Aircraft Engine Noise Research and Testing at the NASA Glenn Research Center

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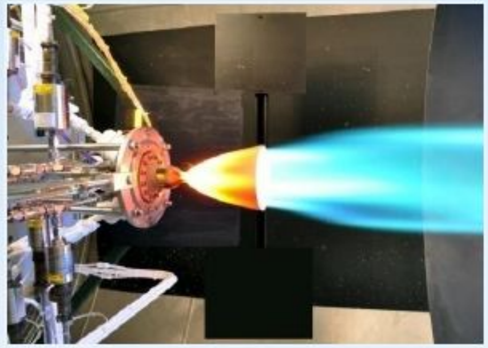
November 6th, 2015

NASA Glenn Research Center

- 1941 -Aircraft Engine Research Laboratory under National Advisory Committee for Aeronautics (NACA)
- 1958 - Renamed Lewis Research Center and incorporated into NASA
- 1999 – Renamed John H. Glenn Research Center
- Center of Excellence in Turbomachinery
- Diversified into certain areas of space research/ management e.g. microgravity, electric propulsion, space power and communications
- Main facility adjacent to Cleveland Hopkins International Airport, second facility Plum Brook near Sandusky

Glenn Core Work Areas

Air-Breathing Propulsion



In-Space Propulsion and Cryogenic Fluids Management

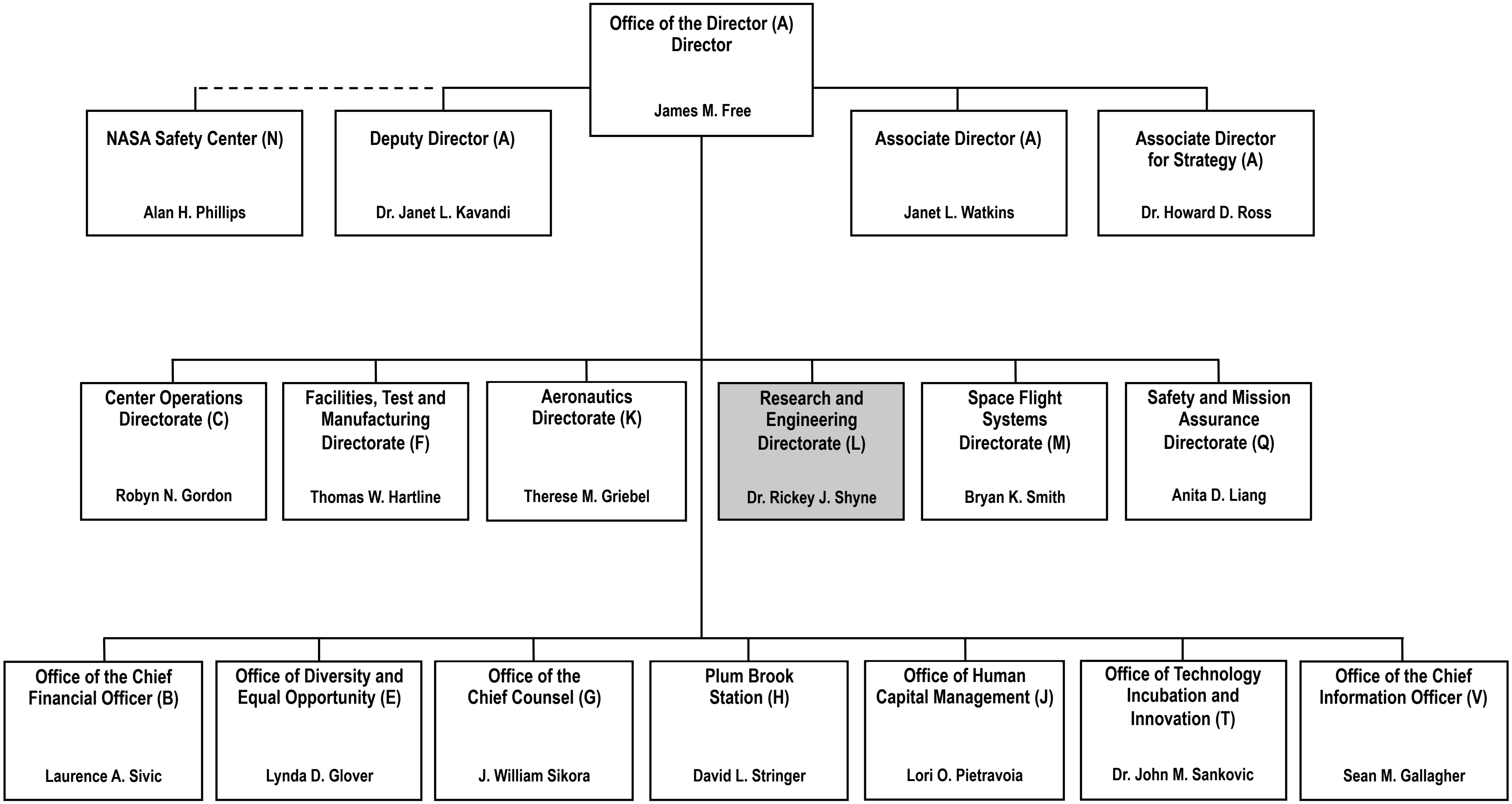
Physical Sciences and Biomedical Technologies in Space

Communications Technology and Development

Power, Energy Storage and Conversion

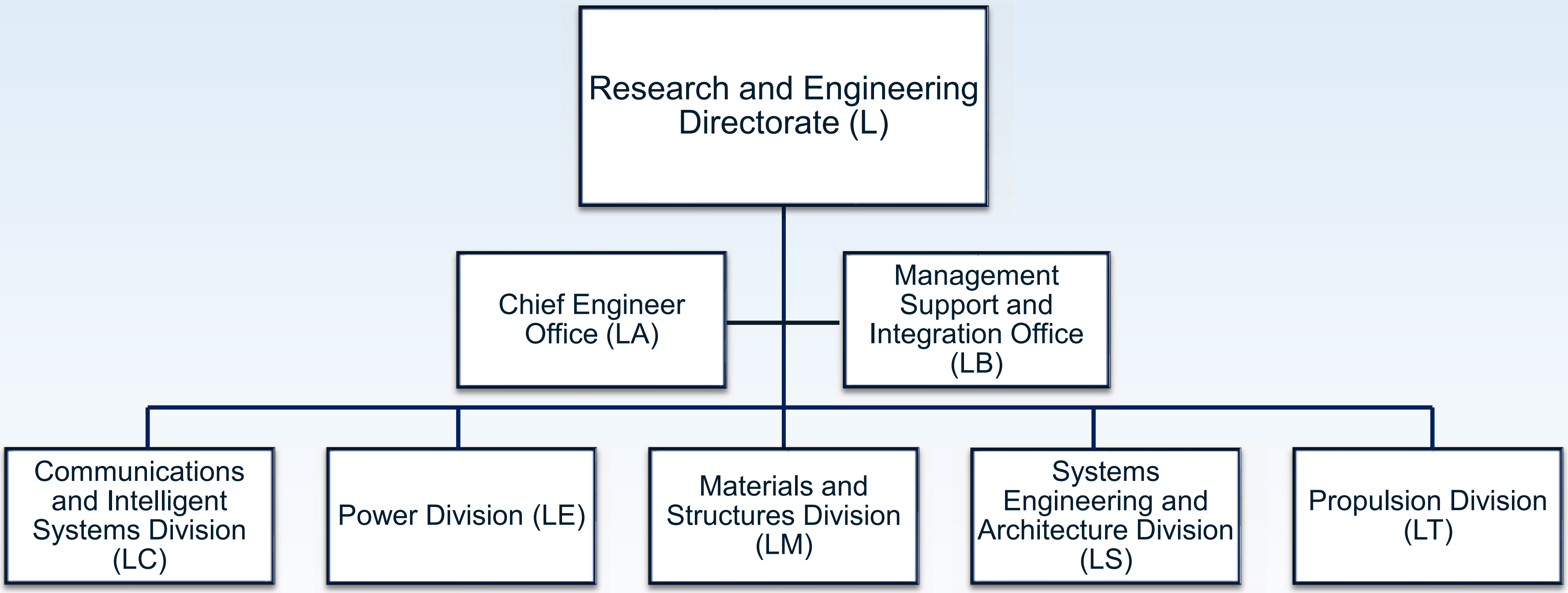
Materials and Structures for Extreme Environments

Acoustics Branch within NASA Glenn Organization



Enclosure 1

Research and Engineering Directorate



For more information on Glenn's Organizational Structure please visit: http://www.grc.nasa.gov/WWW/OHR/Orglist/

Enclosure 2

Propulsion Division

- Propulsion Division (LT)
  - Chemical and Thermal Propulsion Systems Branch (LTR)
  - Electric Propulsion Systems Branch (LTS)
  - Thermal Systems Branch (LTT)
  - Fluid and Cryogenic Systems Branch (LTF)
  - Propulsion Systems Analysis Branch (LTA)
  - Turbomachinery and Turboelectric Systems Branch (LTE)
  - Inlets and Nozzles Branch (LTN)
  - Engine Combustion Branch (LTC)
  - Icing Branch (LTI)
  - Acoustics Branch (LTV)
  - Combustion Physics and Reacting Systems Branch (LTX)
  - Fluid Physics and Transport Processes Branch (LTZ)

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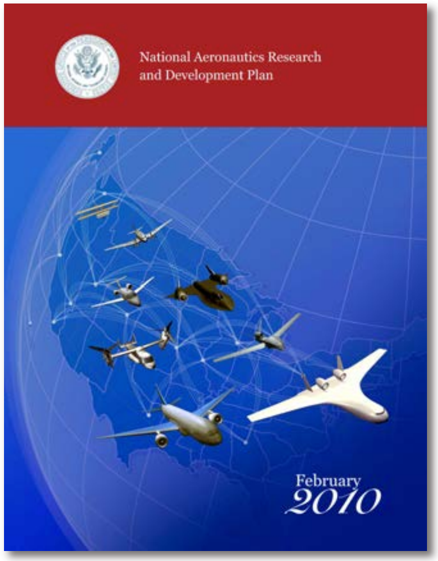
NASA Aeronautics Programs

