESIGN POINT
- CONFIRMED HIGH-SPEED BUFFET BOUNDARY IS OUTSIDE PTA FLIGHT ENVELOPE
- VERIFIED ANALYTICAL FLOW PREDICTION

CD-86-22505

Flight tests

Major Contracts

- **General Electric – UnDucted Fan (UDF)**
- **Hamilton Standard – Large Scale Advanced Propfan (LAP)**
- **Lockheed Georgia – Propfan Test Assessment (PTA)**



Results

Overall Conclusions

- **Fuel consumption can be reduced by 25 - 30% compared to equivalent technology turbofans.**
- **Depending on fuel prices, the operating cost can be reduced by 7 - 15%.**
- **Community noise levels can meet Stage 3 requirements.**

Technology Development

- **High speed propeller design, test methods and data bases.**
- **Aerodynamic and acoustic prediction codes (first application of advanced CFD).**
- **Aeroelastic analyses including blade coupling, composite blades.**
- **Advanced measurement methods.**

Suggested Reading (includes comprehensive bibliography, available from NASA report server):

Hager, R.D. and Vrabel, D., "Advanced Turboprop Project", NASA SP-495, 1988.

National Aeronautics and Space Administration

Open Rotor Noise Research in the US

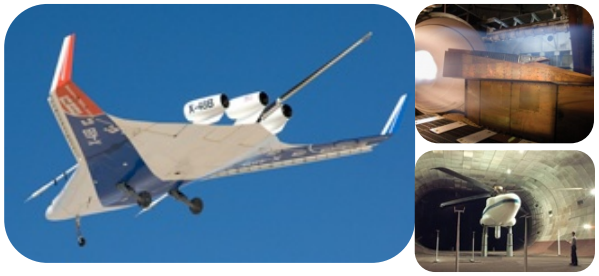
Dr. Dale Van Zante
Project Engineer for Propulsion
Environmentally Responsible Aviation
Integrated Systems Research Program

X-Noise Workshop, Lausanne, Switzerland
March 18, 2011

Outline

- NASA Aeronautics Research Mission Directorate (ARMD)
- Open Rotor Research at NASA
  - NASA/GE collaboration
  - Rig and facility details
  - Low speed isolated/installed data
  - Detailed aero/acoustic measurements
  - Acoustic shielding
  - Propulsion/Airframe aeroacoustics
- FAA Continuous Lower Energy, Emissions and Noise (CLEEN) Program
- FAA/CLEEN Open Rotor Research

NASA Aeronautics Portfolio in FY2010

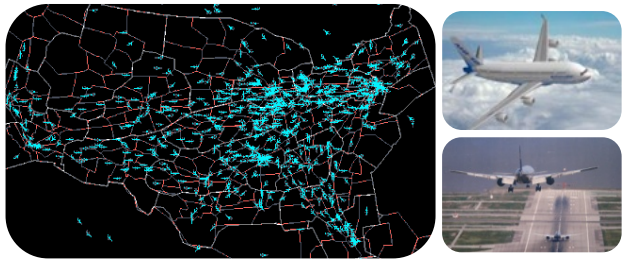


Fundamental Aeronautics Program

Conduct cutting-edge research that will produce innovative concepts, tools, and technologies to enable revolutionary changes for vehicles that fly in all speed regimes.

Integrated Systems Research Program

Conduct research at an integrated system-level on promising concepts and technologies and explore/assess/demonstrate the benefits in a relevant environment

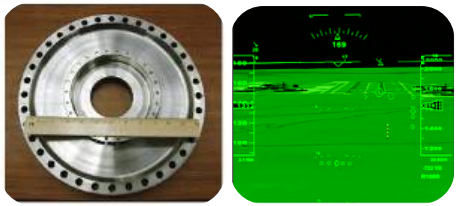


Airspace Systems Program

Directly address the fundamental ATM research needs for NextGen by developing revolutionary concepts, capabilities, and technologies that will enable significant increases in the capacity, efficiency and flexibility of the NAS.

Aviation Safety Program

Conduct cutting-edge research that will produce innovative concepts, tools, and technologies to improve the intrinsic safety attributes of current and future aircraft.



Aeronautics Test Program

Preserve and promote the testing capabilities of one of the United States' largest, most versatile and comprehensive set of flight and ground-based research facilities.

Integrated Systems Research Program Overview

Program Goal:
Conduct research at an integrated system-level on promising concepts and technologies and explore, assess, or demonstrate the benefits in a relevant environment

Environmentally Responsible Aviation (ERA) Project

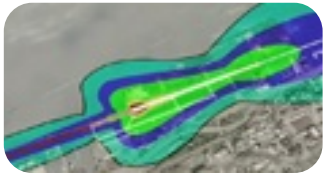
Explore and assess new vehicle concepts and enabling technologies through system-level experimentation to *simultaneously* reduce fuel burn, noise, and emissions

Unmanned Aircraft Systems (UAS) Integration in the National Airspace System (NAS) Project

Contribute capabilities that reduce technical barriers related to the safety and operational challenges associated with enabling routine UAS access to the NAS

Innovative Concepts for Aviation (ICA) Project

Spur innovation by offering research opportunities to the broader aeronautics community through peer-reviewed proposals. Establish incentive prizes similar to the Centennial Challenges and sponsor innovation demonstrations of selected technologies that show promise of impacting aviation challenges.



NASA's Subsonic Transport System Level Metrics

Sumarizing the potential technology payoff …

…. Innovative technology for dramatically reducing noise, emissions and fuel burn

CORNERS OF THE TRADE SPACE	N+1 = 2015*** Technology Benefits Relative To a Single Aisle Reference Configuration	N+2 = 2020*** Technology Benefits Relative To a Large Twin Aisle Reference Configuration	N+3 = 2025*** Technology Benefits
Noise (cum below Stage 4)	-32 dB	-42 dB	-71 dB
LTO NO_x Emissions (below CAEP 6)	-60%	-75%	better than -75%
Performance: Aircraft Fuel Burn	-33%	-50%**	better than -70%
Performance: Field Length	-33%	-50%	exploit metro-plex* concepts

***Technology Readiness Level for key technologies = 4-6. ERA will undertake a time phased approach, TRL 6 by 2015 for "long-pole" technologies

** RECENTLY UPDATED. Additional gains may be possible through operational improvements

* Concepts that enable optimal use of runways at multiple airports within the metropolitan area

Open Rotor Research at NASA

The NASA/GE Collaboration on Open Rotor Testing

- **Objective:** Explore the design space for lower noise while maintaining the high propulsive efficiency from a counter-rotating open rotor system.
- **Approach:** A low-noise open rotor system is being tested in collaboration with General Electric and CFM International, a 50/50 joint company between Snecma and GE. Candidate technologies for lower noise will be investigated as well as installation effects such as pylon integration.

Historical Baseline Blade Set
12 x 10 blade count

Test Program Overview

NASA/GE 9x15 Low Speed Wind Tunnel		**NASA/GE 8x6 High Speed Wind Tunnel**	**NASA/GE/FAA (CLEEN) 8x6/9x15**
GE Gen-1 Blade Designs			GE Gen-2 Blade Designs
Takeoff and Approach Conditions	ERA Diagnostics	Cruise Conditions	TO/Approach and Cruise Conditions
•Aerodynamic performance •**Acoustics** •Hot Film flowfield measurements	•Acoustic phased array •Farfield Acoustics with Pylon •Pressure Sensitive Paint •Stereo Particle Image Velocimetry •Acoustic Shielding	•**Aerodynamic performance** •Near field unsteady pressure	• Aero and acoustic performance of optimized blade designs at low and high speed.

Glenn Research Center
Cleveland, Ohio

8x6 SWT/9x15 LSWT Wind Tunnel Complex

Operating mode: Aerodynamic–Closed loop
Propulsion–Open loop

9ft. x 15ft.
Low Speed Test Section
MACH NO.: 0–0.2

Muffler

Cooler

Flexible nozzle

Air Dryer

Compressor

Drive motors

8ft. x 6ft.
Supersonic Test Section
MACH NO.: 0.25–2.0
Altitude: Sea level to 35,000 ft.
Tunnel pressure: 2400 to 3700 lb/ft^2
Temperature: 80 to 200 °F
Drive motors 87,000 HP

CD-98-77052

The Open Rotor Propulsion Rig (ORPR)

750 SHP per rotor
Rotating force balance:
  430 Lbf thrust per rotor
  550 ft-lb torque per rotor

1/5 to 1/7 of Full Scale
Independently controlled rotor speeds
Digital telemetry units for and aft
12 strain gage channels per rotor
Adjustable rotor spacing

