NASA OPEN ROTOR NOISE RESEARCH

Owing to their inherent fuel burn efficiency advantage compared with the current generation high bypass ratio turbofan engines, there is resurgent interest in developing open rotor propulsion systems for powering the next generation commercial aircraft. However, to make open rotor systems truly competitive, they must be made to be acoustically acceptable too. To address this challenge, NASA in collaboration with industry is exploring the design space for low-noise open rotor propulsion systems. The focus is on the system level assessment of the open rotors compared with other candidate concepts like the ultra high bypass ratio cycle engines. To that end there is an extensive research effort at NASA focused on component testing and diagnostics of the open rotor acoustic performance as well as assessment and improvement of open rotor noise prediction tools. In this presentation and overview of the current NASA research on open rotor noise will be provided. Two NASA projects, the Environmentally Responsible Aviation Project and the Subsonic Fixed Wing Project, have been funding this research effort.

NASA Open Rotor Noise Research

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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

Acknowledgements

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Research work noted here is carried out collaboratively by the NASA acoustics team at the Ames, Dryden, Glenn, and Langley Research Centers.

The collaboration of our partners at General Electric Aviation is gratefully acknowledged.

Motivation

NASA's Subsonic Transport System Level Metrics

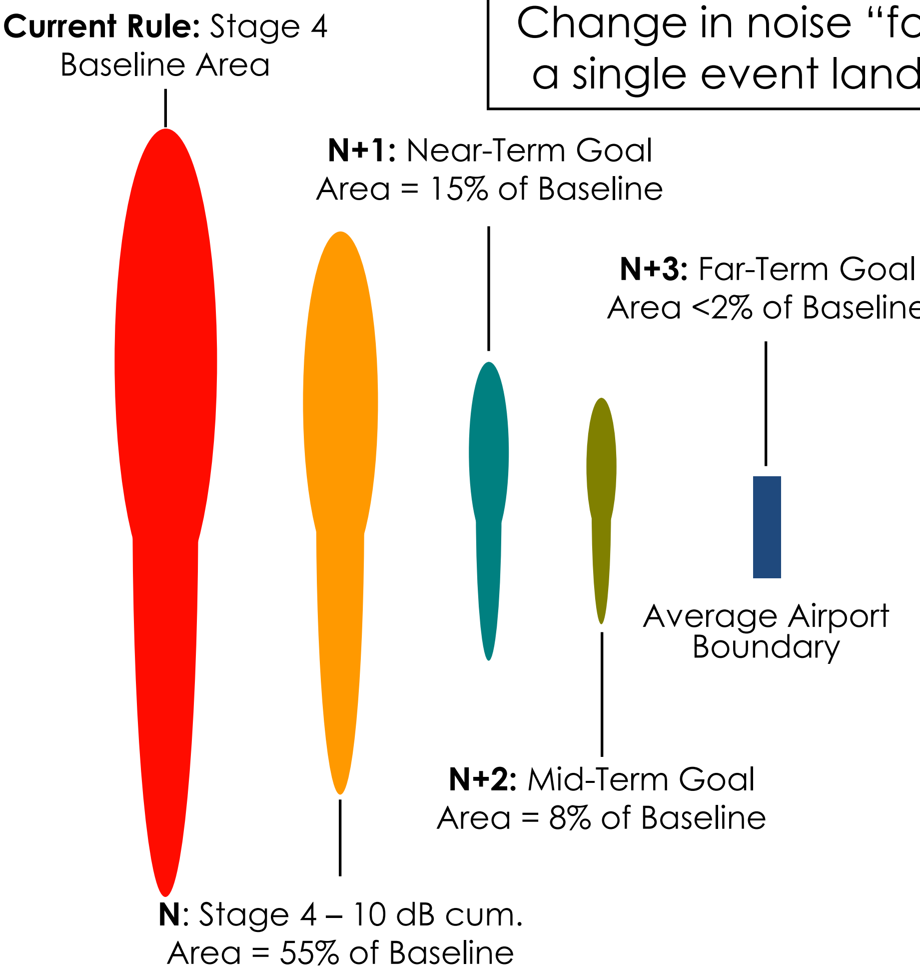
CORNERS OF THE TRADE SPACE	N+1 = 2015*** Technology Benefits Relative To a Single Aisle Reference Configuration	N+2 = 2020*** Technology Benefits Relative To a Large Twin Aisle Reference Configuration	N+3 = 2025*** Technology Benefits
Noise (cum below Stage 4)	-32 dB	-42 dB	-71 dB
LTO NO_x Emissions (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.

Noise Goal

Contain Objectionable Noise Within Airport Boundary

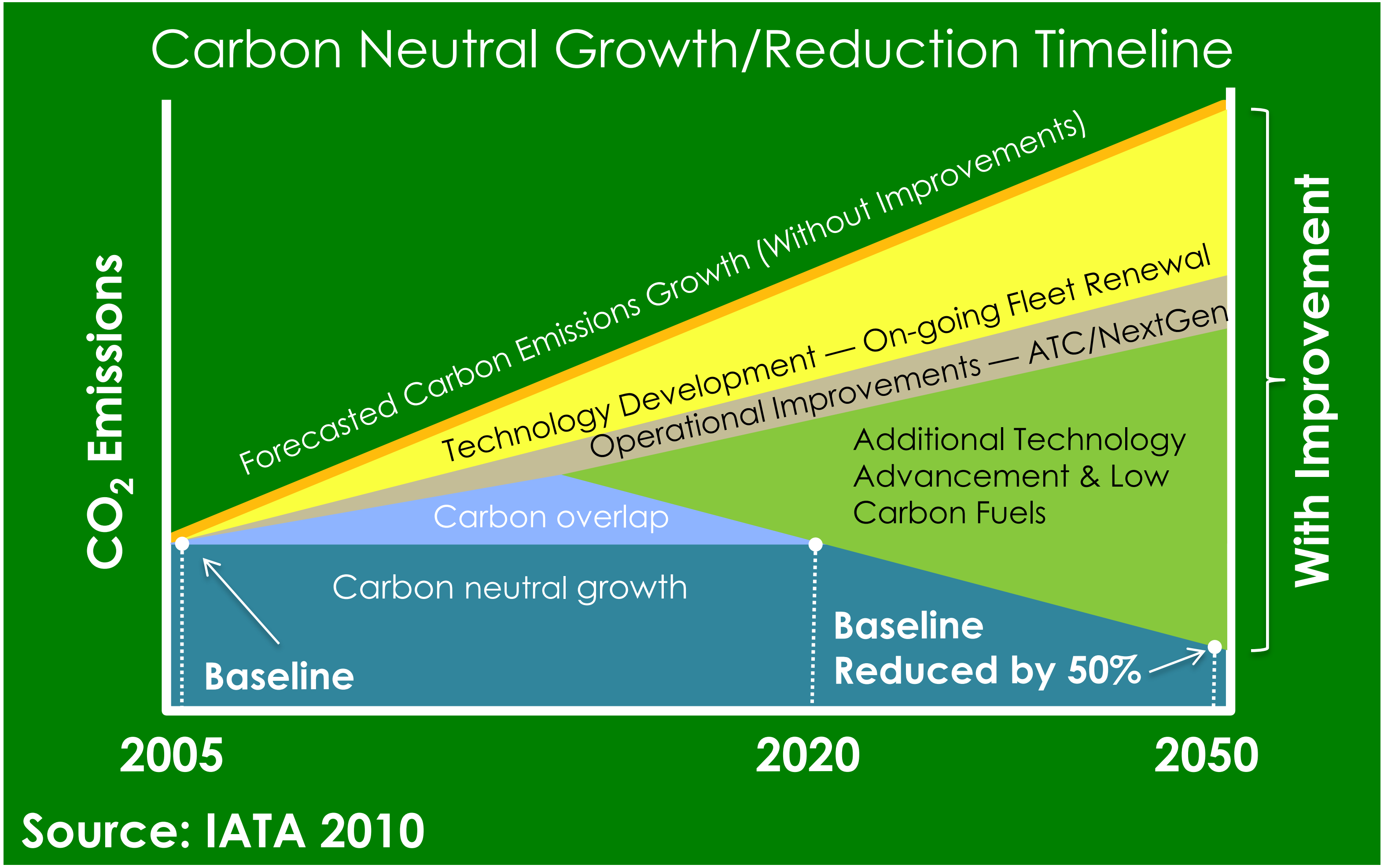
Change in noise "footprint" area for a single event landing and takeoff