- Most acoustic research/testing done under NASA agency programs/projects with milestones
- Some Example Programs/Projects
  - Previous
    - Late 1990's/Early 2000's - Advanced Subsonic Technology (AST) and Quiet Aircraft Technology (QAT)
  - Recent
    - Fundamental Aeronautics Program - Subsonic Fixed Wing Project – longer range technology
    - Environmentally Responsible Aviation Program –near term technology
    - Advanced Air Vehicles Program – Advanced Air Transport Technology - present

http://www.aeronautics.nasa.gov/programs.htm

U.S. Subsonic Transport Noise Goals

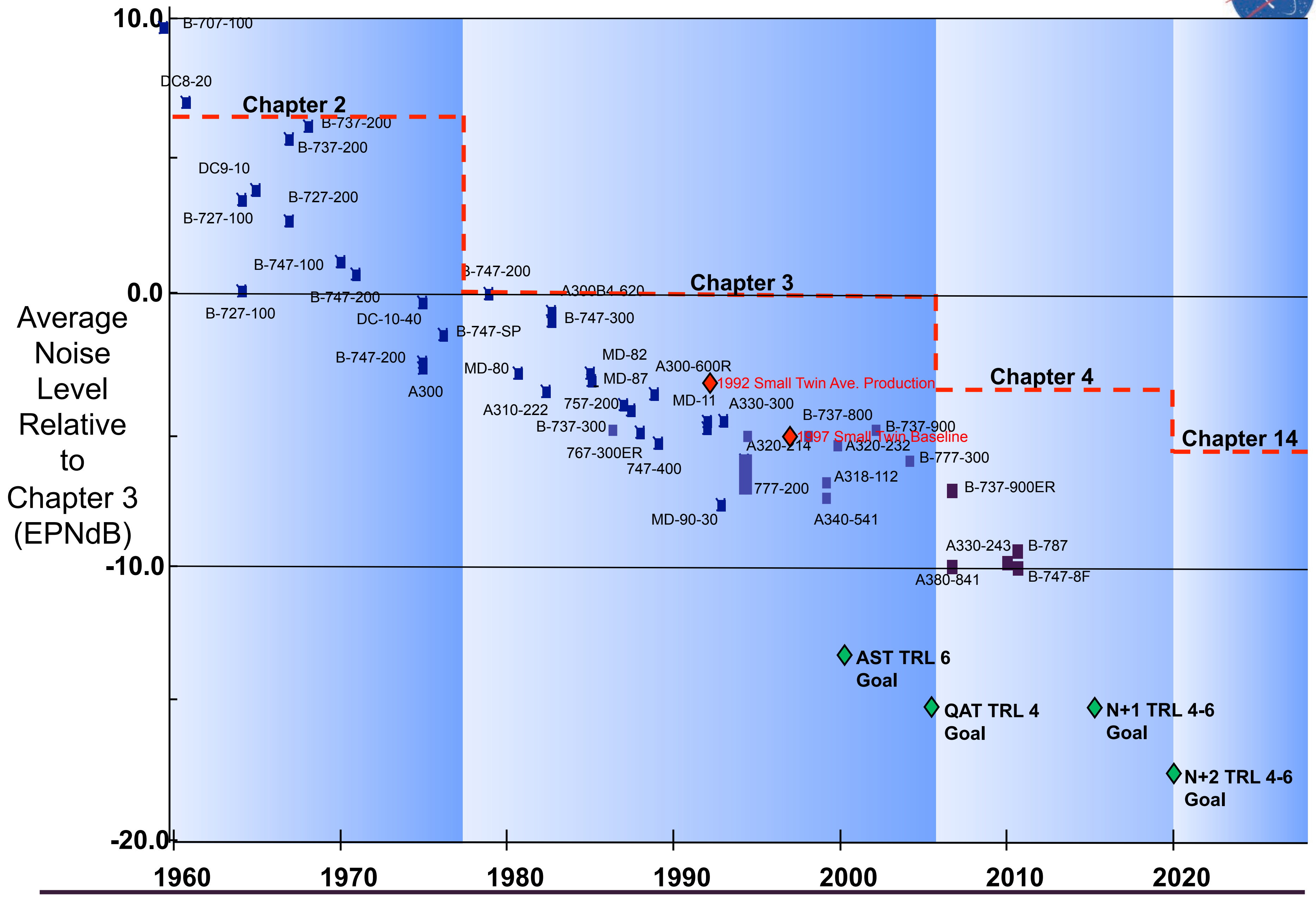
- ❖ To reduce the impact of aviation on the environment, NASA has adopted a set of aggressive noise, emissions, and fuel burn goals for future subsonic transport aircraft.
- ❖ The environmental goals are traceable to the U.S. National Aeronautics Research and Development Plan.



TECHNOLOGY BENEFITS*	TECHNOLOGY GENERATIONS (Technology Readiness Level: 4 – 6)		
	N+1 (2015)	N+2 (2020**)	N+3 (2025)
Noise (cumulative margin rel. to Stage 4)	-32 dB	-42 dB	-52 dB
LTO No_x Emissions (rel. to CAEP 6)	-60%	-75%	-80%
Cruise No_x Emissions (rel. to 2005 best in class)	-55%	-70%	-80%
Aircraft Fuel/Energy Consumption*** (rel. to 2005 best in class)	-33%	-50%	-60%

* Projected benefits once technologies are matured and implemented by industry. Benefits vary by vehicle size. N+1 and N+3 values are referenced to a 737-800 with CFM56-7B engines; N+2 values are referenced to a 777-200 with GE90 engines.
** ERA's time-phased approach includes advancing "long-pole" technologies to TRL 6 by 2015.
*** CO_2 emission benefits depend on life-cycle CO_{2e} per MJ for fuel and/or energy source used.

Subsonic Aircraft Noise Levels & Research Goals

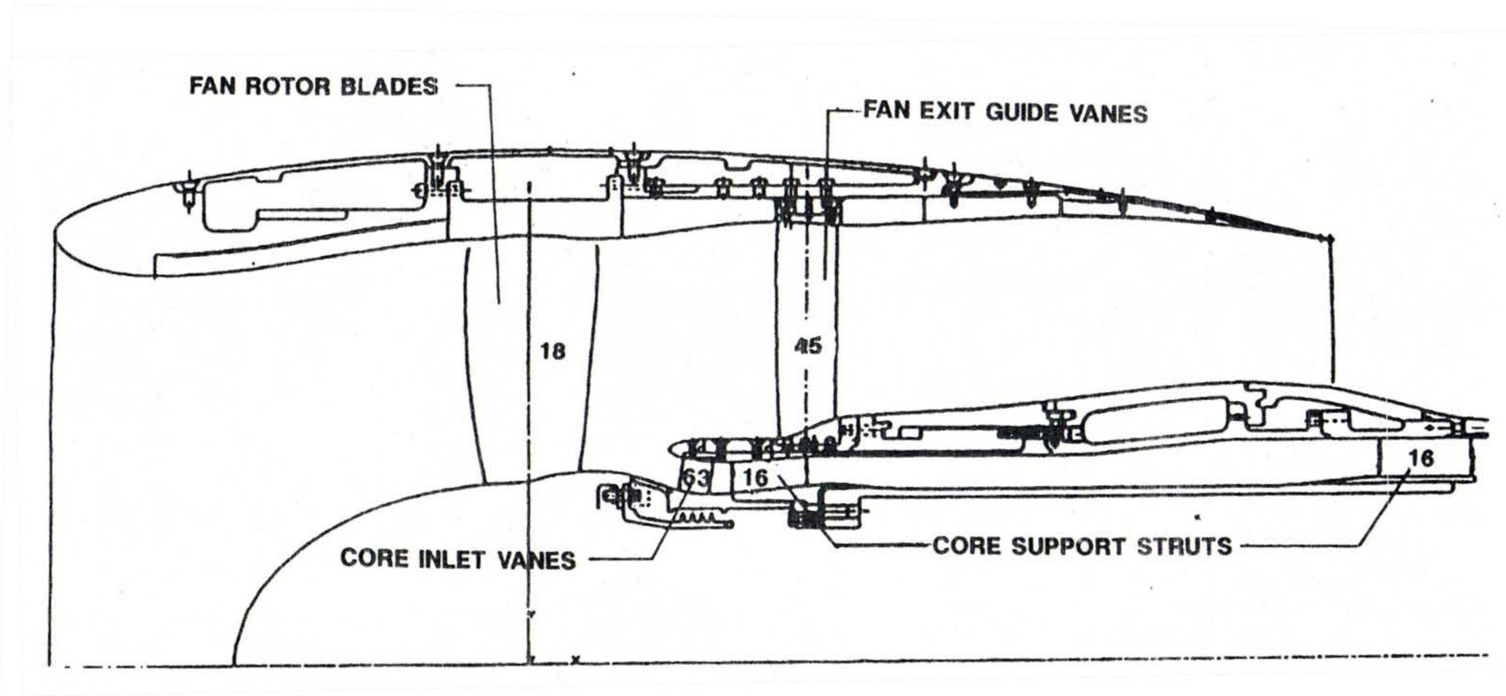


Acoustics Branch Research Focus

Conduct research for reduction of aircraft propulsion system noise

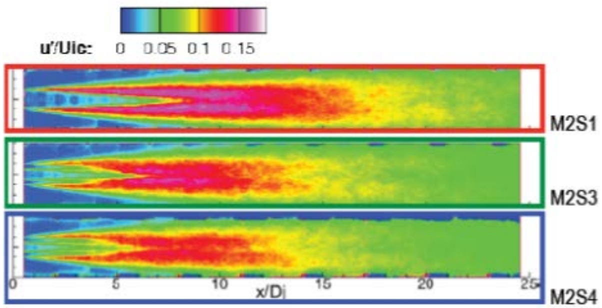
- Focus on engine **noise reduction** technologies that maintain acceptable aerodynamic performance for both subsonic and supersonic applications.
- Perform **diagnostic** experimental and analytical studies to understand underlying fundamental physics of noise generation and mitigation.
- Engine noise **prediction** codes are developed and validated using experimental data ranging from empirical to Computational Aeroacoustics (CAA) tools that directly compute the noise generation and propagation.
- Maintain world-class experimental capability in the 9x15 Low Speed Wind Tunnel, Aero-Acoustic Propulsion Lab, and the Acoustical Testing Lab. Use capability for concept validation, to generate benchmark databases for code development, and available for reimbursable use.