Acoustic Configuration

18° forward to
140° aft angles

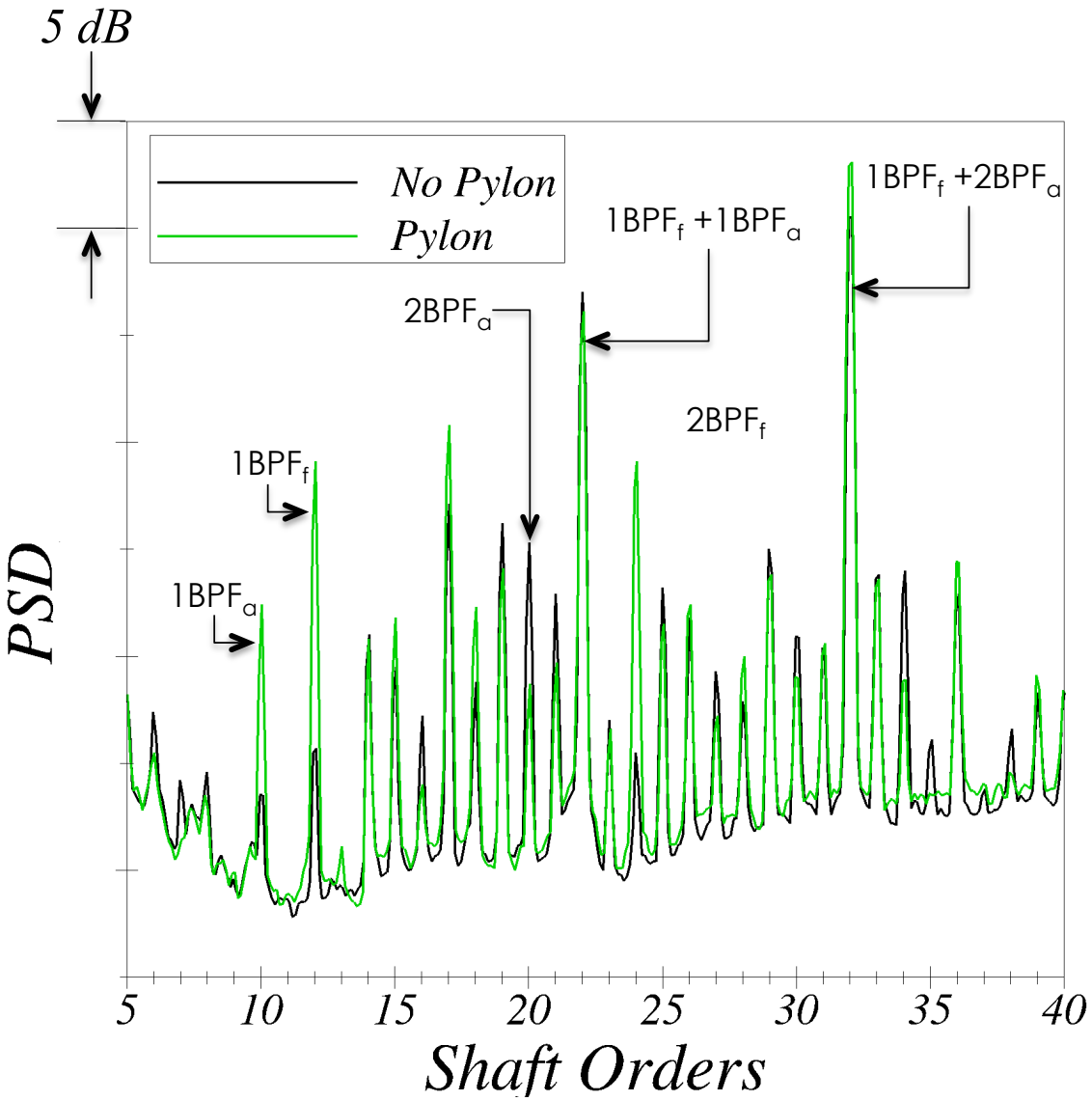
NASA/GE Collaboration
9x15 Low Speed Wind Tunnel test

Test Matrix
Freestream Mach number variation
Blade pitch angle setting variation
Series of RPMs at a set pitch
Model angle of attack

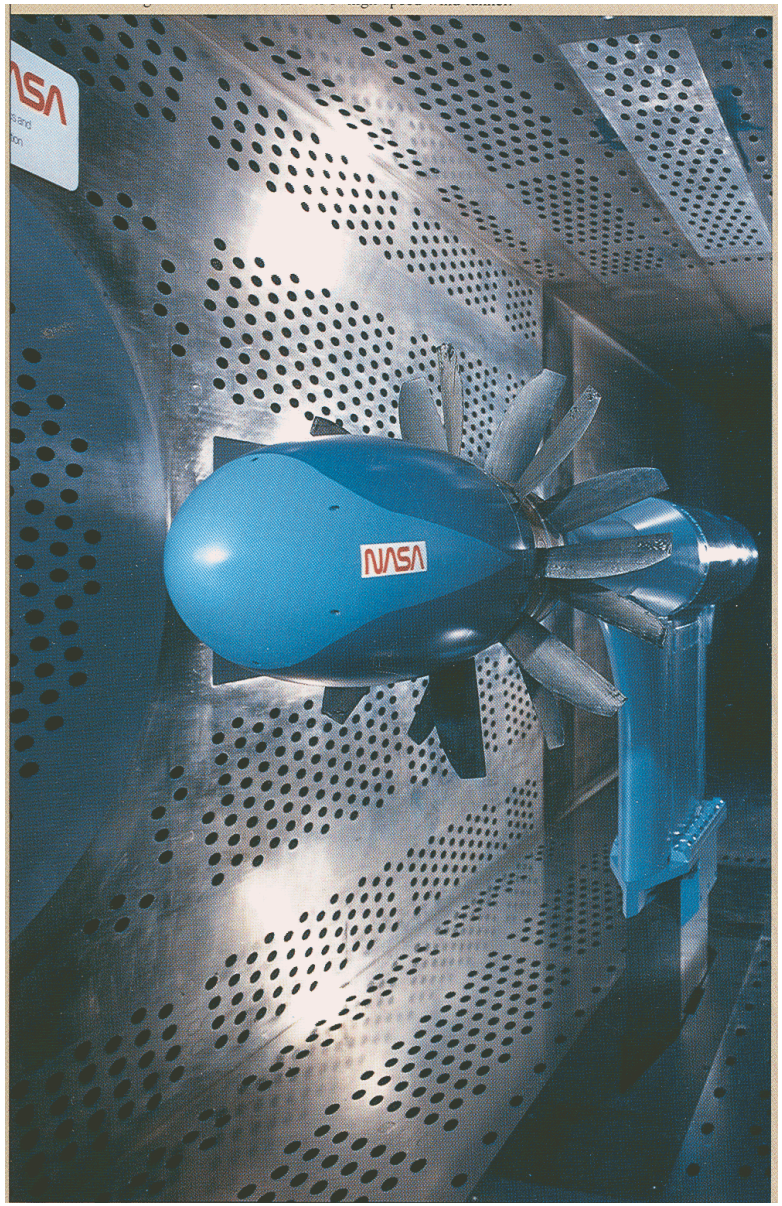
A detailed aerodynamic performance data set was acquired for all blade sets as well as acoustic measurements at 18 axial locations.

ERA Diagnostics:
Historical Baseline Installation effects

The presence of the CFMI pylon induces distortions into blade rows causing noticeable increase in the levels of the individual rotor harmonics.



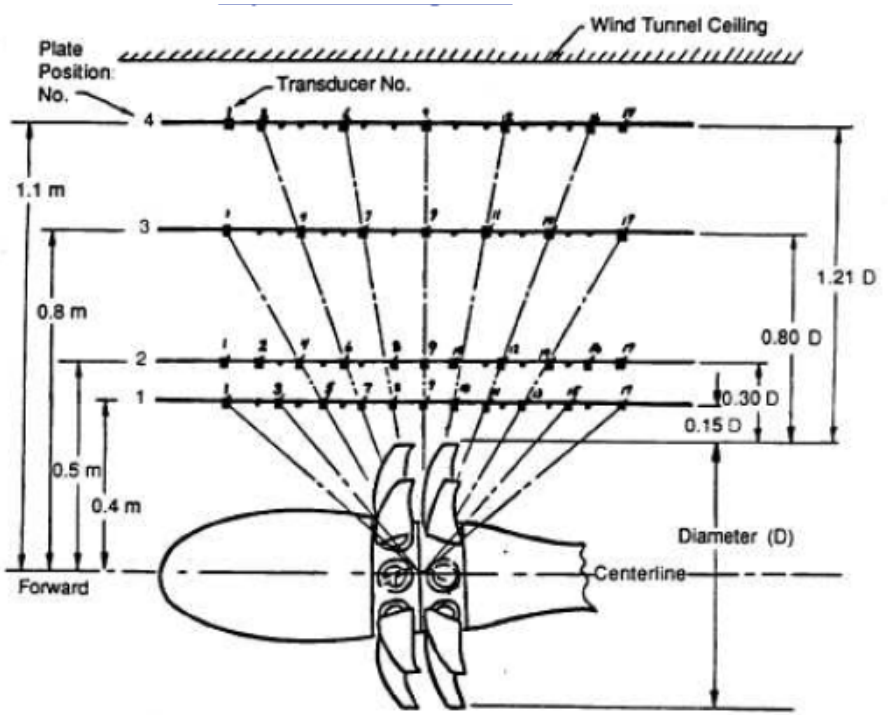
NASA/GE Collaboration
8x6 High Speed Wind Tunnel test



NASA C85-6031

Objectives: Aerodynamic performance and near field unsteady pressure measurements at cruise Mach number.

Installation of ORPR into the 8x6 began in December 2010.