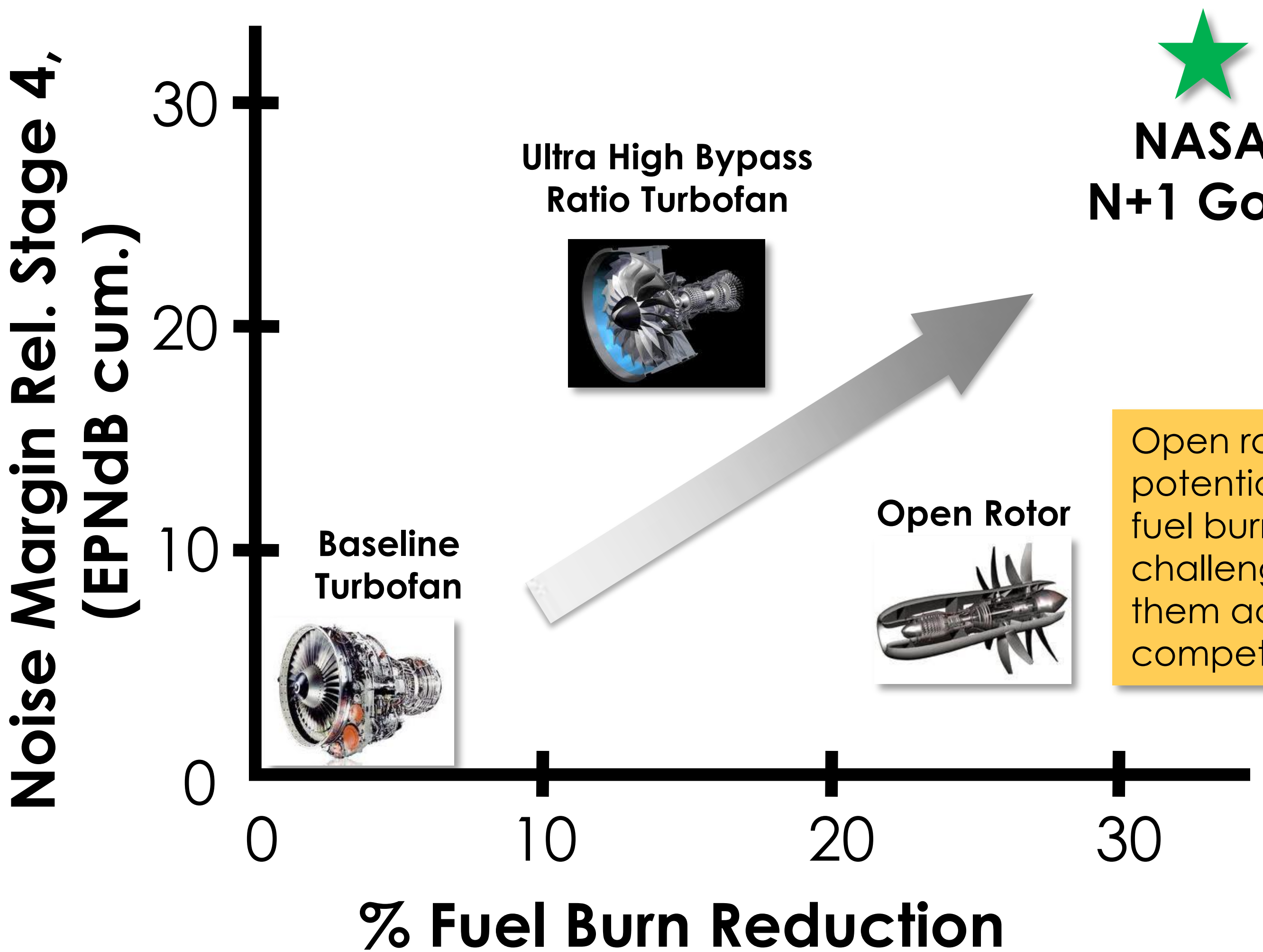
- Relative ground contour areas for notional Stage 4, current, and near-, mid-, and far-term goals
  - Independent of aircraft type or weight
  - Independent of baseline noise level
- Noise reduction assumed to be evenly distributed between the three certification points
- Effects of source directivity, wind, etc. not included

Carbon Emissions Goal

Reduce CO_2 Emissions to 50% of 2005 Levels



Propulsor Technology Roadmap



Open rotors have the potential for significant fuel burn savings. The challenge is to make them acoustically competitive.

Icons represent notional numbers based on published information

Research Objective

Unducted Fan (UDF) Model in NASA Wind Tunnel (1985)

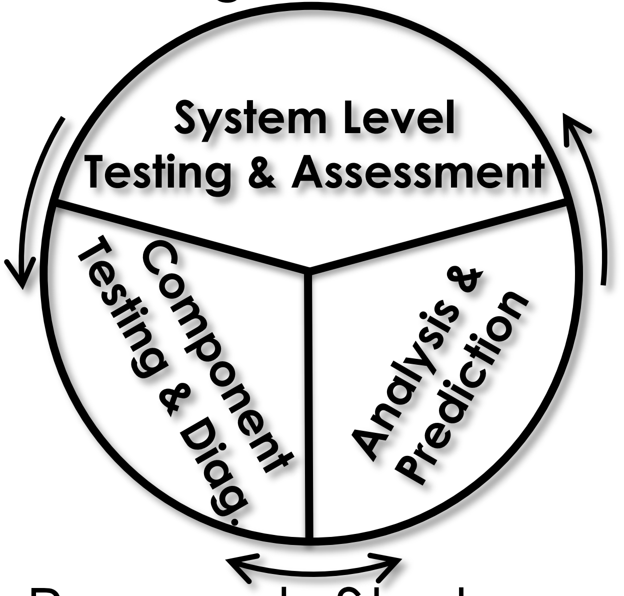
GE UDF Engine on MD-80 Aircraft (1987)

PW/Allison 578-DX Engine on MD-80 Aircraft (1989)

- The feasibility of open rotor technology and its fuel burn advantage were demonstrated in the 1980’s. <u>So what is new?</u>
- Improvements in 3D aerodynamic design tools has made possible the **development of open rotor systems with decreased noise emissions while maintaining their fuel burn performance**.