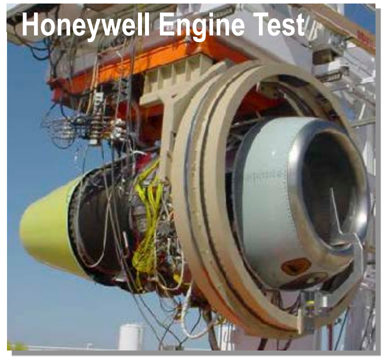
Cross Sectional Drawing of Turbofan Model used in Wind Tunnel Testing



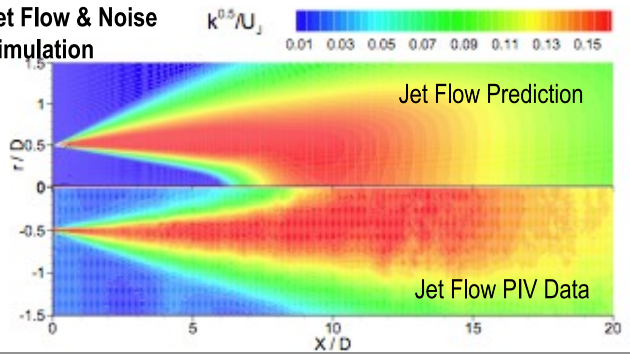
RTA/ Acoustics Branch

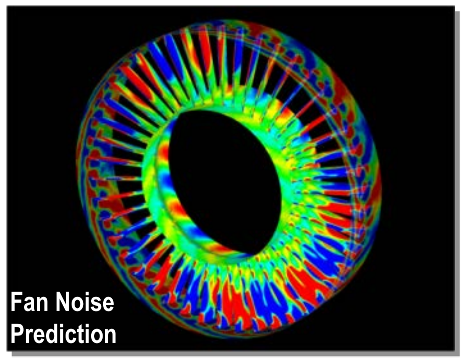
Jet Flow Turbulence via PIV

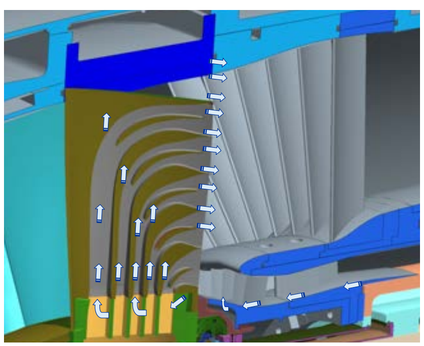




Jet Flow & Noise Simulation







Trailing Edge Blowing for Fan Noise Reduction

Nozzle Chevrons for Jet Noise Reduction

Noise Diagnostics

- Concept Investigation
- Engine Noise Source Identification

Noise Prediction

- Model Development
- Simulations

Noise Reduction

- Concept Development
- Testing & Evaluation

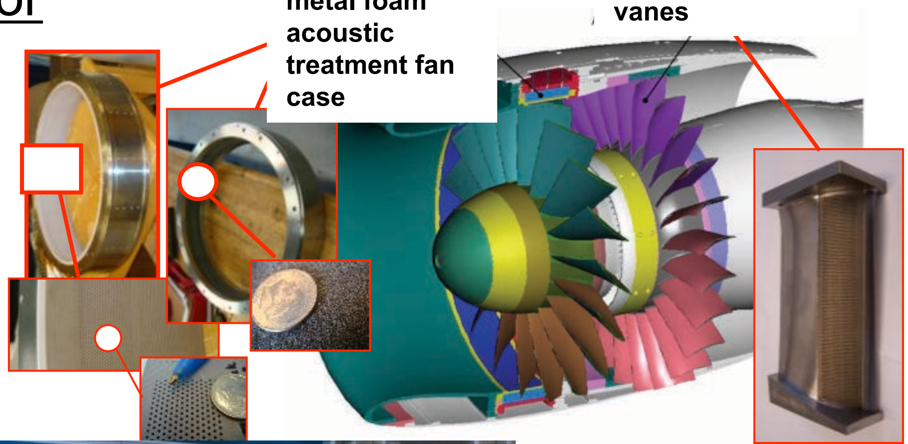
Noise Reduction

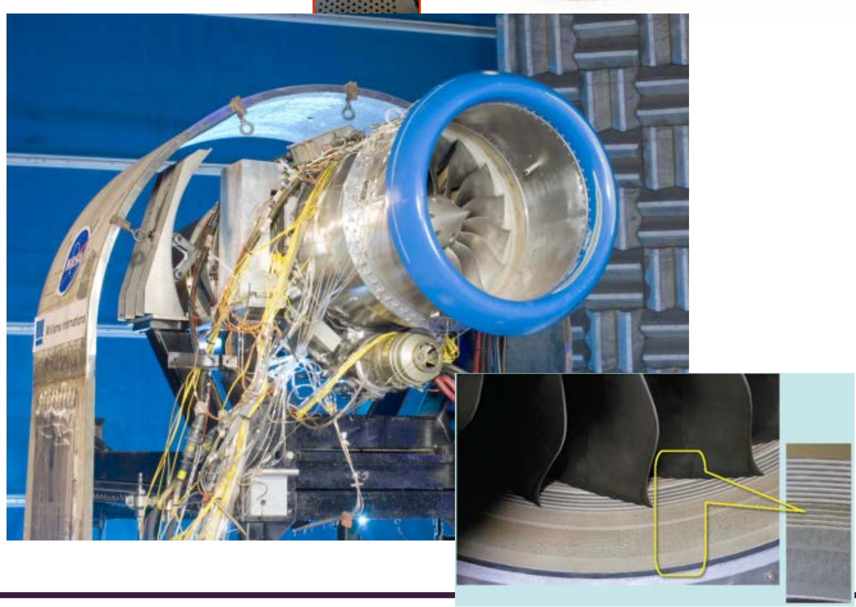
Source Noise, Attenuation, Cancellation

Propulsor

Over-the-Rotor metal foam acoustic treatment fan case

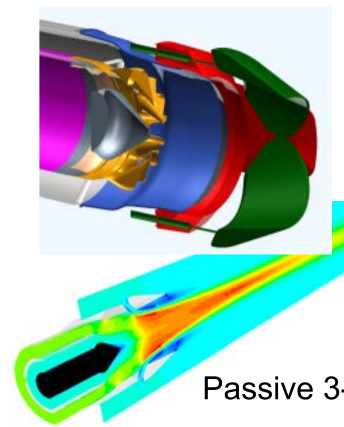
Acoustically treated soft vanes





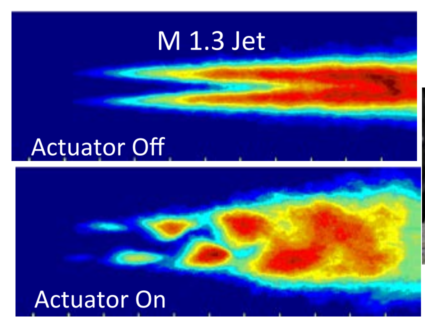
Exhaust Systems

Model hardware



Passive 3-D nozzle concepts

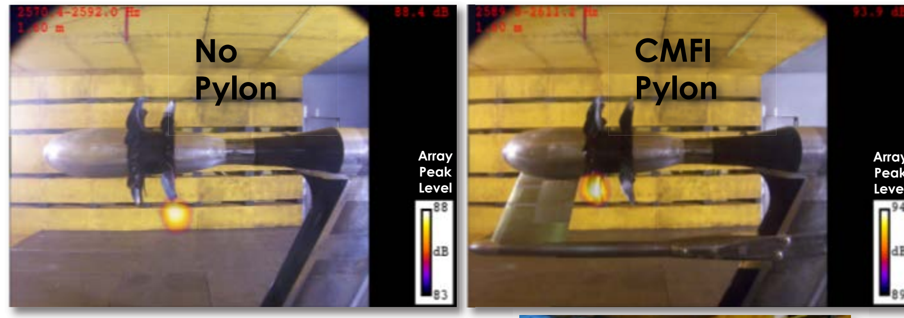
Active control of jet

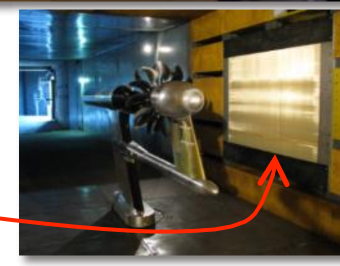


Diagnostics

Phased Arrays, PSP, PIV, HW/HF, Rotating Rake, FF Microphone

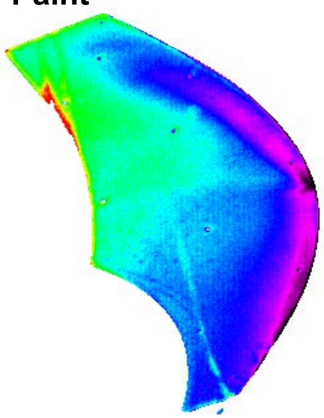
In a cooperative effort with NAVAIR, phased array measurements were obtained for an F404 engine with a modified nozzle that included chevrons



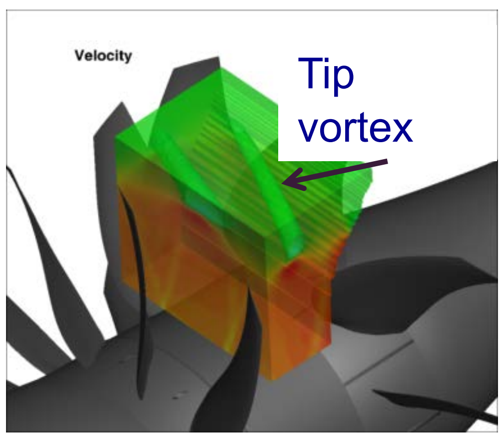


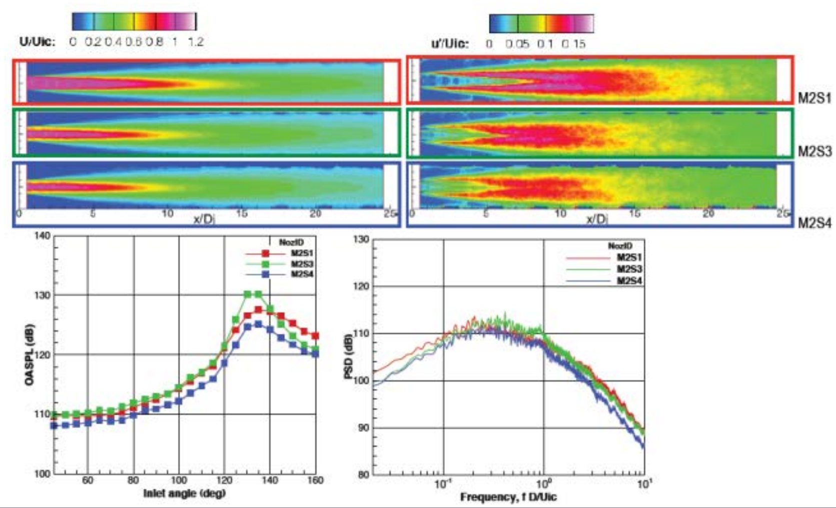
Flush Kevlar Acoustic Cover

Pressure Sensitive Paint



Particle Image Velocimetry (PIV)

