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

Ed Envia
NASA Glenn Research Center
U.S.A.

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

The research described here is sponsored and funded by NASA’s Environmentally Responsible Aviation (ERA) and the Subsonic Fixed Wing (SFW) projects. Dr. Fay Collier is the ERA Project Manager and Dr. Rubén Del Rosario is the SFW Project Manager.

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

### Noise (cum below Stage 4)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Noise (cum below Stage 4)</td>
<td>-32 dB</td>
<td>-42 dB</td>
<td>-71 dB</td>
</tr>
</tbody>
</table>

### LTO NOx Emissions (below CAEP 6)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>LTO NOx Emissions (below CAEP 6)</td>
<td>-60%</td>
<td>-75%</td>
<td>better than -75%</td>
</tr>
</tbody>
</table>

### Performance: Aircraft Fuel Burn

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance: Aircraft Fuel Burn</td>
<td>-33%</td>
<td>-50%**</td>
<td>better than -70%</td>
</tr>
</tbody>
</table>

### Performance: Field Length

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance: Field Length</td>
<td>-33%</td>
<td>-50%</td>
<td>exploit metro-plex* concepts</td>
</tr>
</tbody>
</table>

***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

Current Rule: Stage 4 Baseline Area

N: Stage 4 – 10 dB cum. Area = 55% of Baseline

N+1: Near-Term Goal Area = 15% of Baseline

N+2: Mid-Term Goal Area = 8% of Baseline

N+3: Far-Term Goal Area <2% of Baseline

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

Carbon Neutral Growth/Reduction Timeline

- Baseline
- Carbon neutral growth
- Carbon overlap
- Forecasted Carbon Emissions Growth (Without Improvements)
- Operational Improvements — On-going Fleet Renewal
- Additional Technology Advancement & Low Carbon Fuels
- With Improvement

Source: IATA 2010
Icons represent notional numbers based on published information.

Open rotors have the potential for significant fuel burn savings. The challenge is to make them acoustically competitive.
The feasibility of open rotor technology and its fuel burn advantage were demonstrated in the 1980’s. So what is new?

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.
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

- System Level Testing & Assessment
- Component Testing & Diag.
- Analysis & Prediction

Research Strategy
This presentation will cover Component Testing & Diagnostics and Analysis & Prediction efforts. System Level Testing and Assessment is currently being developed.
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.
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
Phased array is used for source diagnostic/localization purposes. The array is embedded in the tunnel sidewall broadside to the open rotor drive rig.

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.
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.
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.
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.

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

PSP Coated Blade

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

Static Pressure

High

Low

Oil Damage to PSP Coating

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)

Open Rotor Rig with a Barrier Wall Installed

Open Rotor Model

“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

Long Barrier Wall
Long and Short Wall
In Forward Position
Flow

Sideline Microphone Traverse Track

Long Barrier Wall

Short Barrier Wall

Long and Short Wall
In Aft Position
Flow

90°
~34°
19°
~136°
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

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.
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.
ASSPIN (Advanced Subsonic and Supersonic Propeller Induced Noise) 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
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

- Baseline Configuration
- Aft Blade Clipping
- Blade Count Increase
- Blade Row Spacing Increase
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

$p_{\text{eq}} = 0.2$ (Uniform), $f = 155.2$ Hz (1xBPF) Full-Scale

Symmetry Plane

Rotor Plane
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.