NASA Open Rotor Research Focus

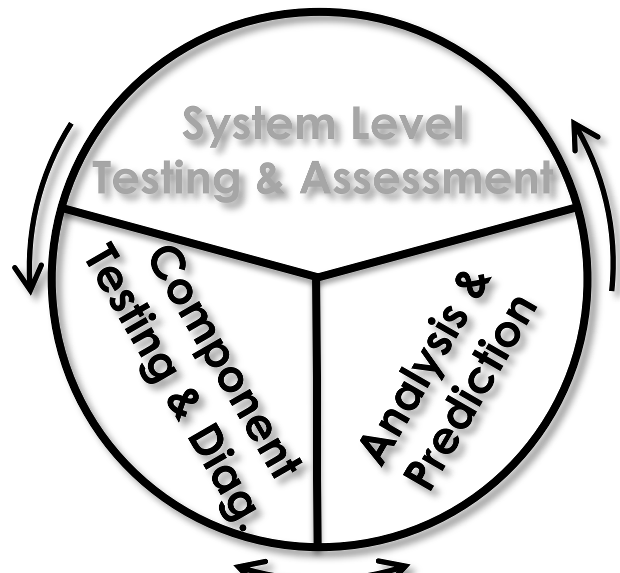
- In collaboration with industry and academic partners, NASA is exploring the design space for low-noise open rotor systems.
- The focus is on system level assessment of the merits of open rotor propulsion system in meeting NASA's subsonic transport goals.



Research Strategy

NASA Open Rotor Research Focus

- This presentation will cover **Component Testing & Diagnostics** and **Analysis & Prediction** efforts. System Level Testing and Assessment is currently being developed.



Research Strategy

Component Testing & Diagnostics

- NASA has been conducting detailed experiments to characterize the aerodynamics and aeroacoustics of an open rotor blade set called the GE HISTORICAL BASELINE. These include:
    - Sideline, phased and linear array data
    - Optical flow diagnostic data
    - Basic shielding experiments

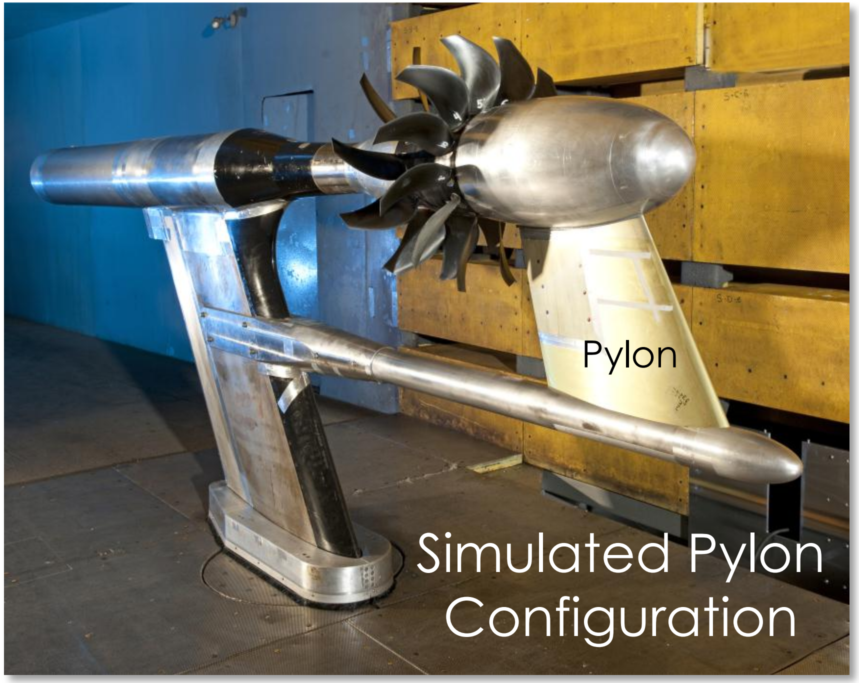
- In partnership with Boeing, NASA is also carrying out a propulsion aeroacoustics (PAA) test of a model open rotor in conjunction with both conventional and advanced airframe simulators.

Model Scale GE **HISTORICAL BASELINE** Blade Set Installed in NASA Wind Tunnel

Component Testing & Diagnostics

Test Hardware/Test Facility

Test Rig: NASA Open Rotor Propulsion Rig (10,000 rpm & 750 SHP per Rotor)