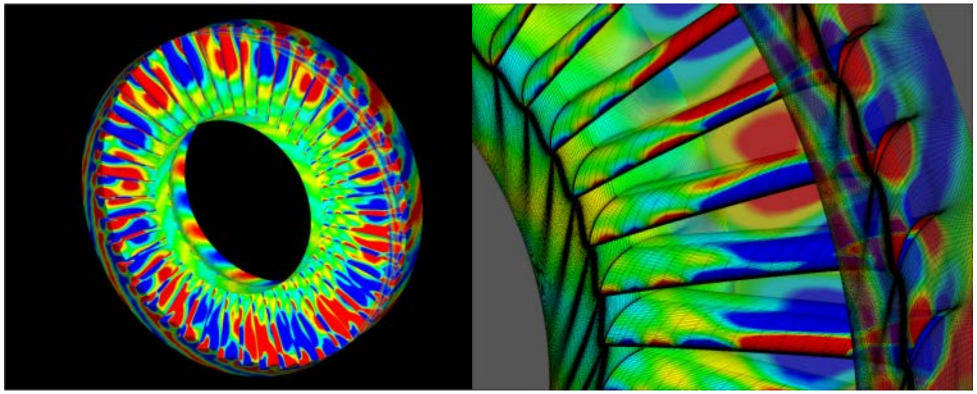




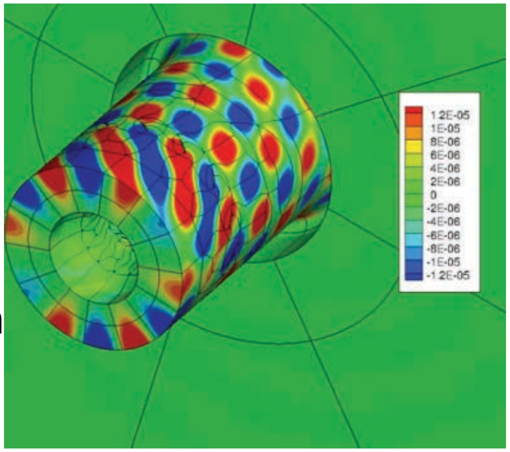
Prediction

Empirical (ANOPP), RANS Based, Non-Linear High Order

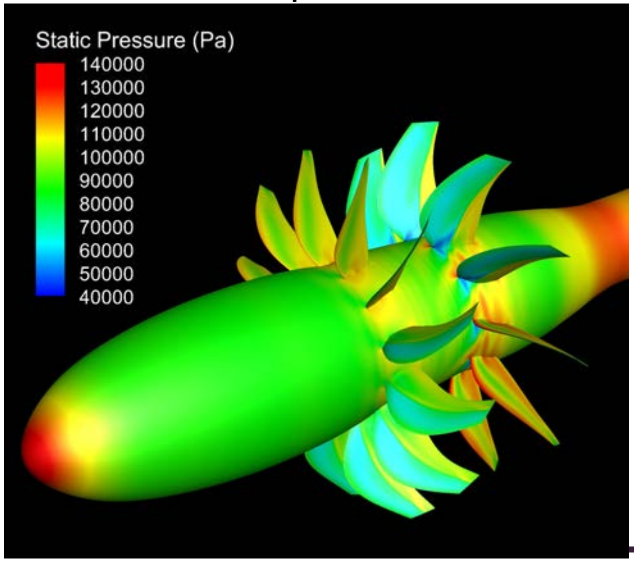
FEGV Wake Interaction, RANS Based



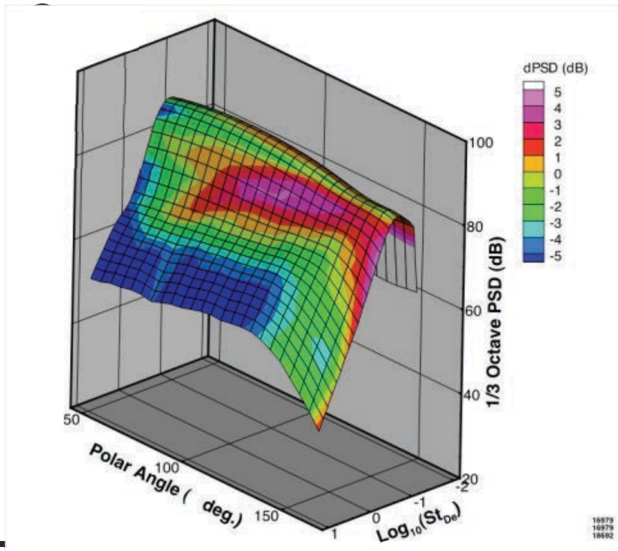
Broadband Aeroacoustic Stator Simulation (BASS) Code, ANCF simulation, high order, high accuracy



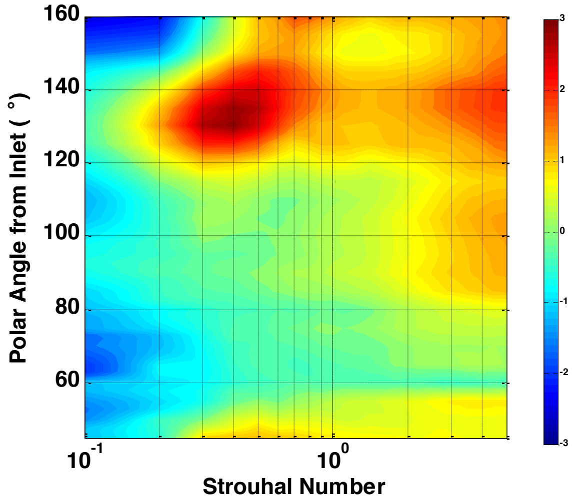
Fine Turbo, Open Rotor RANS



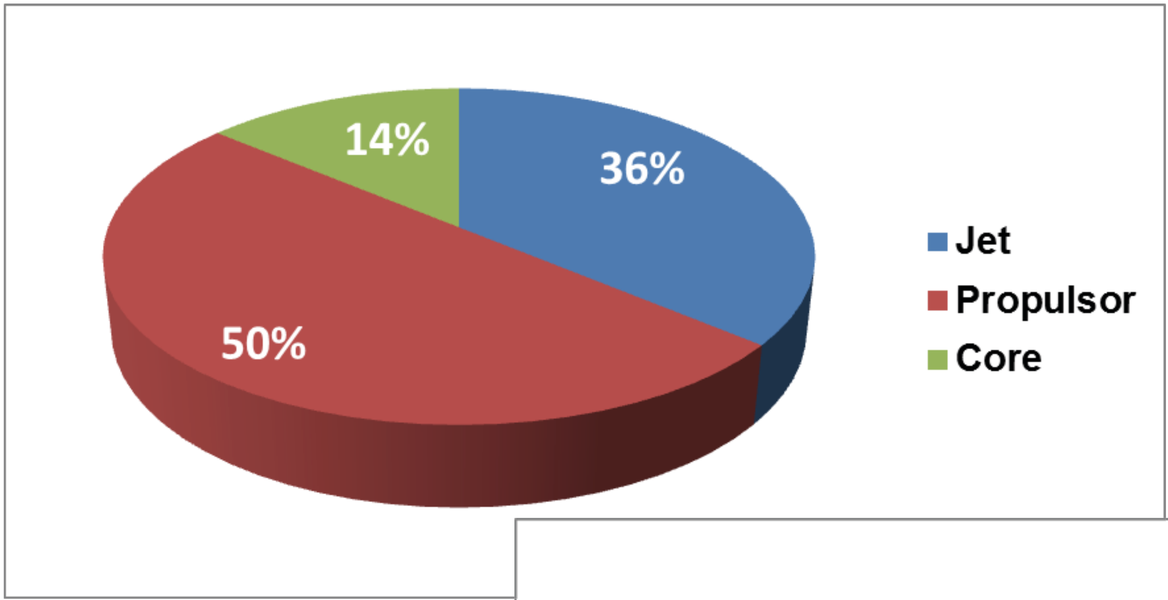
dPSD = (PSD Modeled) – (PSD Measured)