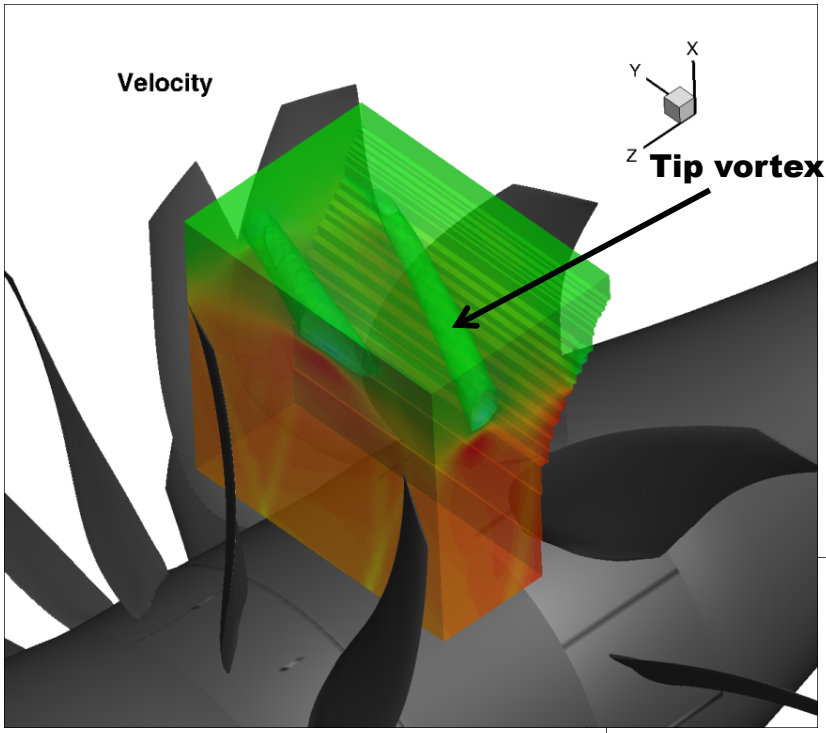
NASA NAS3-24080, Task V Final Report

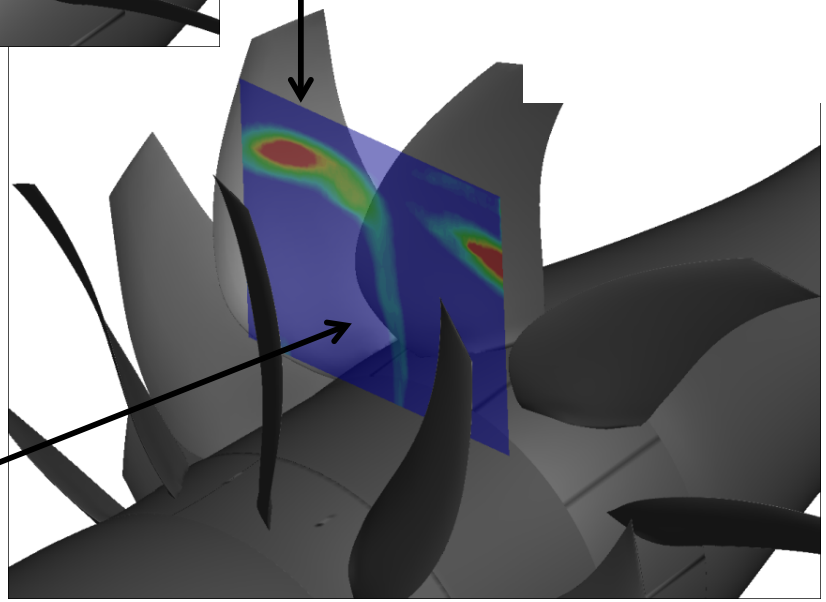
The ERA Diagnostics Program

Acoustic Phased Array	**Farfield acoustics with Pylon**	**Pressure Sensitive Paint**	**Stereo Particle Image Velocimetry**	**Acoustic Shielding**

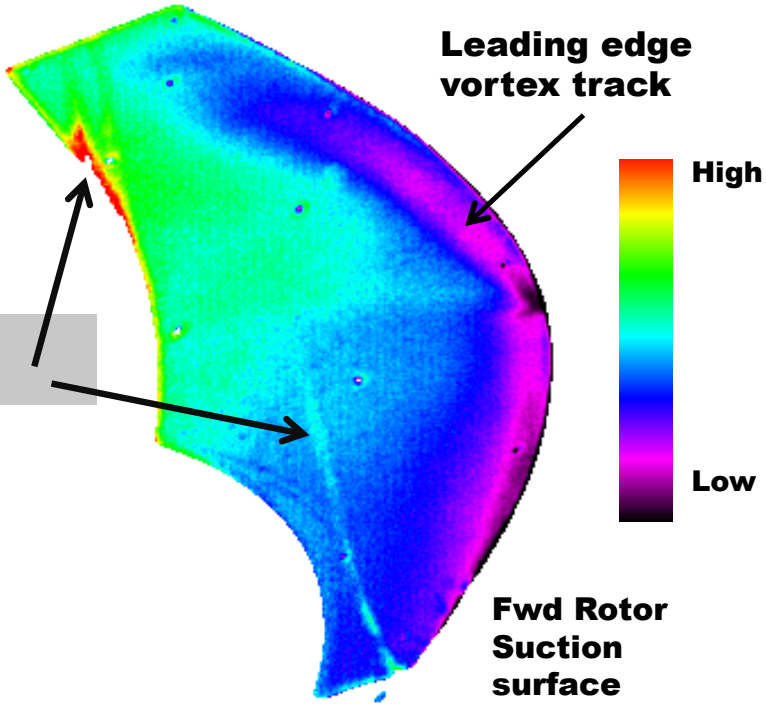
The goal is a comprehensive data set that will identify noise sources and enable improved performance and acoustic modeling of open rotor systems.

ERA Diagnostics:
Detailed Historical Baseline flowfield measurements



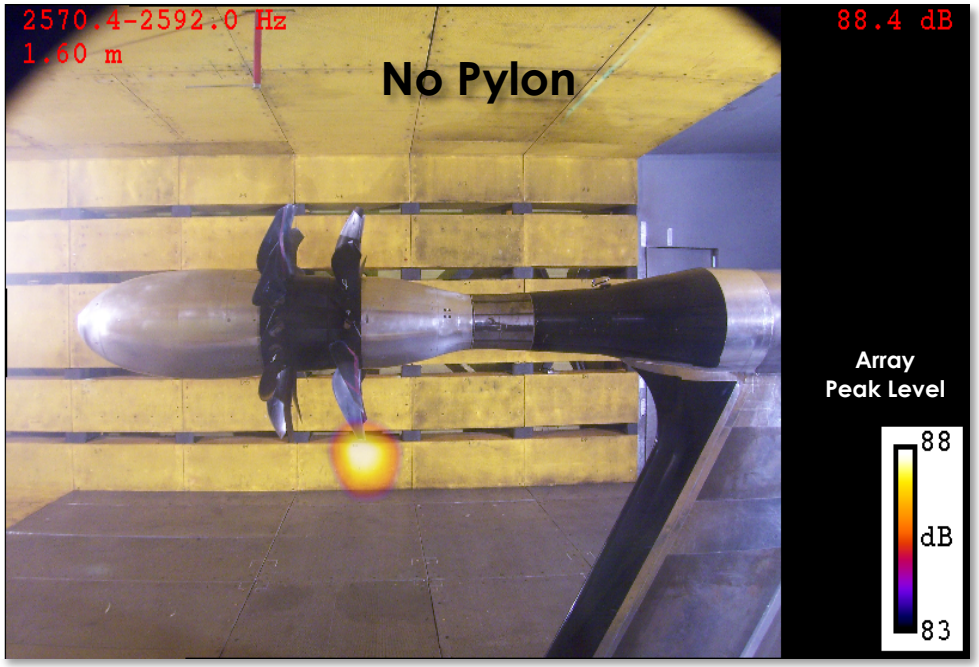


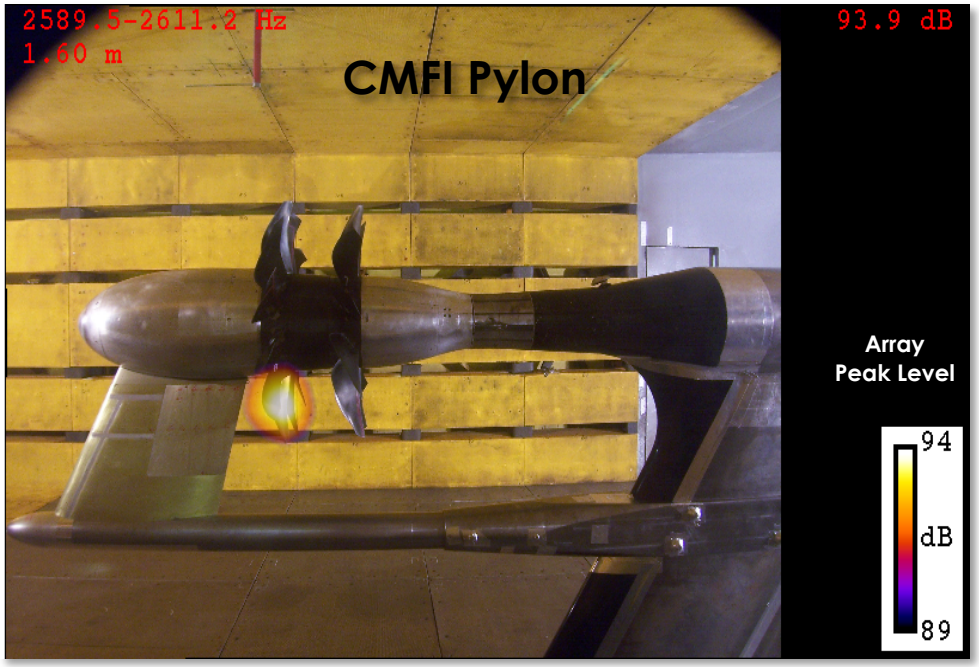
The 3D **PIV** measurements provide a wealth of information about the blade wakes and vortex track.