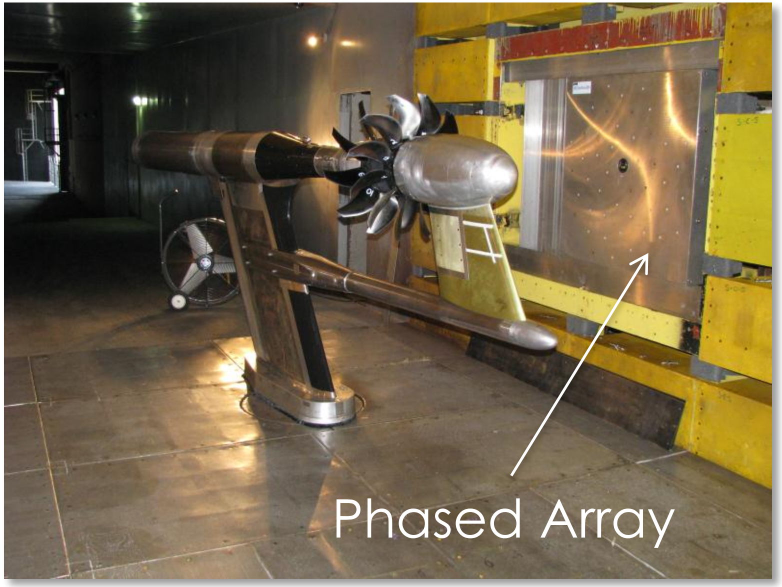


Open Rotor Rig Installed in NASA 9'x15' Acoustic Wind Tunnel

Lead Test Engineer/Coordinator: Dale Van Zante

Component Testing & Diagnostics

Phased Array

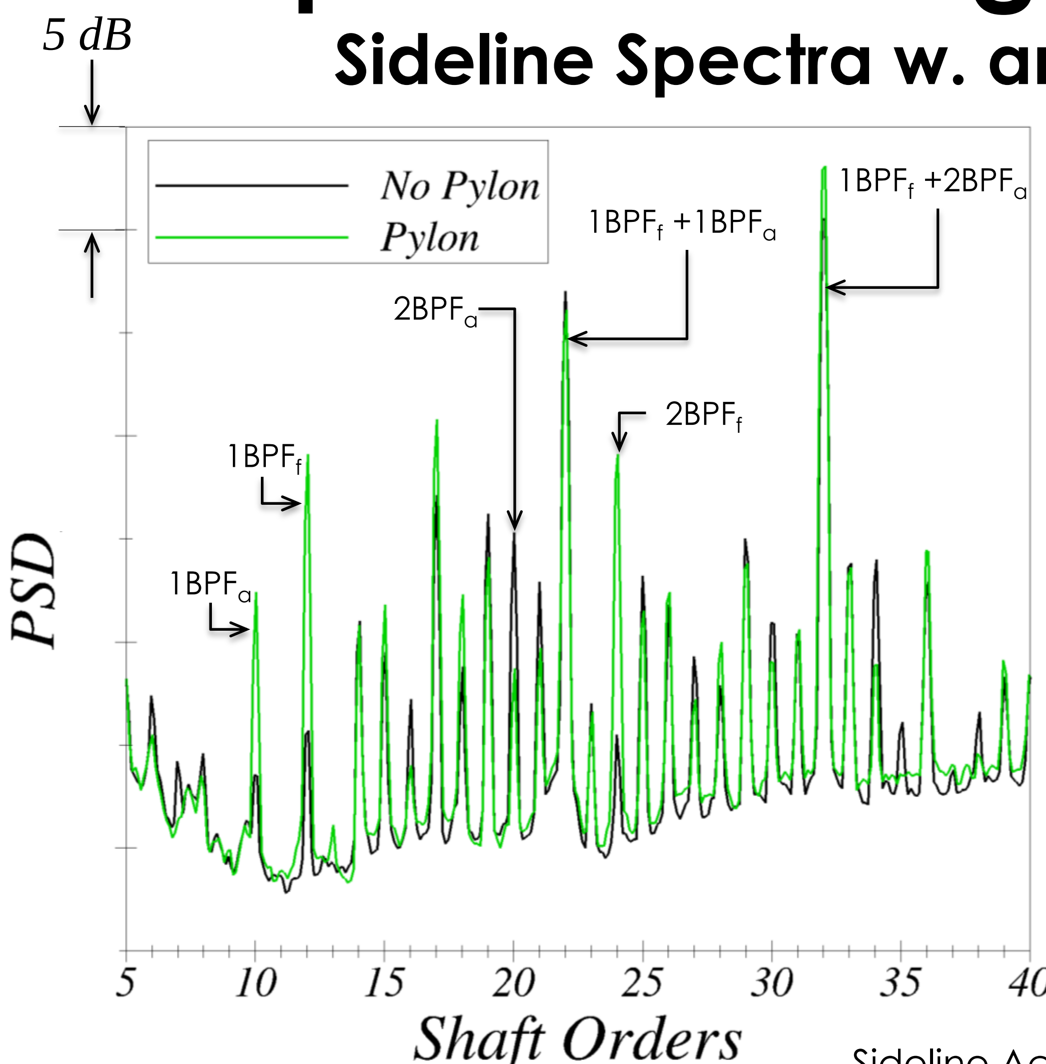


48-Microphone Phased Array System Deployed in NASA Acoustic Wind Tunnel

- Phased array is used for source diagnostic/localization purposes. The array is embedded in the tunnel sidewall broadside to the open rotor drive rig.

Component Testing & Diagnostics

Sideline Spectra w. and w/o Pylon



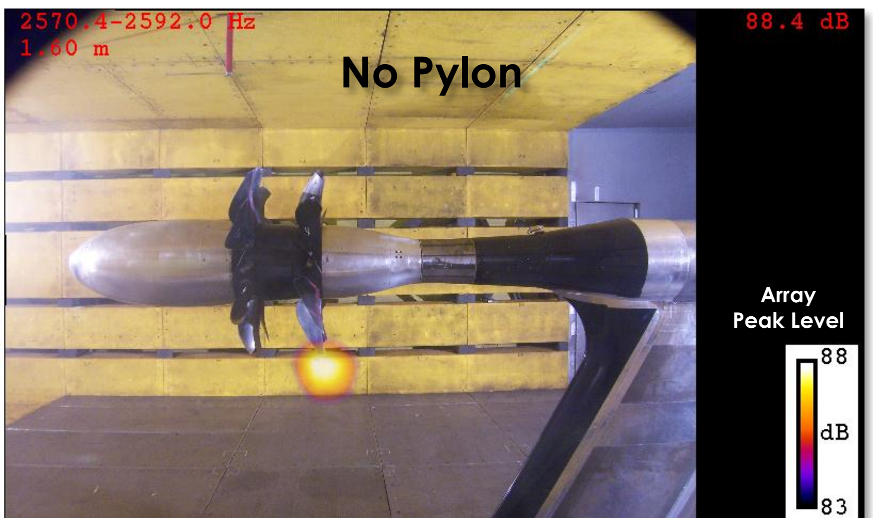
- As expected, the presence of the pylon induces distortions into blade rows causing noticeable increase in the levels of the individual rotor harmonics.
- By contrast, the interaction harmonics don't show as much sensitivity to the ingested distortion indicating their different origins.
- These differences can be localized and visualized using a phased array.

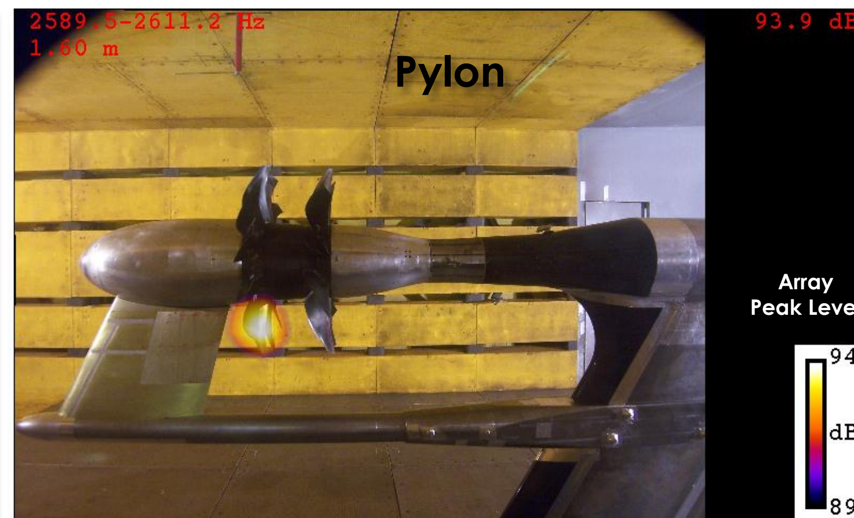
Sideline Acoustics Research Engineer: David Elliott