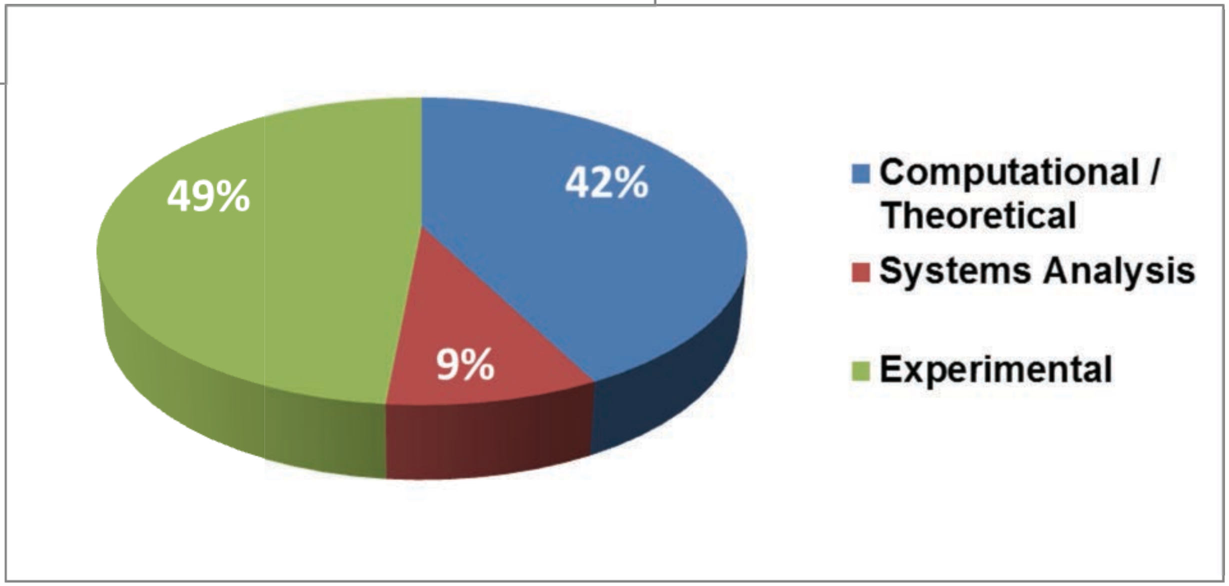


Twin Jet Effect: Sample, ΔSPL



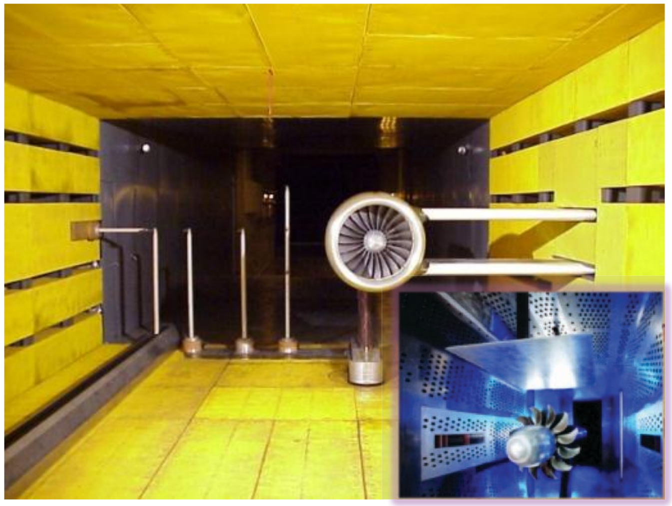
Distribution by Technical Focus





Facilities and Advanced Testing Techniques for Database Generation and Concept Evaluation for Exhaust Systems, Fan Systems, Open Rotors, and small engines.

Aero-acoustic Propulsion Lab

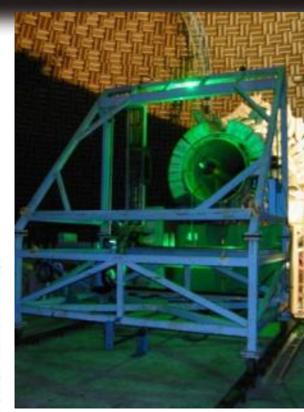


9x15/8x6 Wind Tunnel

Acoustical Testing Lab (ATL)

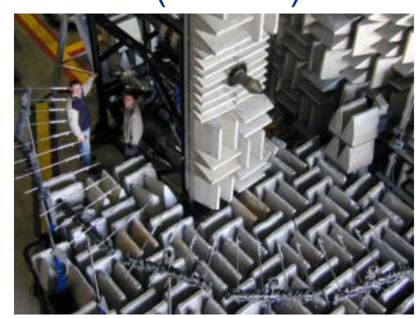
CW-17 Free Jet Facility

Advanced Noise Control Fan (ANCF)



Nozzle Acoustic Test Rig (NATR)

Small Hot Jet Acoustic Rig (SHJAR)

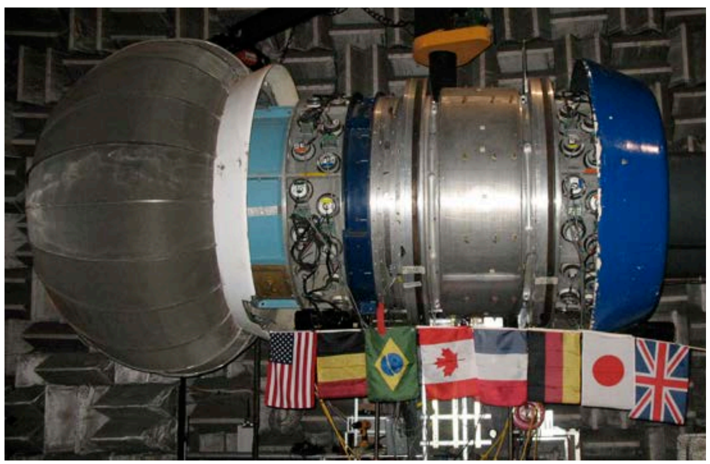


Advanced Noise Control Fan

Design, test, and evaluation for technical risk-mitigation of most of the innovative fan noise reduction technologies developed by NASA over the past 20 years.

1992 – 2014 : Low-TRL research performed on ANCF enabled the advancement of multiple noise reduction and measurement technologies.

The ANCF has been used in over 6 internal, 8 external programs (2 reimbursable), 2 NRAs, 3 SBIRs, and 2 Aero Acoustic Research Consortium programs. These were integrated in GRC's noise reduction program milestones. It is the only complete aero-acoustic data/geometry set publically available. Over 100 papers written based on ANCF data. (~4 -6 per AIAA Aero-Acoustics Conference)

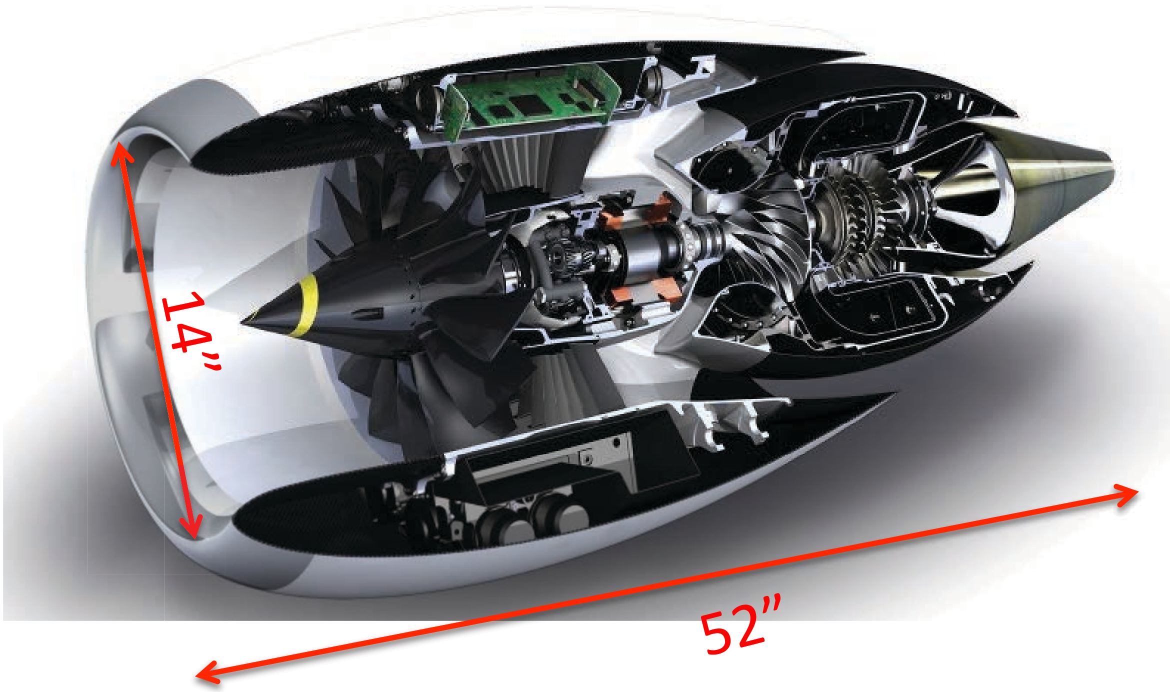


Highly flexible, fundamental test bed.
Multiple configurations, including rotor alone.
4-foot diameter ducted fan
Low speed: (variable)
~1800 rpm, V_{tip} ~375 ft/sec, M_{duct} ~ 0.15
Used to provide aero-acoustic database and to evaluate noise reduction technologies
Data acquired by externally clocking data system from rig tachometer signal

Investigating transferring the ANCF to a university to jointly operate the ANCF to maintain research capability, and provide relevant STEM opportunities, in the area of fan acoustics.

DGEN380 Turbofan Engine

The DGEN engine is the world's smallest turbofan: it is intended for 4-5 seat twin-engine Personal Light Jets flying under 25,000ft and 250kts. The DGEN engine is manufactured by Price Induction.



The characteristics of the DGEN380 enable it to be an excellent representation of modern turbofan engines.

Aircraft Engine Noise Sources

- Fan noise
  - Consists of broadband and tonal
  - Broadband primarily random and generated by rotor alone
  - Tonal (Blade Passage Frequency and harmonics) generated by rotor wakes impinging on stator vanes, correlated to shaft orders or engine RPM
- Jet noise
  - Due to mixing of high temperature high velocity streams with lower velocity lower temperature streams
- Core noise
  - Produced by the combustion process, compressor and turbine noise

Experimental Fan Noise Testing

- 9x15 Low Speed Wind Tunnel Facility
- Models
  - Turbofan
  - Counter Rotating Open Rotor
- Data Acquisition
- Data Analysis
- Noise Reduction Technologies