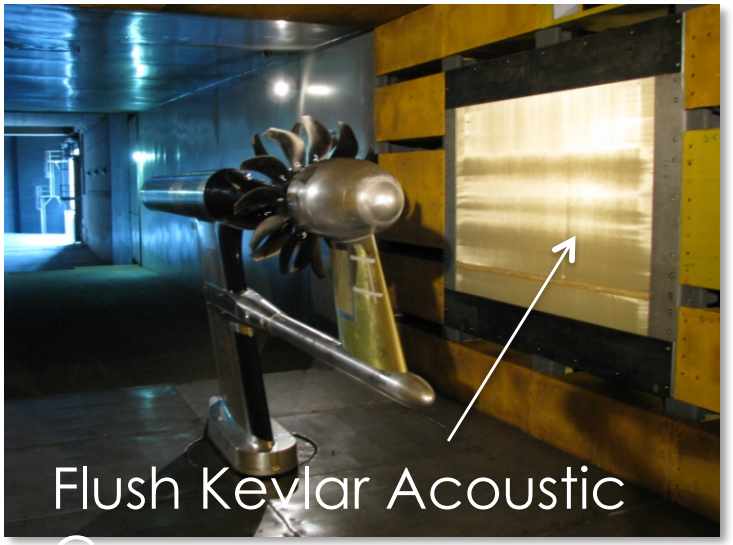
The **Pressure Sensitive Paint** measurements show phase locked static pressure on the surface of the rotating blade.

ERA Diagnostics:
Historical Baseline Installation effects (1)





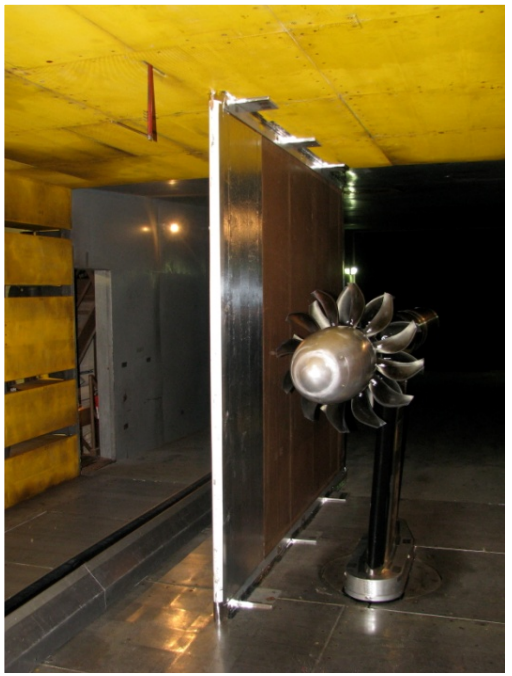
The location of peak noise level in the **phased array** map changes in the presence of the CFMI pylon indicating a change in the relative strength of sources.



ERA Diagnostics:
Historical Baseline Acoustic Shielding

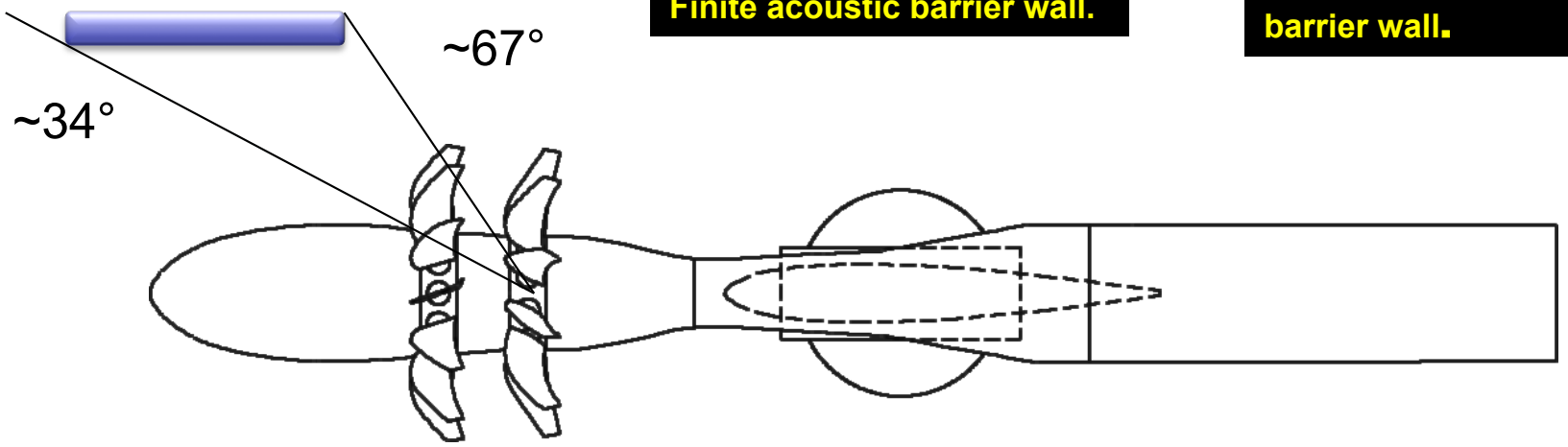
Test Matrix
2 Barrier wall lengths
2 Barrier wall positions Forward and Aft
2 Rotor speeds
2 Freestream Mach numbers

Finite acoustic barrier wall.

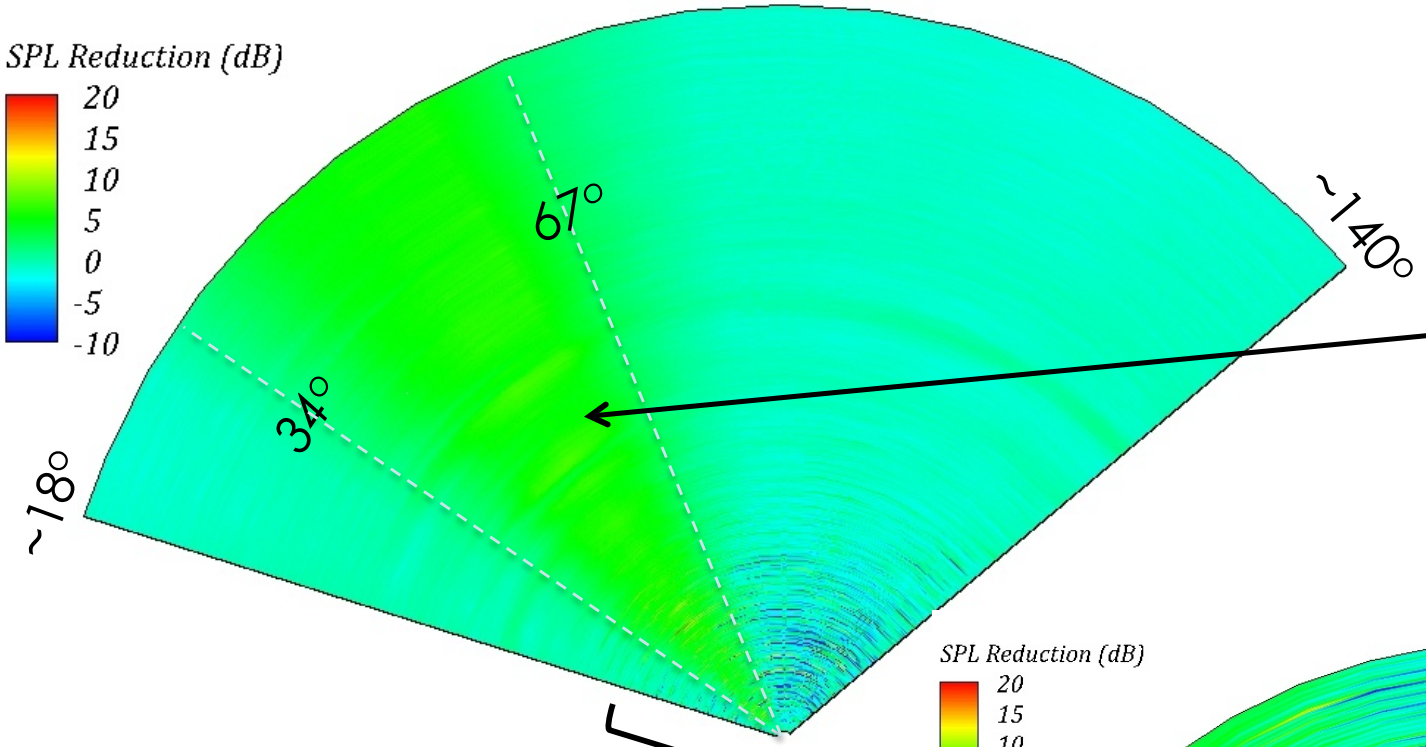


Semi-infinite acoustic barrier wall.

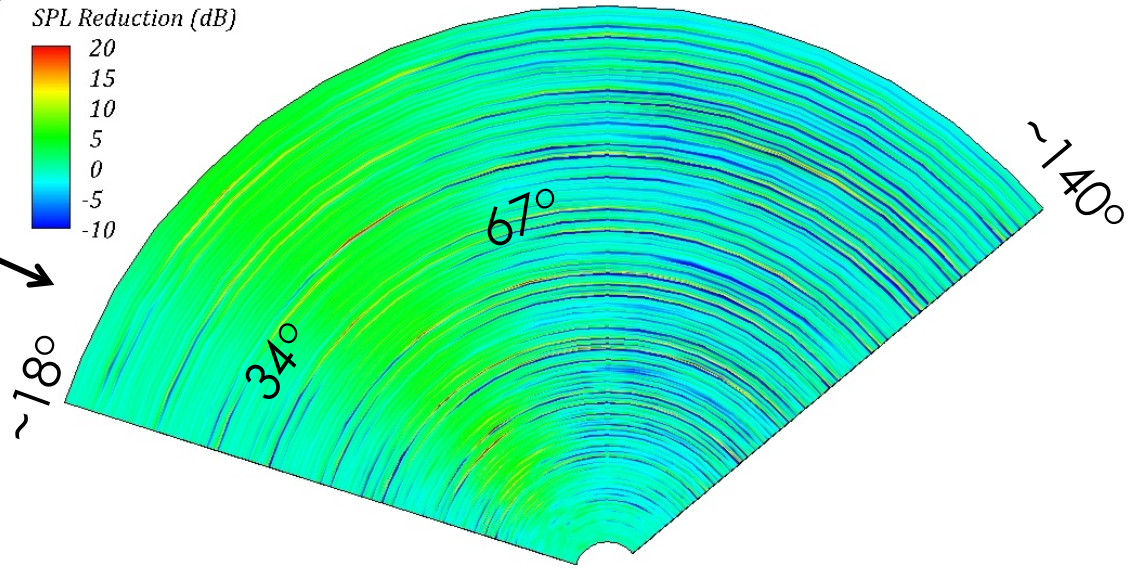
Short barrier, Forward position



ERA Diagnostics:
Historical Baseline Acoustic Shielding (2)



The ‘shadow’ of the barrier wall is visible as a 5 dB reduction region in this view from 0.5 kHz to 50 kHz, however the behavior of tones is more complicated.