Component Testing & Diagnostics

Phased Array Sample Results

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



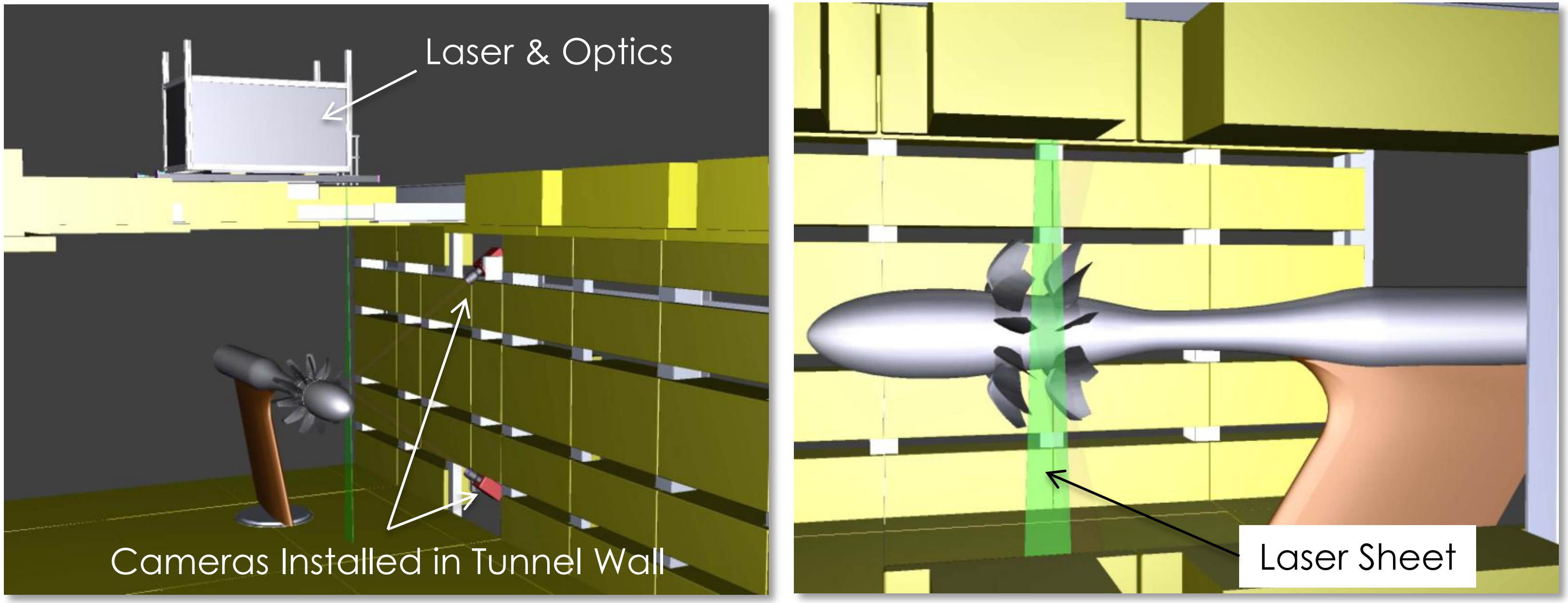


Phased Array Research Engineer: Gary Podboy

Component Testing & Diagnostics

Particle Image Velocimetry (PIV)

- PIV was used to map the flowfield of the baseline open rotor to track front blade row tip vortex and measure turbulence intensity between the blade rows. The results will be used for flow code validation and broadband noise prediction.



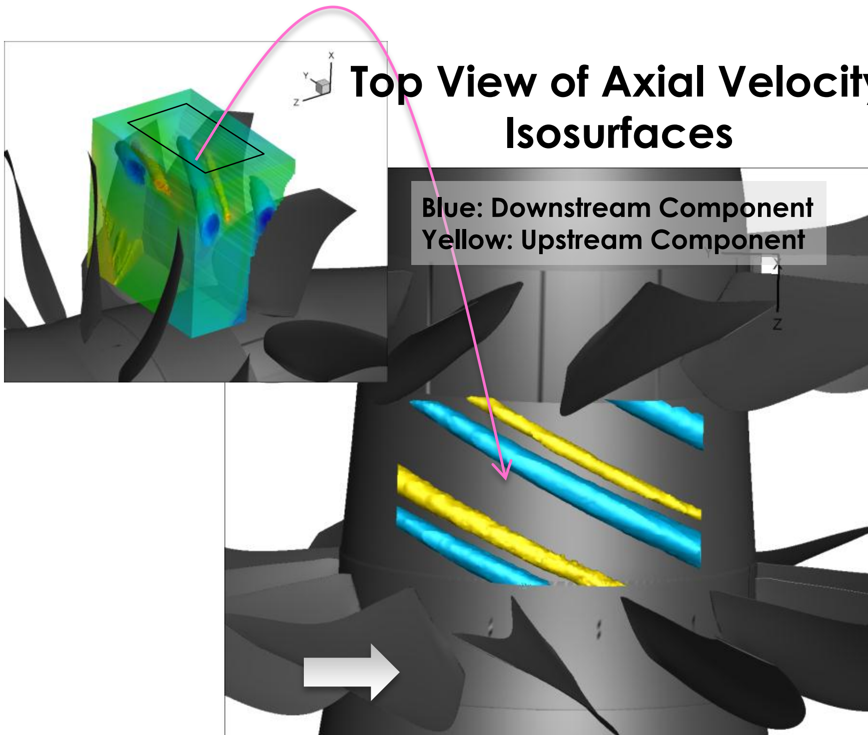
Sketch of A PIV System Deployed in NASA Acoustic Wind Tunnel

Component Testing & Diagnostics

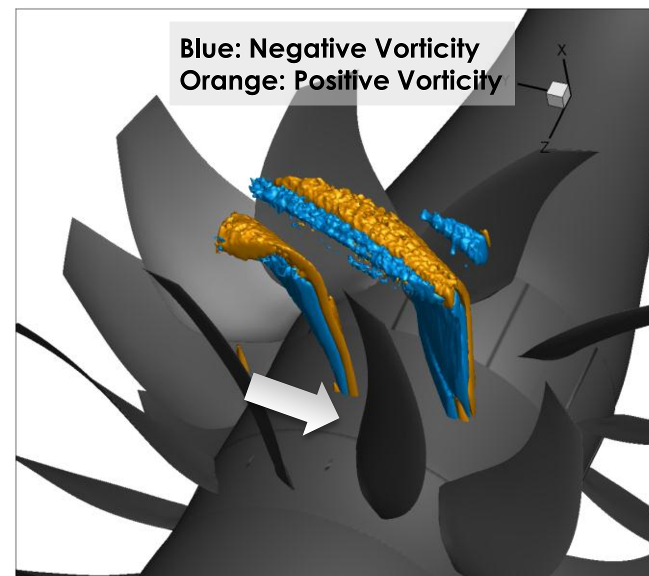
PIV Sample Results

- Left: Isosurfaces of the axial velocity component showing tip vortex trajectory.
- Right: Isosurfaces of vorticity magnitude showing blade wakes and vortex roll up.