NASA Glenn 8x6/9x15 Wind Tunnel Complex

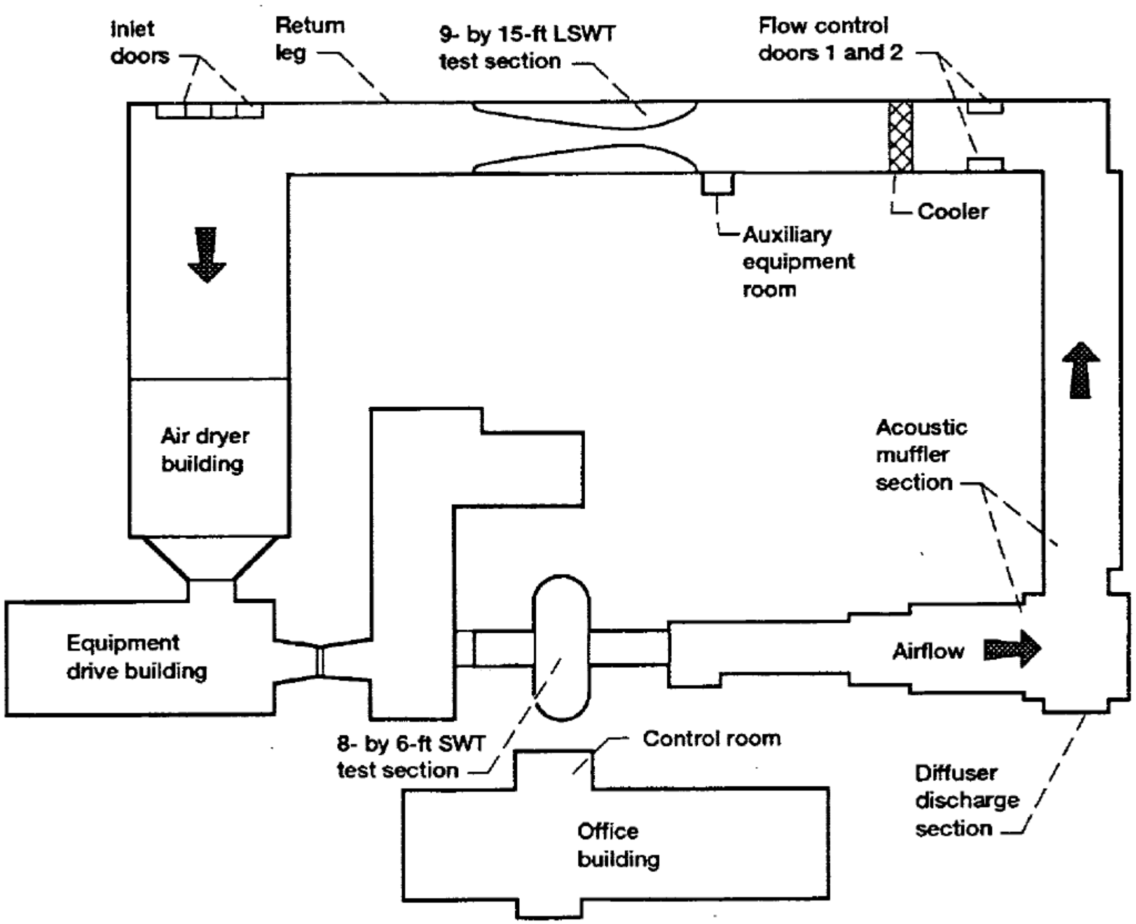
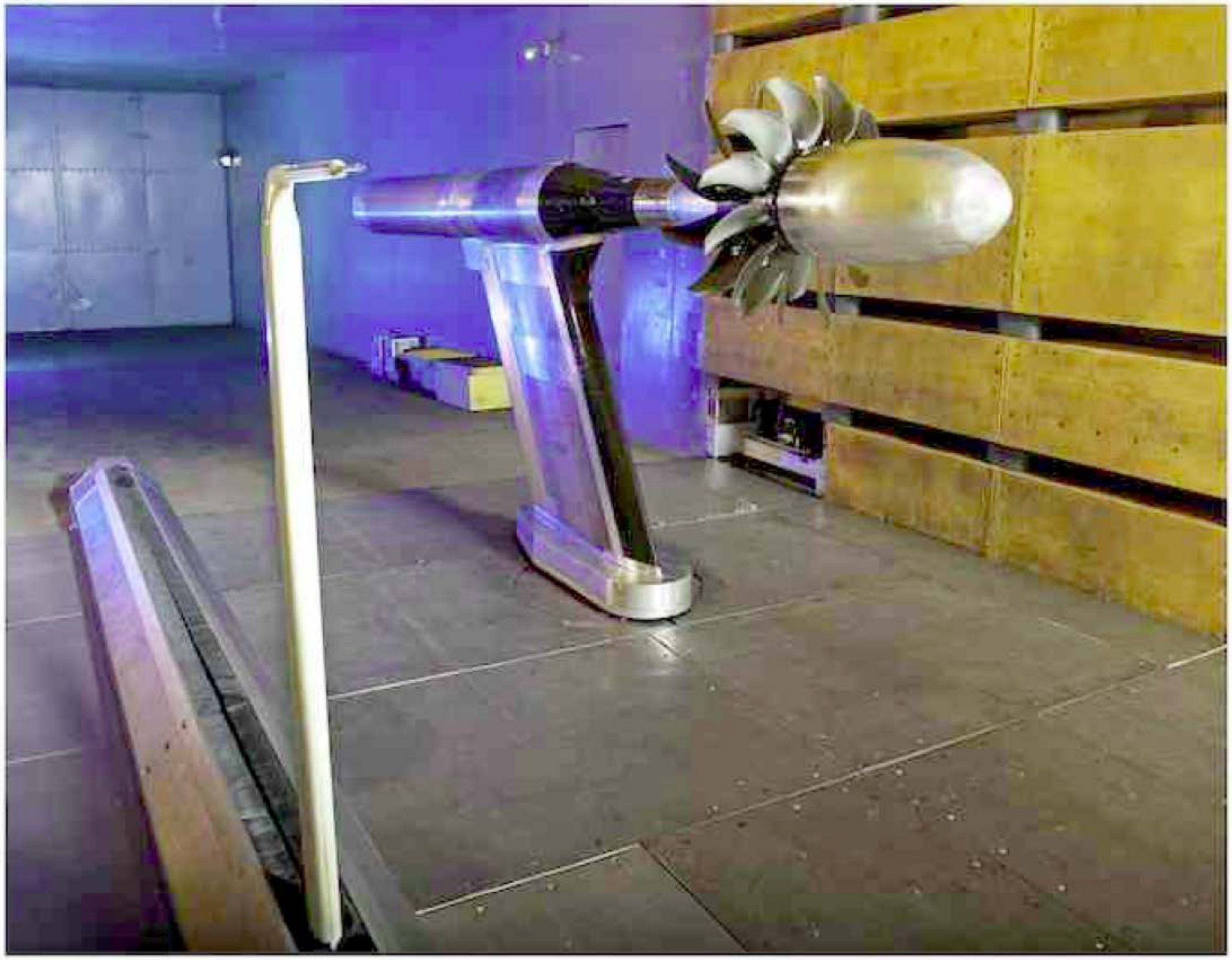


Figure 15.—Plan view of the test section in the return leg of SWT/LSWT facility.

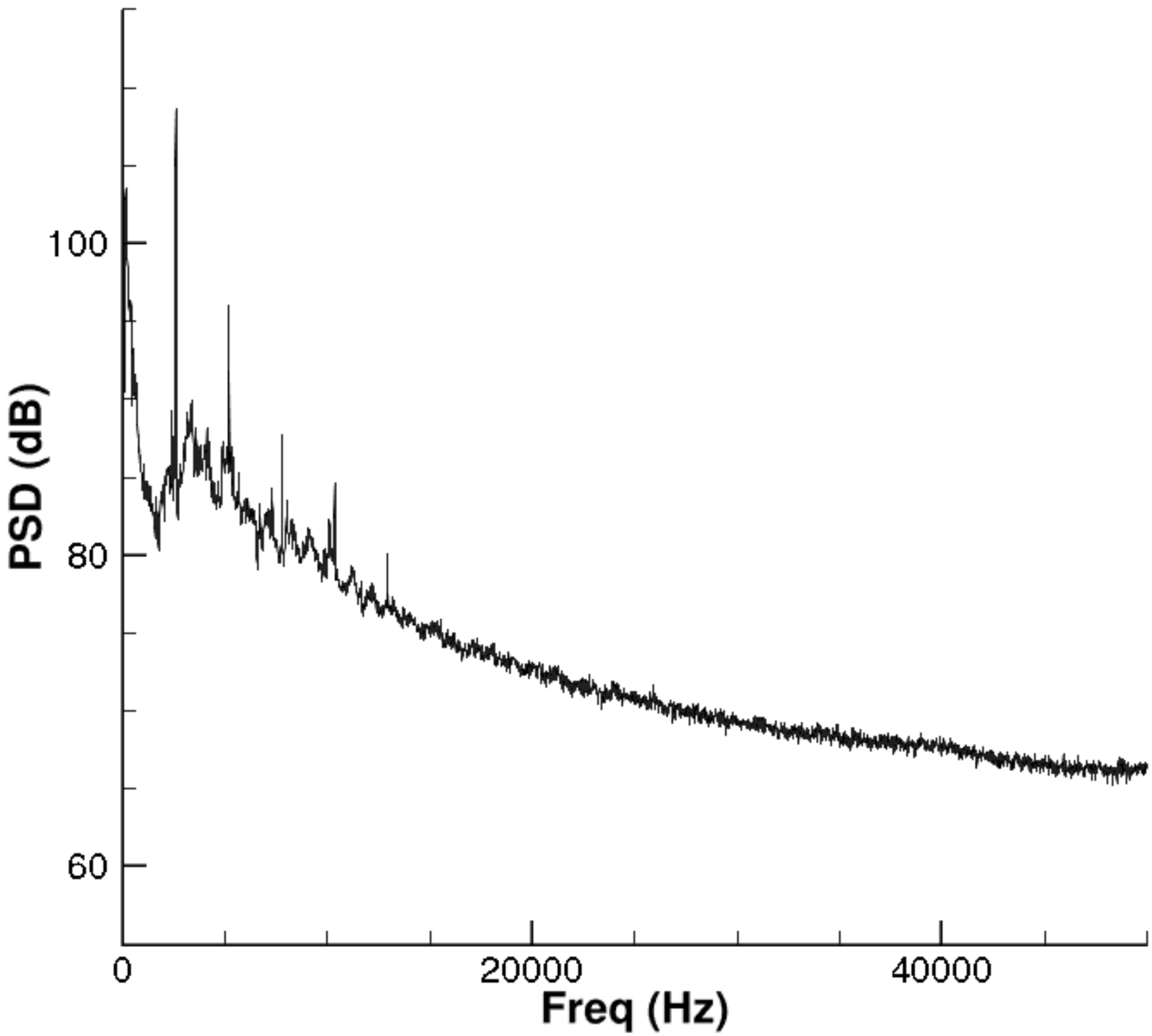
9x15 LSWT:
Up to Mach 0.23
Treated test section using
Kevlar batting behind
steel perforate facesheet
450 PSI turbine drive rig
Turntable for Angle of Attack
measurements