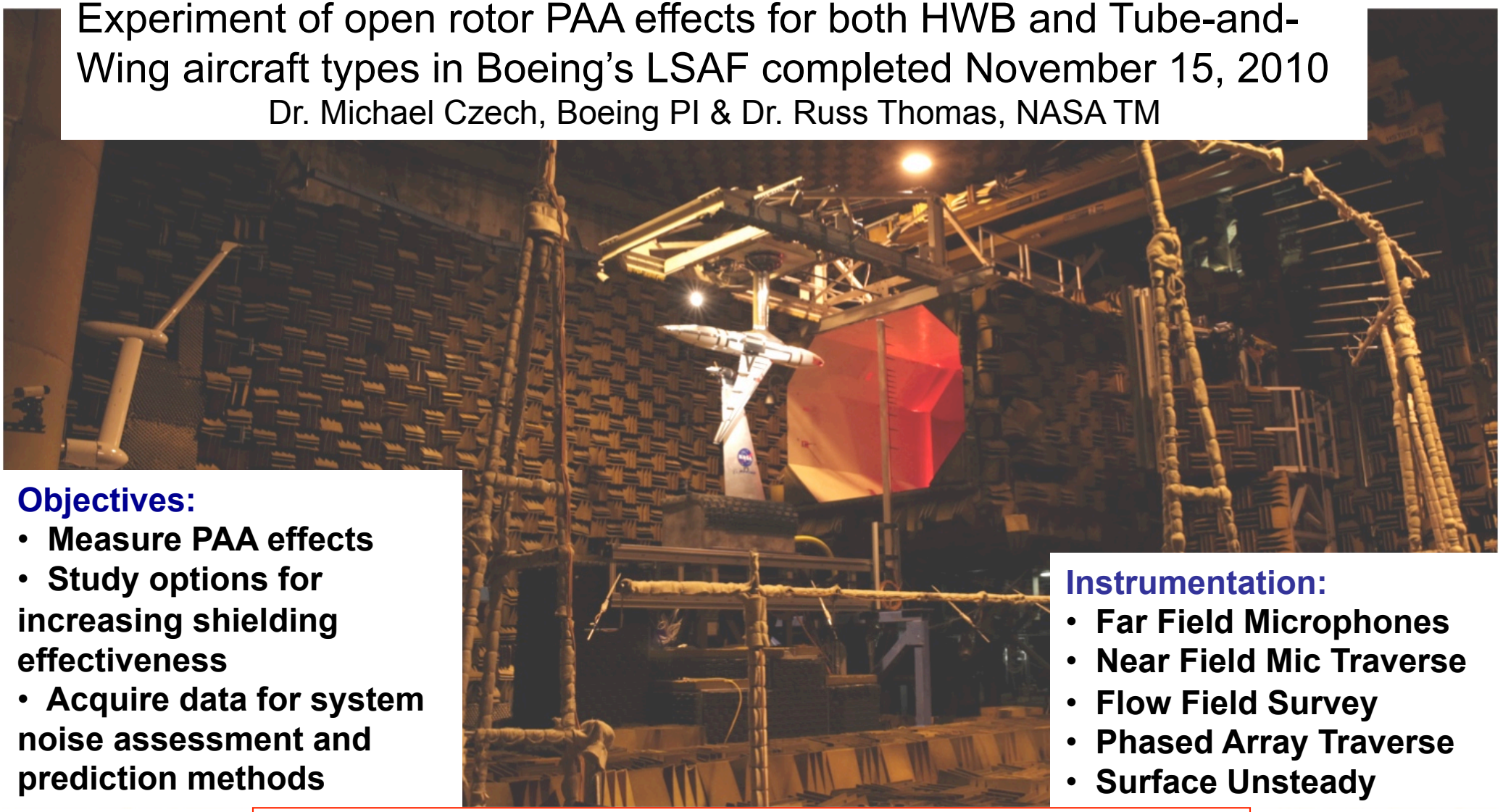


Detail from 0.5 kHz to 10 kHz
A complex pattern of tone constructive and destructive interference is apparent.

NASA/Boeing Open Rotor PAA Experiment

Experiment of open rotor PAA effects for both HWB and Tube-and-Wing aircraft types in Boeing's LSAF completed November 15, 2010

Dr. Michael Czech, Boeing PI & Dr. Russ Thomas, NASA TM



Objectives:

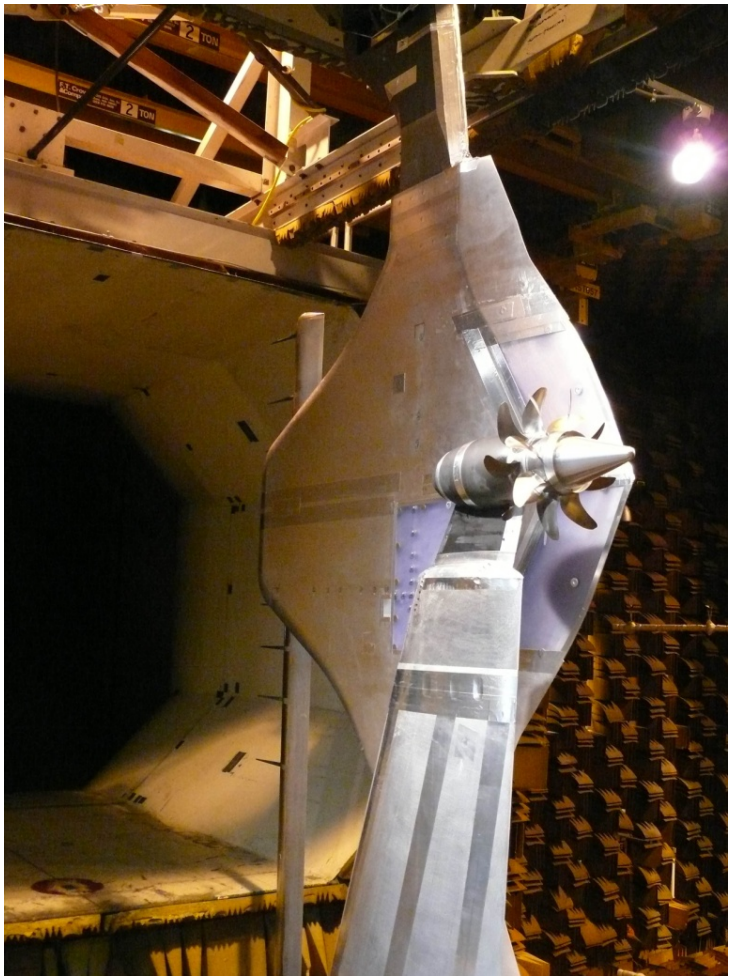
- **Measure PAA effects**
- **Study options for increasing shielding effectiveness**
- **Acquire data for system noise assessment and prediction methods**

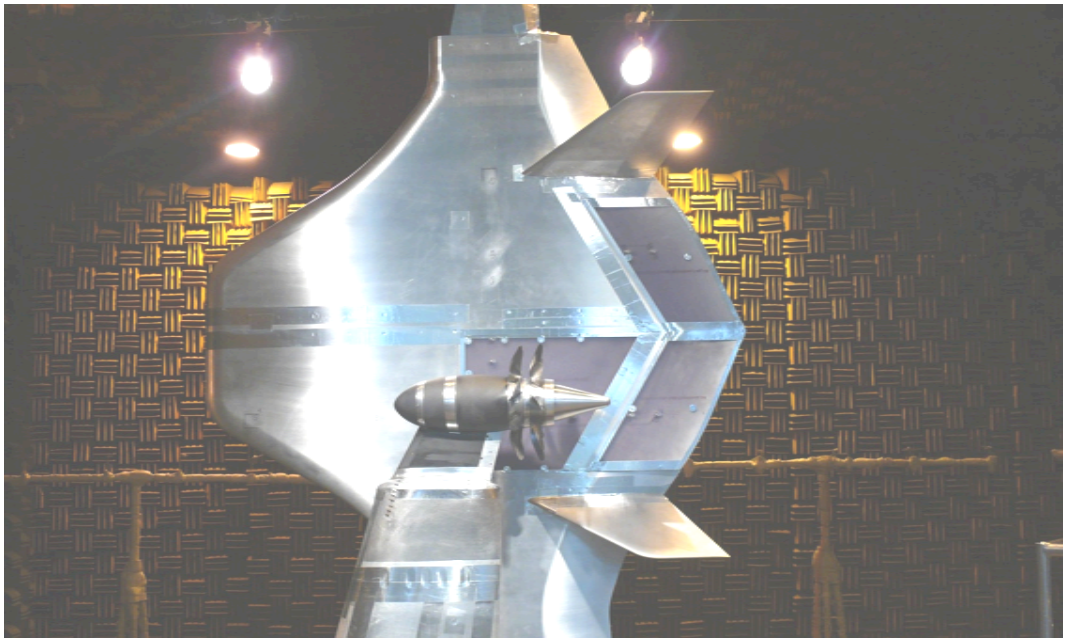
Instrumentation:

- **Far Field Microphones**
- **Near Field Mic Traverse**
- **Flow Field Survey**
- **Phased Array Traverse**
- **Surface Unsteady**

Funded by the NASA Environmentally Responsible Aviation Project, Dr. Fay Collier, Project Manager

NASA/Boeing Open Rotor PAA Experiment





Experimental Parameter Summary:

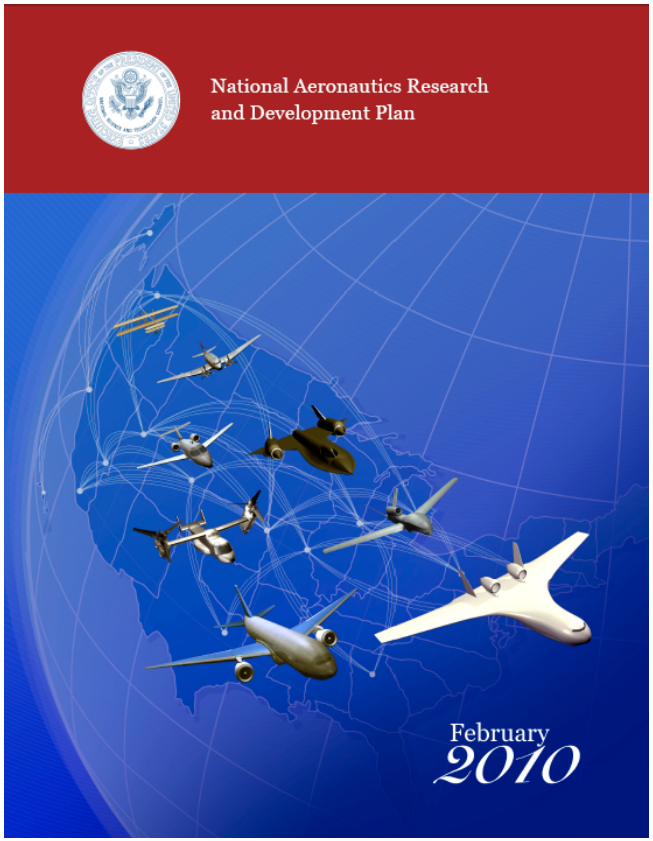
- rotor speed variation
- wind tunnel Mach variation

- rotor to airframe relative position, axial and vertical
- off-center and centerline positions
- inboard verticals, size and cant angle
- elevon deflection

For HWB aircraft concept, there has been rapid progress in technology and assessments to meet the noise goal of the N+2 goals

FAA CLEEN Program

- Address NextGen environmental goals in partnership with industry (50% cost share, $125M over 5 yrs)
- Mature and demonstrate promising energy efficient, clean and quiet technologies
- Advance sustainable alternative fuels for aviation
- Assess technology suitability for retrofit or re-engine
- Meet national R&D goals



Boeing | GE | Honeywell | Pratt & Whitney | Rolls-Royce

CLEEN Program* Goals

Develop and demonstrate (TRL 6-7) certifiable aircraft technology

CORNERS OF THE TRADE SPACE	CLEEN (N+1) (2015)** Ref: B737/CFM56-7B	N+2 (2020)*** Ref: B777-200/GE-90	N+3 (2025)***
Noise (cum below Stage 4)	-32 dB	-42 dB	-71 dB
LTO NO_x Emissions (Below CAEP 6)	-60%	-75%	better than -75%
Aircraft Fuel Burn	-33%	-50%	better than -70%

* Consistent w/ National Aeronautics Research and Development Plan

** EIS beginning in 2015

*** Technology Readiness Level for key technologies = 4-6

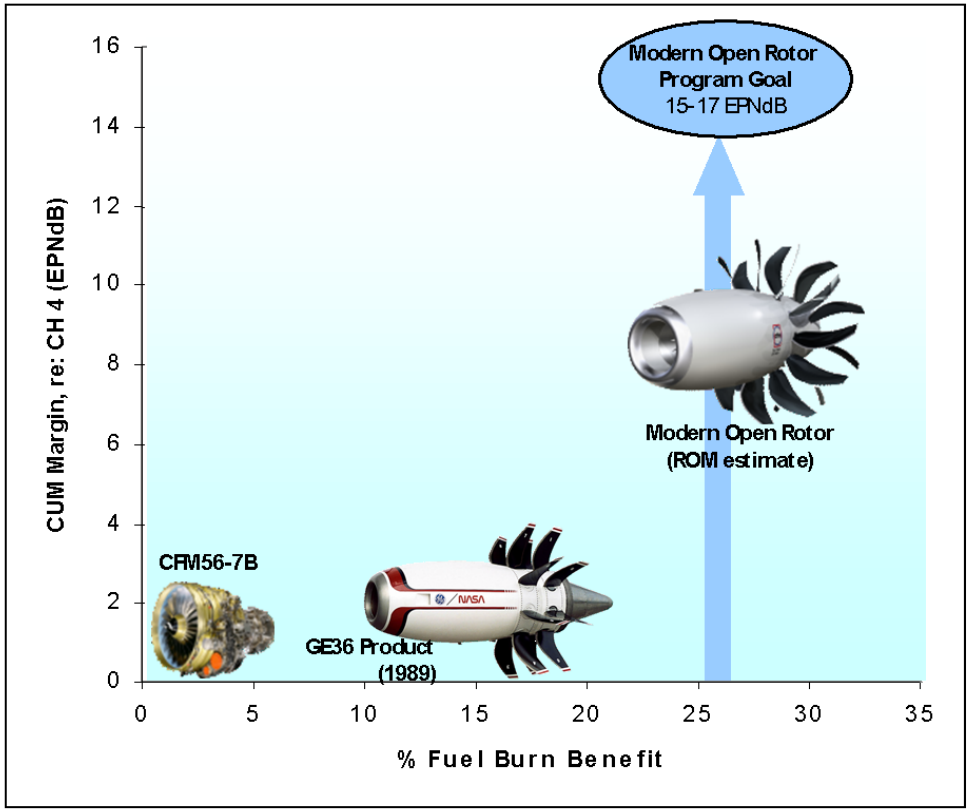
FAA/CLEEN Open Rotor Overview

- **Goal for CLEEN Open Rotor effort with GE**
  - 26% fuel burn reduction (relative to CFM56-7B)
  - 15 to 17 EPNdB noise reduction (relative to stage 4)

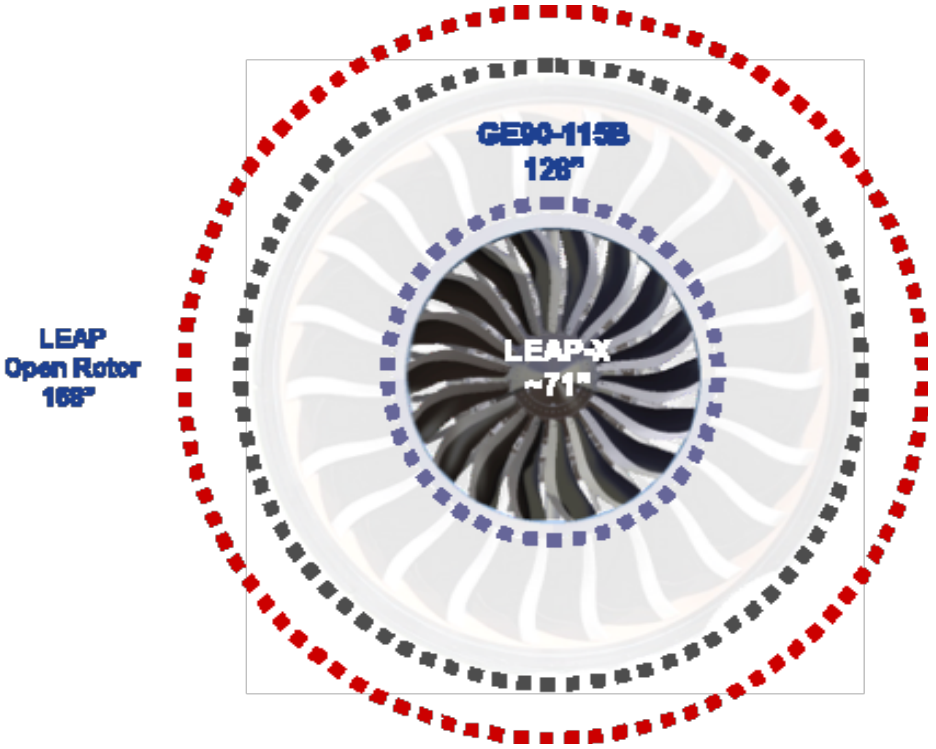
- **OR Technology Program has two work elements:**
  - Blade aero-acoustic assessment and
  - Pitch Change Mechanism (PCM) including control system integration