Top View of Axial Velocity Isosurfaces



Vorticity Isosurfaces

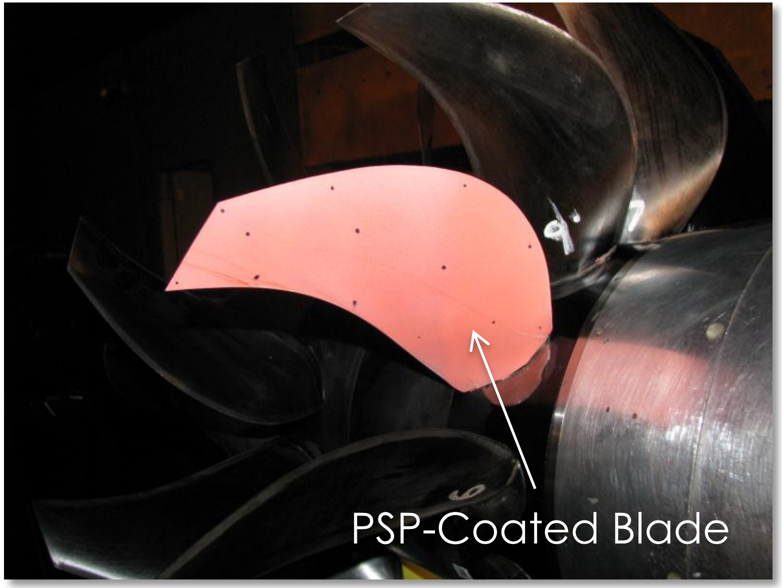


PIV Research Engineers: Mark Wernet, Adam Wroblewski and Randy Locke

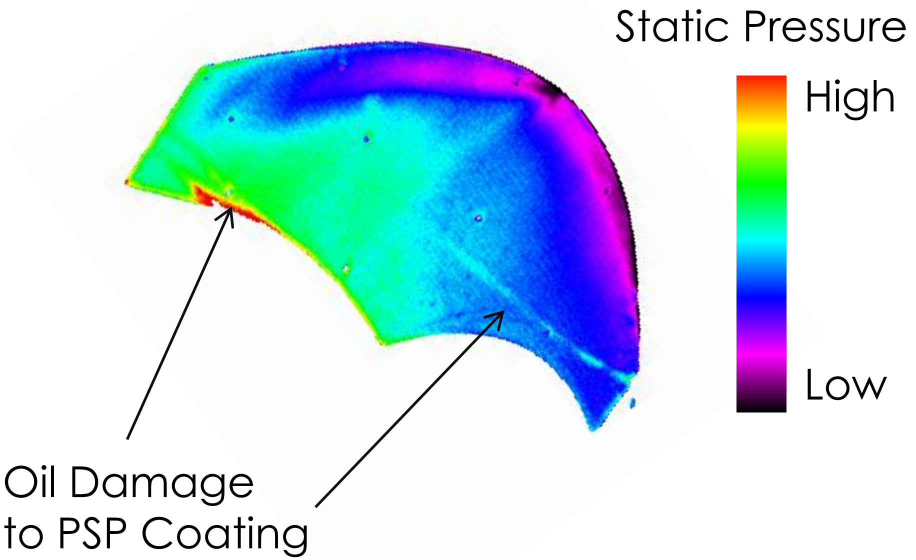
Component Testing & Diagnostics

Pressure Sensitive Paint (PSP) & Sample Results

- Unsteady PSP was used to acquire time variations of the static pressure distribution on the rotating blades.



Surface pressure acquired with PSP lifetime acquisition technique synchronized to the rotor



Snapshot in Time of Static Pressure Distribution on the Blade Suction Side

PSP Research Engineer: Tim Bencic

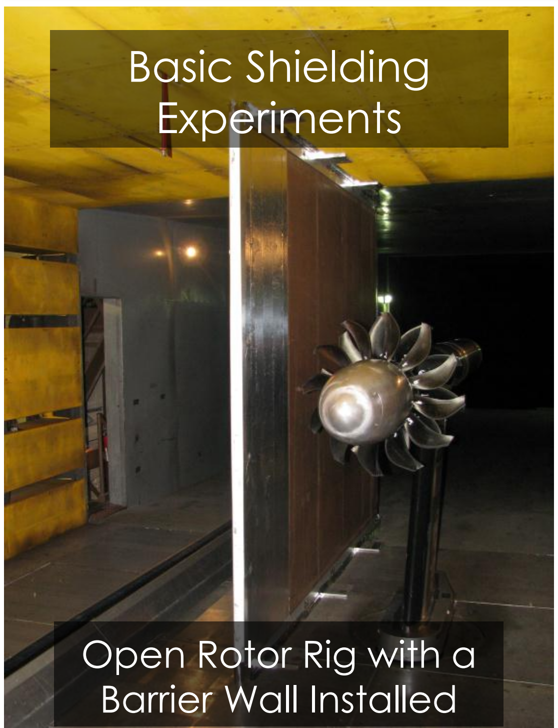
Acoustically Advantageous Propulsion Airframe Integration

Significant potential exists for blocking some of the engine noise directed towards the ground by judicious installation of the engines.

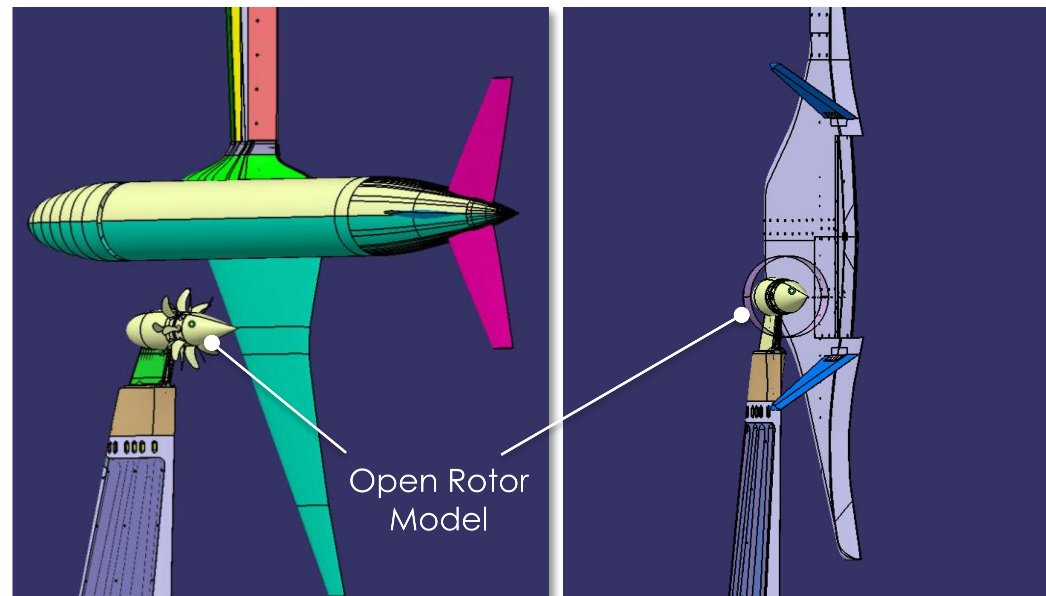
Component Testing & Diagnostics

Shielding and PAA Tests

Basic Shielding Experiment in NASA Wind Tunnel (Recently Completed)



Advanced Shielding (PAA)Experiment in Boeing's LSAF Facility (in Progress)