C-2010-3454

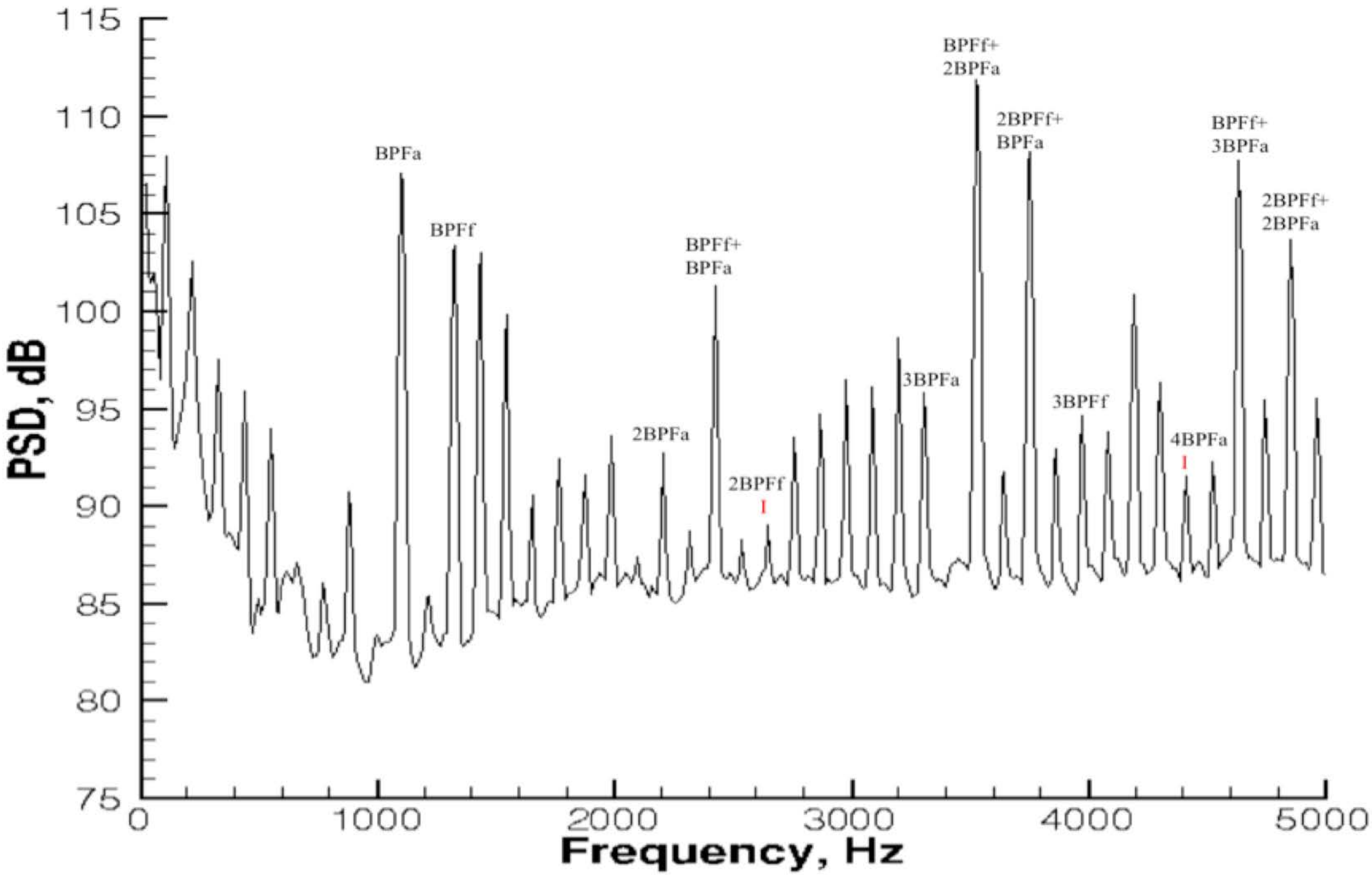


National Aeronautics and Space Administration
Glenn Research Center at Lewis Field

Representative spectra of the Source Diagnostic Test Fan
at 6961 RPMc and 135 degrees directivity angle



Power Spectrum Density from 0 to 5 kHz of the Counter Rotating Open Rotor Historical Baseline Blades at 6450 corrected RPM with takeoff pitch angle and 141 degrees relative to the rear rotor pitch change axis. Blade Passage and Interaction Tones are labeled.



9x15 LSWT acoustic measurement techniques

Objective: Examine acoustic measurement techniques to improve data accuracy/increase acquisition efficiency.

Techniques tested:

- Linear Microphone Array
- Multi-microphone traversing probe
- Continuous Traversing Microphone

Approach:

- Design and test techniques and compare with present acquisition methods

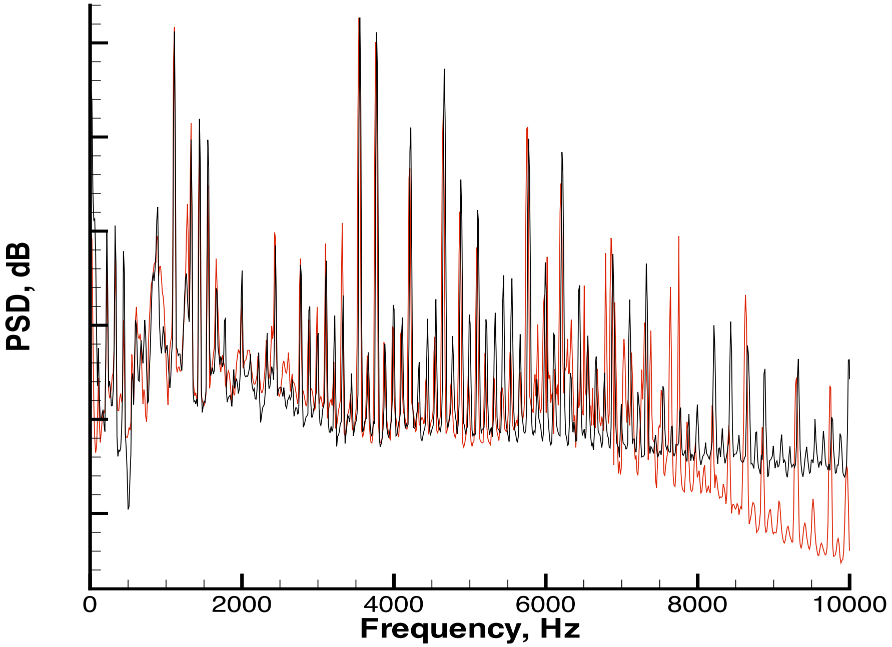
Results/Conclusions

- Linear array compares well with standard traversing microphone over compressed frequency range
- 3 headed microphone had low background noise level relative to single mic stand while allowing two additional azimuthal angle measurements
- Continuous traverse has shown excellent comparison with discrete traverse and has ability to save time

Linear Array

3 Mic Traverse

Auto Spectra of Traversing Microphone vs Linear Array Cross Spectra at 90 degrees relative to Rear Rotor Pitch Axis for Historical Baseline at 100% Design Speed, M=0.2
6 dB Plate Correction included for Linear Array



Acoustic Data Acquisition

- Bruel & Kjaer
  - ¼" Microphones with nosecones
  - Nexus Signal Conditioning Units
- RC Electronics Datamax for acquisition using 200 kHz sample rate
- One traversing microphone for capturing model directivity
  - Previously fixed stop
  - Recently converted to continuous sweep
    - More directivity resolution
    - Time Savings
- Fixed Microphones
- Model timing signals (once per rev) and traverse position recorded
- Facility system records tunnel ambient and model conditions
  - Pressure, Temp, Humidity, Mach No.
  - RPM, Angle of Attack

Acoustic Data Analysis

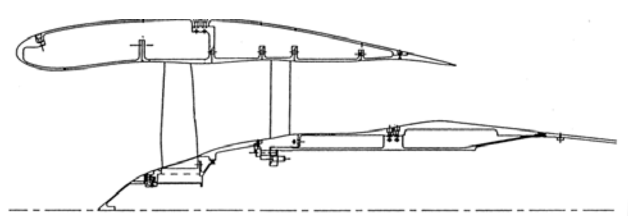
- Data taken is model scale – frequency scales inversely
- Fast Fourier Transform - time to frequency domain
- Corrections included for microphone and nosecone calibrations
- 1 foot lossless – results often projected to one foot distance with atmospheric attenuation removed, enables comparison of data taken at different distances
- Usually in Power Spectral Density (dB/Hz) - allows direct comparison of data taken at different sampling frequencies, different bandwidths
- Overall Sound Pressure Level (OASPL) – Used to give a total value for each directivity angle measured
- Overall Sound Power Level (OAPWL) – Gives a single value for the acoustic power by integrating OASPL for each angle over the entire directivity surface
- Effective Perceived Noise Level (EPNL) – Common NASA and industry calculation to give single value for an aircraft condition (e.g. takeoff), weights frequency bands and includes a time element simulating aircraft flyover, data is full scale and usually utilizes an aircraft configuration (medium twin engine etc.)

Major Challenge:
Reducing noise without adversely affecting engine performance or efficiency

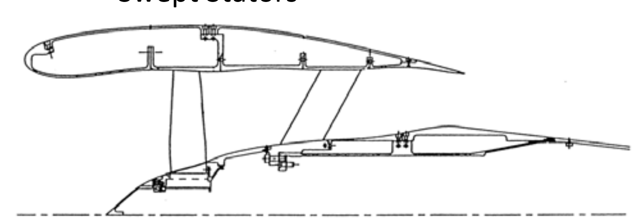
Fan Noise Reduction Technologies

- Cycle Change - Higher Bypass Ratio
  - Increase amount of weight flow through the bypass duct while reducing flow through core engine
  - Results in larger fan diameter
  - Larger fan has lower tip speed while maintaining thrust (noise is a function of fan tip speed, supersonic tip speed produces Multiple Pure Tones due to shock noise)
  - Lower fan loading and tip speed should reduce noise
  - Aft fan dominant noise signature
- Rotor/Stator
  - Increased spacing – reduces wake impact on stators
  - Swept Stators – larger distance between rotor and stator at tip, reduces tip vortex on stators
  - Leaned Stators – Orients stators more in line with swirl, wake angle of impact less severe

Radial Stators



Swept Stators



Fan Noise Reduction Technologies (Cont.)