Open Rotor Fan Technology
Key Technical Challenges

FUEL BURN OPPORTUNITY/ NOISE CHALLENGE



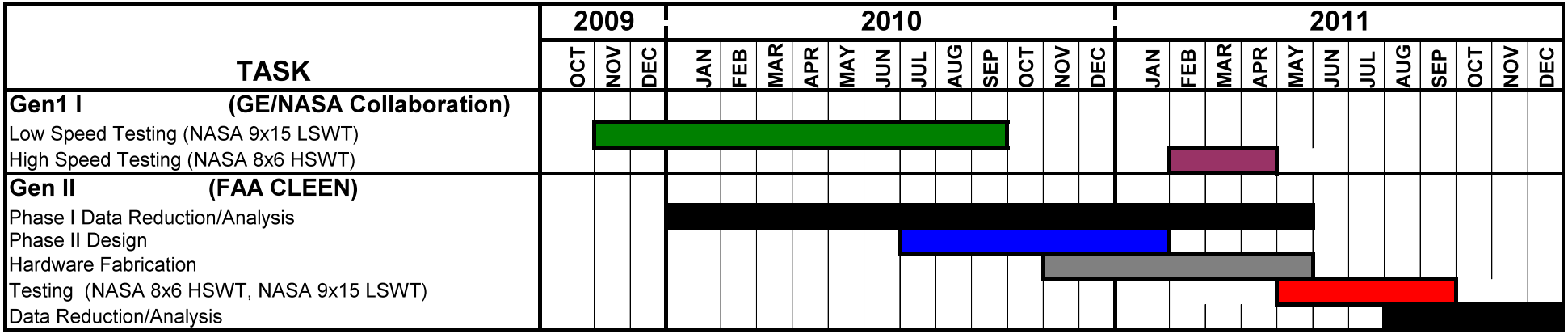
INSTALLATION CHALLENGE



Revolutionary Fuel Burn Advantage … Significant Challenges

Open Rotor Aero Acoustic Technology Program Plan

- Develop advanced technology blade designs
- Refine designs thru model scale testing
- Project model-scale results to full-scale application



Summary

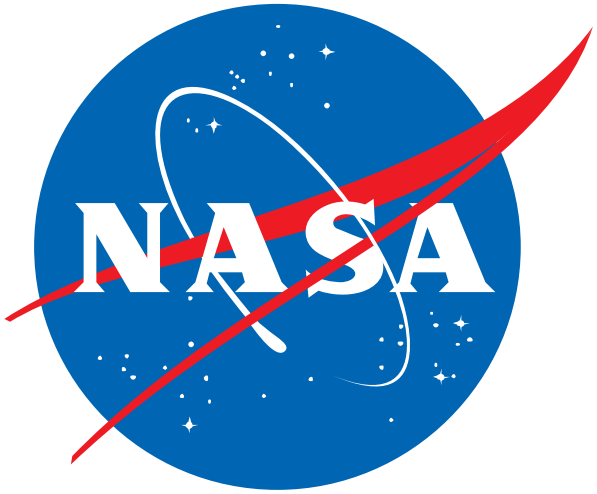
• Under the NASA/GE collaboration, 5 modern design blade sets have been tested for aero/acoustic performance at Takeoff/Approach Mach and are currently being tested for performance at cruise Mach.

• The Historical Baseline blade set is also being tested at low and high speed for acoustic and aerodynamic performance characteristics. Data from this blade set will form a benchmark test case for open rotors.

• The NASA ERA program produced a comprehensive data set of flow field and acoustic data which includes phased array, particle image velocimetry, and pylon installed acoustics.

• Acoustic shielding and Propulsion Airframe Aeroacoustics research is making good progress.

FAA/CLEEN Program is a collaborative technology development effort.
Evaluate current state-of-the art of Open Rotor Fan Blade designs relative to program goals:
• 26% fuel burn reduction (relative to CFM56-7B)
• 15 to 17 EPNdB noise reduction (relative to stage 4)
• Leverages Historic GE/NASA UDF Program and GE 1980's product development
Closely linked to the NASA Environmentally Responsible Aviation (ERA) Program


NASA

GE

cfm
THE POWER
OF FLIGHT

FEDERAL AVIATION
ADMINISTRATION

Open Rotor Simulation Work at NASA

Dr. Dale Van Zante
Project Engineer for Propulsion
Environmentally Responsible Aviation
Integrated Systems Research Program

Original content by:
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NASA Glenn Research Center
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14th CEAS-ASC Workshop & 5th Scientific Workshop of X3-Noise Aeroacoustics of High-Speed Aircraft Propellers and Open Rotors

Institute of Aviation, Warsaw, Poland
October 7-8, 2010

X-Noise Workshop, Lausanne, Switzerland
March 18, 2011

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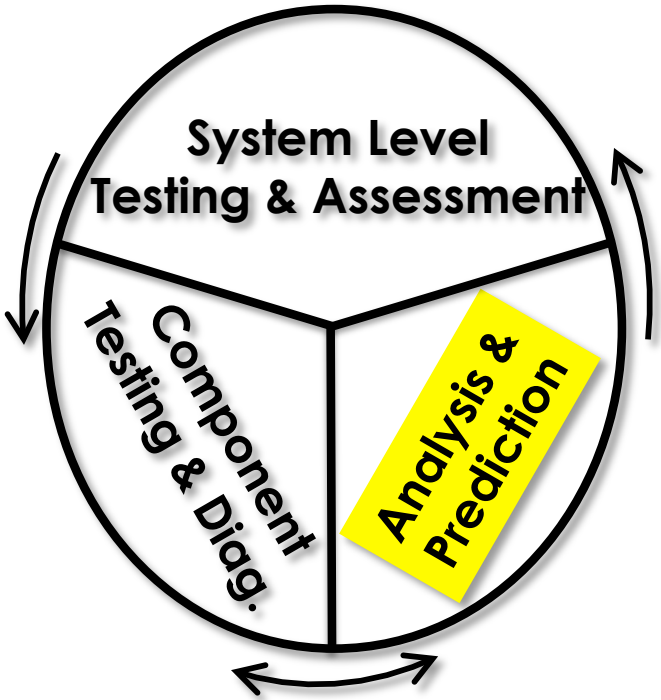
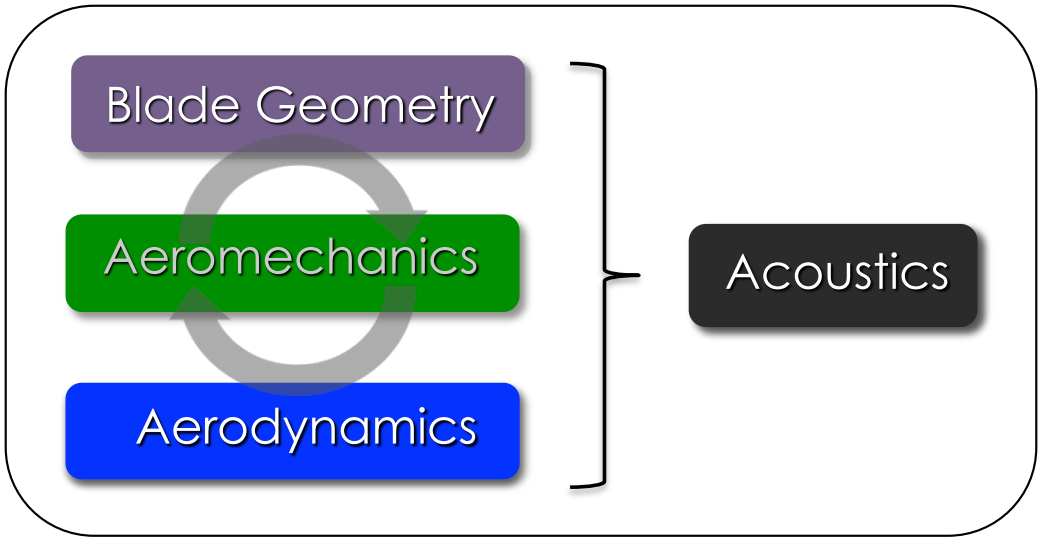
NASA Open Rotor Research Focus

- In collaboration with industry and academic partners, NASA is exploring the design space for low-noise open rotor systems.
- The focus is on system level assessment of the merits of open rotor propulsion system in meeting NASA's subsonic transport goals.



Research Strategy

Analysis & Prediction



- Unlike conventional propellers, for open rotors, blade aeroelastics and aerodynamics are coupled and, together with blade geometry (planform, hot shape, tip design, airfoil distribution, etc.), influence the blade acoustic signature.
- Large-scale flow aerodynamic simulation work has been undertaken to generate the aerodynamic input needed by the noise codes.

Analysis & Prediction

Open Rotor Noise Source Modeling

Noise Sources

Tone & Broadband

- **Thickness** (tone only)
- **Loading**
- **Quadrupole**

Empirical Models
Typically Used in System Analyses

Acoustic Analogy Methods
Bulk of Existing Component Capability

Direct Noise Simulations
Very Few Attempts to Date

Note:
State of the art (or practice) for modeling and prediction is not the same for all noise sources or types.

Increasing Complexity

Increasing Resource Req.

Analysis & Prediction

Acoustic Analogy Challenges

Aerodynamic Calculation Step

Steady/Unsteady Aerodynamic Simulations
Used to Define Acoustic Source Strength Distribution

Acoustic Calculation Step

Ffowcs-Williams Hawkings Eq., Kirchhoff Surface Method
Used for Computing Acoustic Radiation from the Blade

- Accuracy of the acoustics results is strongly influenced by the underlying aerodynamic input.
- Need efficient computational methods and strategies for computing aerodynamic input. Currently using ADPAC for steady calculations and TURBO for unsteady.