"Integration" with a Conventional Airframe

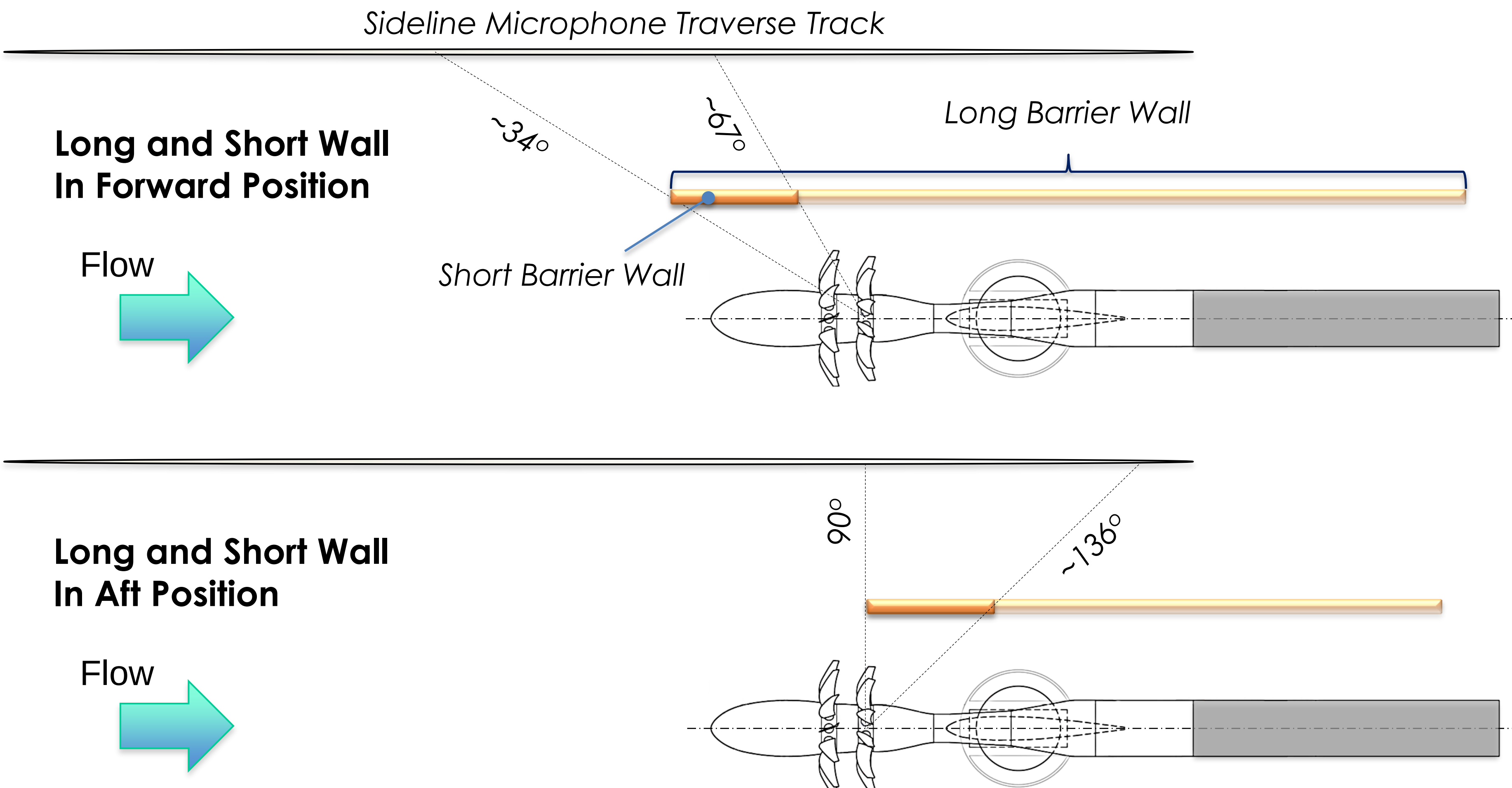
"Integration" with an Advanced Airframe

Shielding Test Engineer: David Stephens

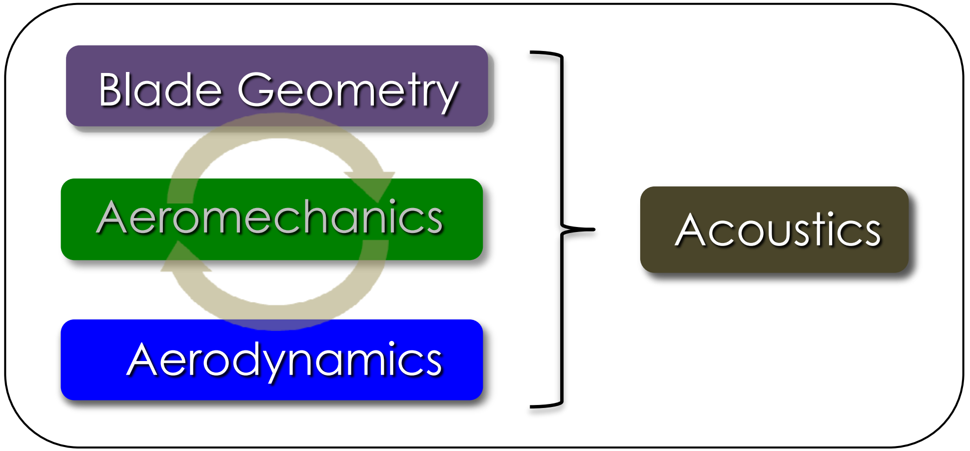
PAA Research Engineers: Michael Czech and Russ Thomas

Component Testing & Diagnostics

Basic Shielding Experiment Layout



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

Increasing Complexity →

Increasing Resource Req. →

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

Analysis & Prediction

Direct Noise Simulation Issues

- Fundamental challenge of direct aeroacoustic simulations is to predict, accurately, two vastly different ranges of pressure level scales simultaneously;
  - Aerodynamic: $p \,/\, p_{amb.} \sim O(1)$
  - Acoustic: $p \,/\, p_{amb.} \sim O(10^{-6})$
- Other challenges include the need for robust & efficient algorithms, good turbulence models, and parallel code capability among others.

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

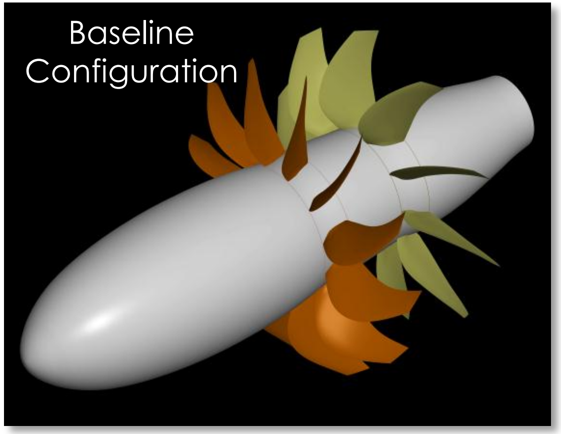
Analysis & Prediction

Source Noise Prediction Codes (Cont'd)

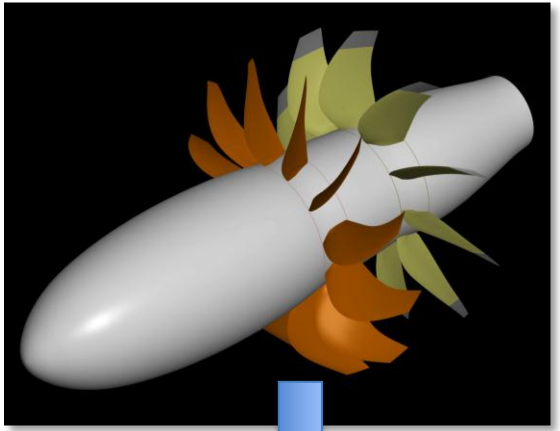
- Like ASSPIN, LINPROP and QPROP are based on the Ffowcs-Williams & Hawkings Equation and have similar features/capabilities/requirements. However, they are formulated in the frequency-domain and use large-blade-count asymptotic approximation to compute the various source terms.
  - The asymptotics are 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

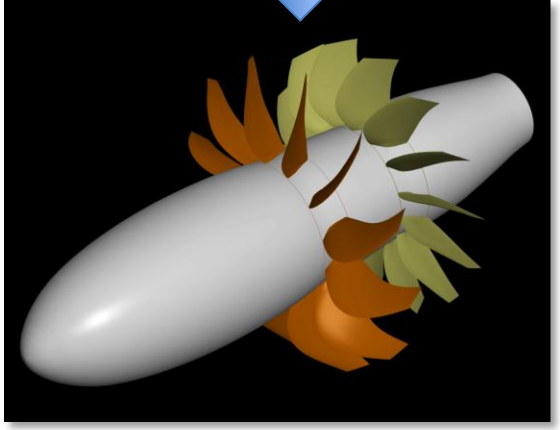
Low-Noise Configurations to Be Investigated



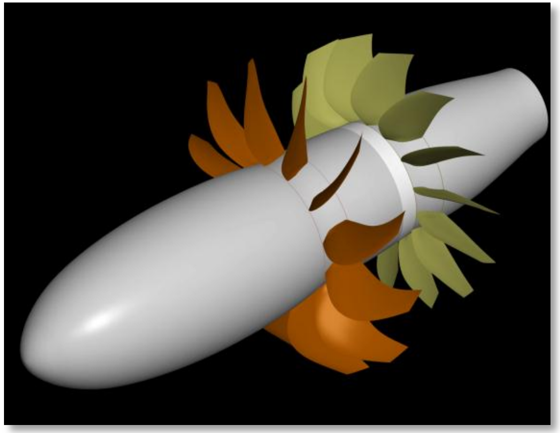
Aft Blade Clipping



Blade Count Increase



Blade Row
Spacing Increase



Analysis & Prediction

Noise Shielding/Scattering Prediction Code

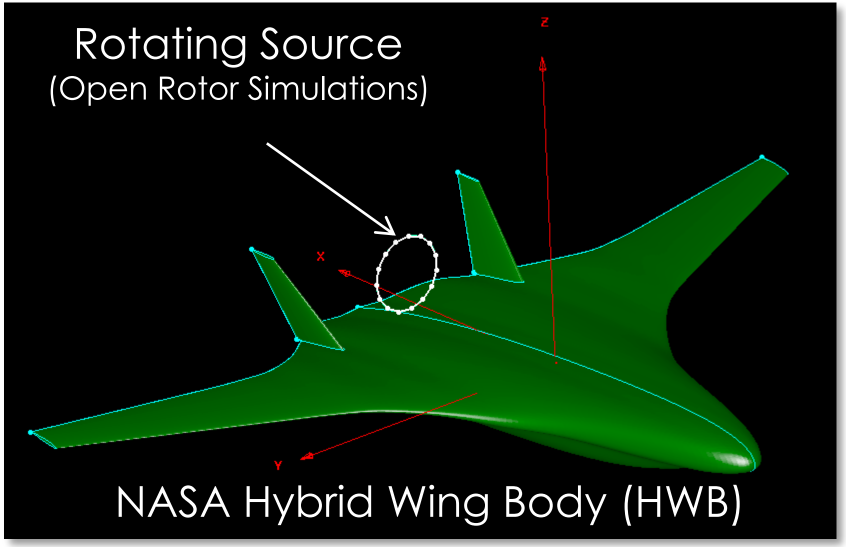
- Fast Scattering Code (FSC) is a numerical code for calculating the scattering and reflection of incident acoustic waves on an arbitrary surface.
- It is based on the equivalent sources method and uses fast multi-pole technique to reduce CPU time requirements.

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*

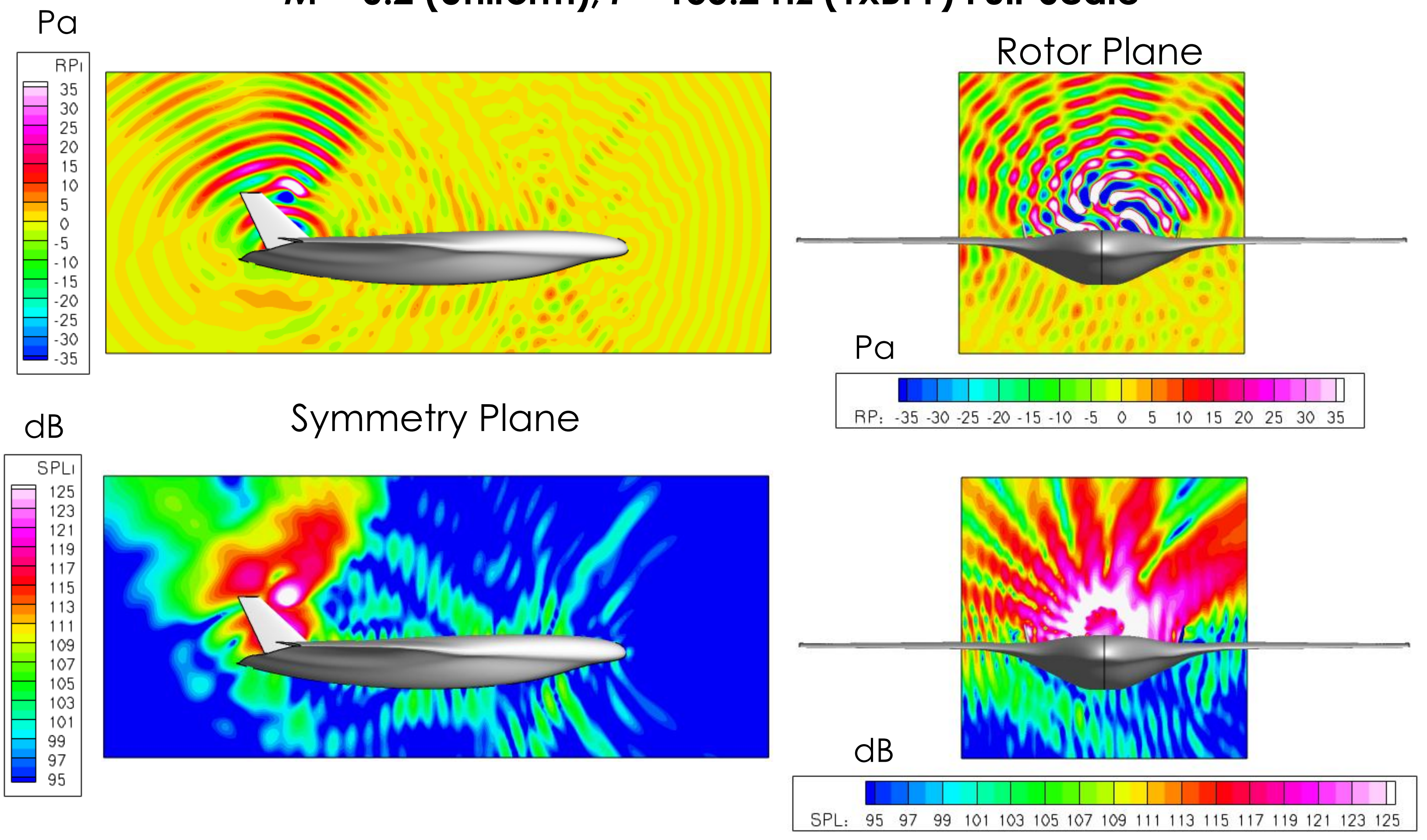


FSC Code Research Engineers: Ana Tinetti & Mark Dunn

Analysis & Prediction

Shielding/Scattering Prediction Sample Results

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



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.

Questions?

ABSTRACT

Owing to their inherent fuel burn efficiency advantage compared with the current generation high bypass ratio turbofan engines, there is resurgent interest in developing open rotor propulsion systems for powering the next generation commercial aircraft. However, to make open rotor systems truly competitive, they must be made to be acoustically acceptable too. To address this challenge, NASA in collaboration with industry is exploring the design space for low-noise open rotor propulsion systems. The focus is on the system level assessment of the open rotors compared with other candidate concepts like the ultra high bypass ratio cycle engines. To that end there is an extensive research effort at NASA focused on component testing and diagnostics of the open rotor acoustic performance as well as assessment and improvement of open rotor noise prediction tools. In this presentation and overview of the current NASA research on open rotor noise will be provided. Two NASA projects, the Environmentally Responsible Aviation Project and the Subsonic Fixed Wing Project, have been funding this research effort.