Analysis & Prediction
Source Noise Prediction Codes

- ASSPIN (**A**dvanced **S**ubsonic and **S**upersonic **P**ropeller **I**nduced **N**oise) is a time domain code that computes the Green's function solutions of the Ffowcs-Williams and Hawkings equation for propellers in forward flight. Its features are:
  - Thickness and loading noise sources are included, but quadrupole source is neglected.
  - Valid through subsonic, transonic, and supersonic helical blade speeds.
  - User provides blade geometry, aerodynamic loading (steady/unsteady), and operating conditions. Code produces acoustic pressure time signals.
  - Developed in 1980s by Farassat, Dunn, and Padula.

- ASSPIN2 – Code was modernized in 2009 to include general unsteady blade loading for broadband, counter-rotating rotors, and component installation applications.

ASSPIN Research Engineers: Feri Farassat and Doug Nark

Analysis & Prediction
Source Noise Prediction Codes (Cont'd)

- Like ASSPIN, LINPROP and QPROP are based on the Ffowcs-Williams & Hawkings Equation and have similar features/capabilities/requirements. However, they are formulated in the frequency-domain and use large-blade-count asymptotic approximation to compute the various source terms.
  - The asymptotics are applied to the source efficiency integral only and the full details of the blade geometry and flowfield are retained.
  - Formulation is uniformly valid across helical blade speed range.
  - LINPROP computes thickness and loading noise contributions. QPROP computes quadrupole source contribution.
  - Developed in early 1990s by Envia and recently extended to account for counter-rotating rotors and installation effects.

Analysis & Prediction

Noise Shielding/Scattering Prediction Code

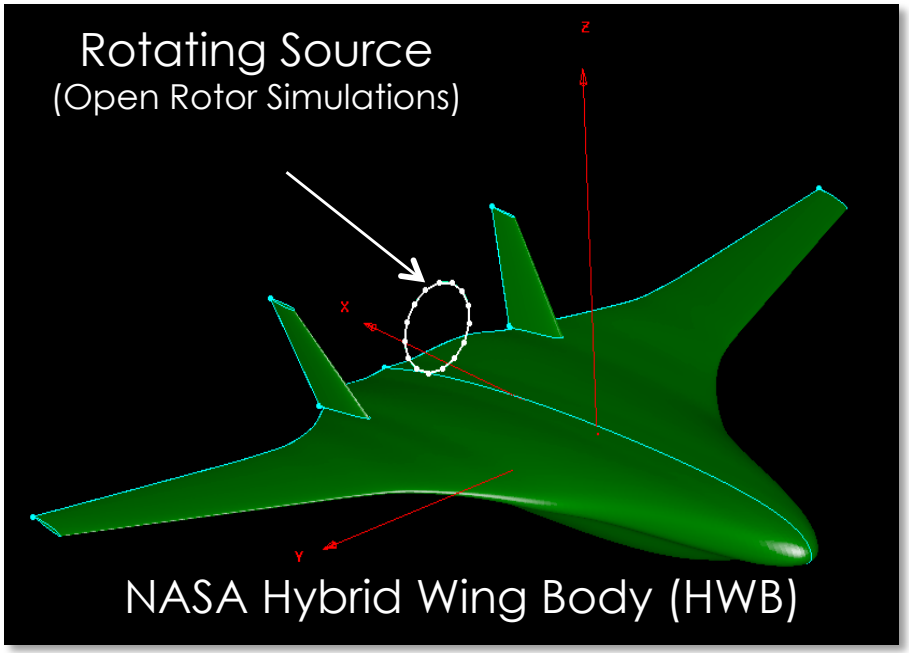
- Fast Scattering Code (FSC) is a numerical code for calculating the scattering and reflection of incident acoustic waves on an arbitrary surface.
- It is based on the equivalent sources method and uses fast multi-pole technique to reduce CPU time requirements.

Hybrid Wing Body

L = 41*m*
b = 64 *m*

Simulated Open Rotor Sources

R = 2.65 *m*
B = 8
M_{tip} = 0.95
Clearance = 0.3 *m*



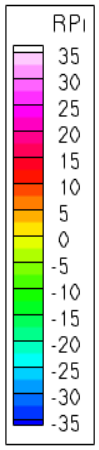
FSC Code Research Engineers: Ana Tinetti & Mark Dunn

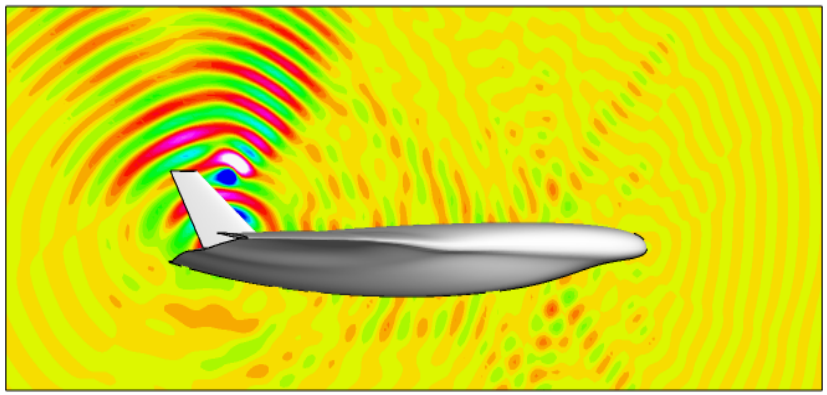
Analysis & Prediction

Shielding/Scattering Prediction Sample Results

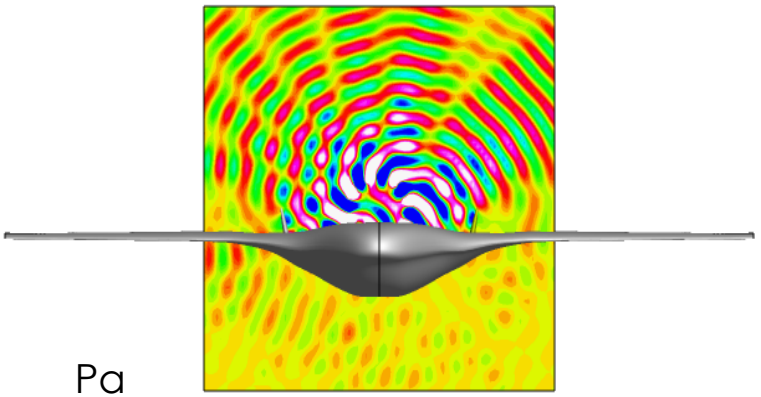
M = 0.2 (Uniform), f = 155.2 Hz (1xBPF) Full-Scale

Pa





Rotor Plane



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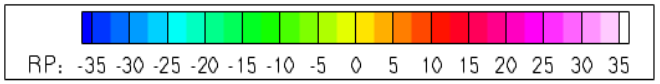
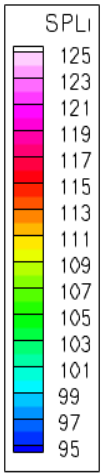
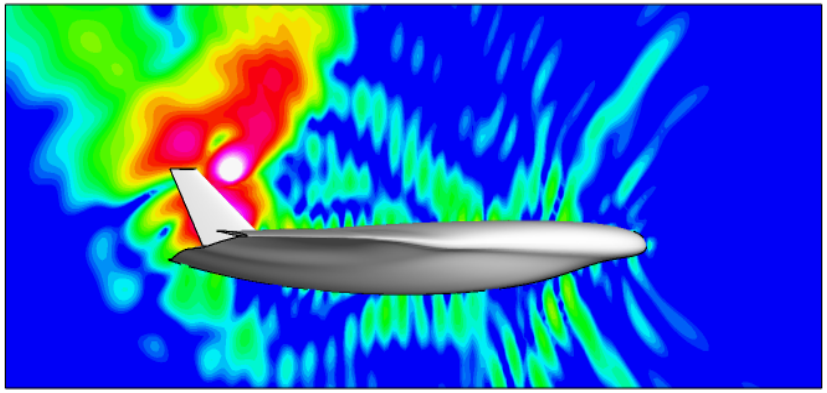
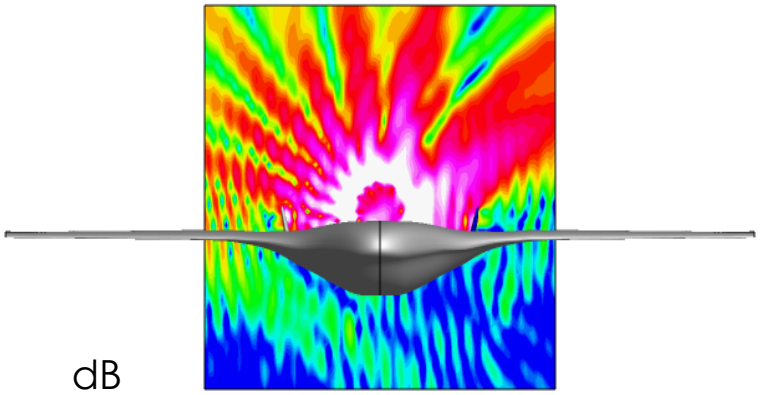


dB



Symmetry Plane





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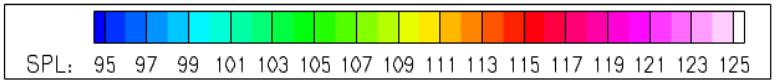

Summary

- NASA is researching open rotor propulsion as part of its technology research and development plan for addressing the subsonic transport aircraft noise, emission and fuel burn goals.
- The open rotor research is focused on system level metrics, but it also encompasses research at component level to build knowledge and improve the design and analysis tools.
- Ultimately, the objective is to provide a portfolio of low-noise open rotor technologies to aircraft designers that do not compromise the other performance aspects of the aircraft.
- A complementary objective is to develop and improve NASA's noise prediction tools for advanced engines and installation configurations.