- Acoustic Liners/Treatments
  - Usually used on inner duct of nacelle, also inner hub locations
  - Other locations investigated such as aft splitter
  - Over the Rotor Treatment
  - Soft/Treated Stator Vanes
- Fan Trailing Edge Blowing
  - Fills in wakes produced by blades lowering fan stator interaction

NASA/P&W Fan 1 Liner and Fan 2 Test

Objective:

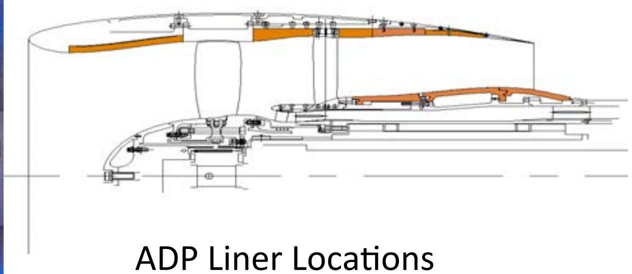
- Acoustic performance of various liner designs
- Validate noise dependence on tip speed
- Determine noise of advanced casing treatment used to increase stall margin

Approach:

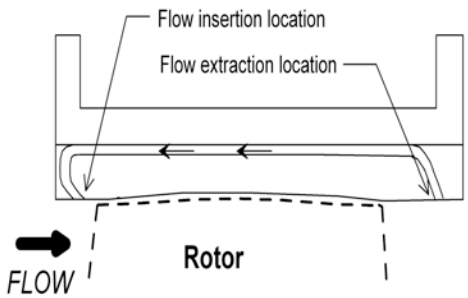
- Test combinations of bulk, SDOF, DDOF liners in inlet, mid, and aft locations of Pratt ADP Fan 1
- Test lower tip speed Fan 2 while keeping pressure ratio as Fan 1

Results:

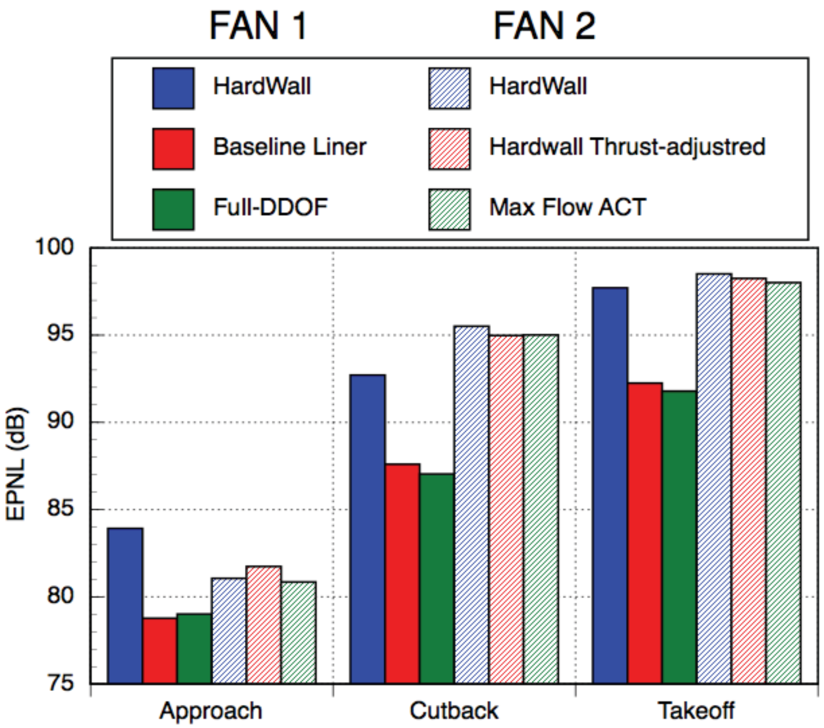
- Full DDOF liner set showed additional noise attenuation compared to very effective 1995 Baseline liner
- Fan 2 showed limit of reduced tip speed/higher loading due to increase in noise relative to Fan 1
- Advanced casing treatment showed no acoustic penalty while increasing stall margin
- Develop acoustic database for ultra-high bypass ratio turbofan model



ADP Liner Locations



Max Flow Advanced Casing Treatment



Aft Duct Treated Splitter

Objective:

- Reduce aft fan noise
- Keep performance losses to minimum

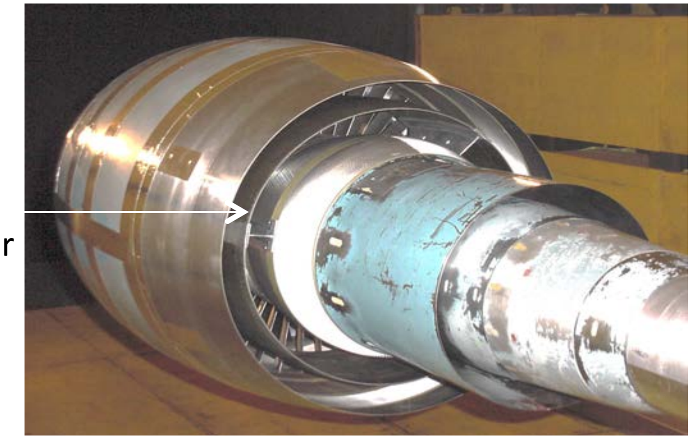
Approach:

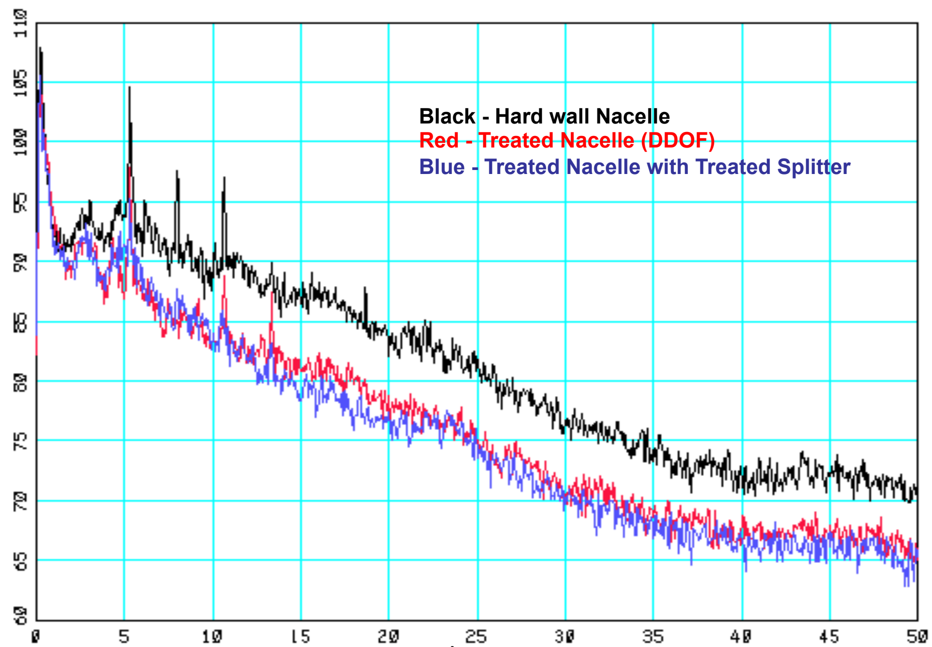
- Design and test aft acoustically treated splitter on Pratt ADP model in 9x15 LSWT

Results:

- Trailing edge of splitter must be kept thin to eliminate Strouhal shedding tones
- Splitter tuned to 17 kHz model scale to attenuate highest annoyance noise
- Splitter did not show expected noise reduction possibly due to tunnel background noise or mounting method
- Static test did show splitter provided attenuation at design frequency
- Performance loss kept to 1% of thrust and was primarily due to skin friction
- Added technology such as micro-blowing could reduce skin friction

Aft Splitter





ADP Takeoff - 136 degrees

Over the Rotor – Soft Vane Concepts

Objective:

- Use treatment over the rotor to reduce rotor alone noise
- Reduce rotor/stator noise at source using soft vanes

Approach:

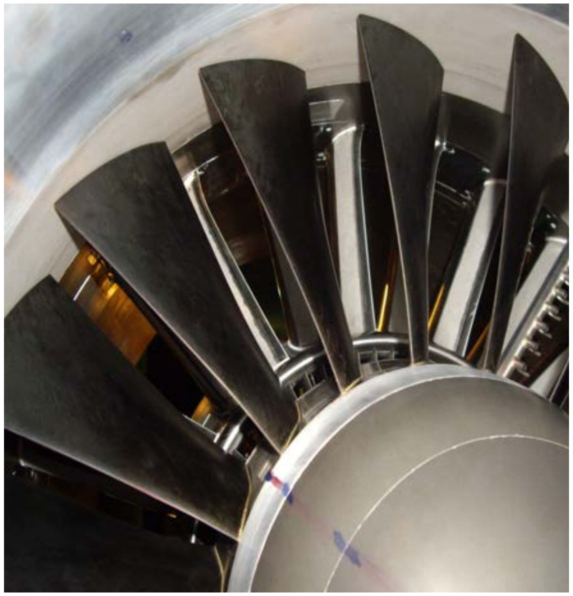
- Design and Test concepts on turbofan model in 9x15 LSWT

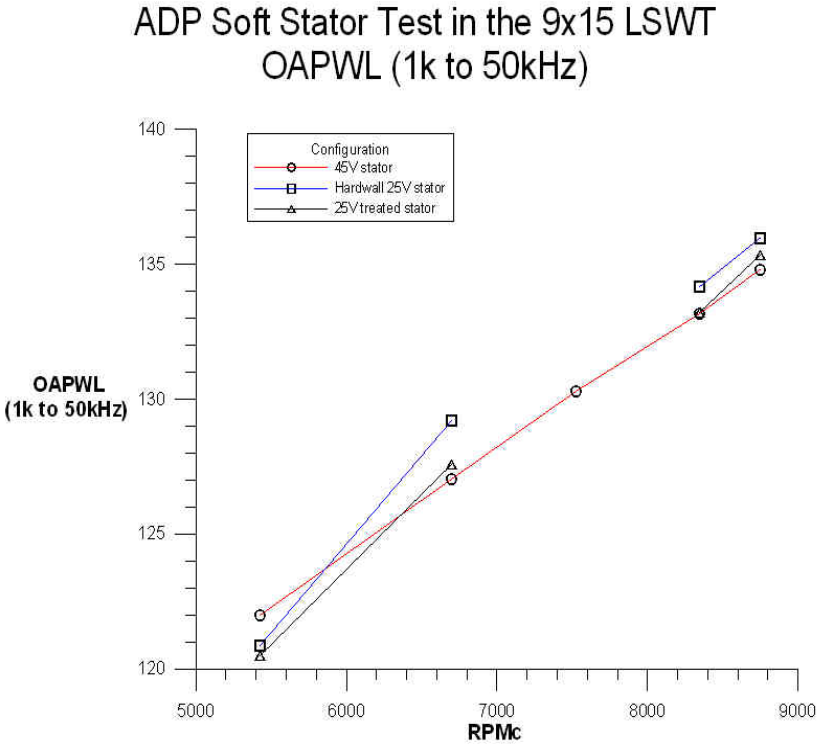
Conclusions

- OTR treatment not effective in reducing noise unlike other previous tests had shown
- Soft Vanes showed PWL reductions on the order of 1 dB relative to hard vanes for certain shaft speeds

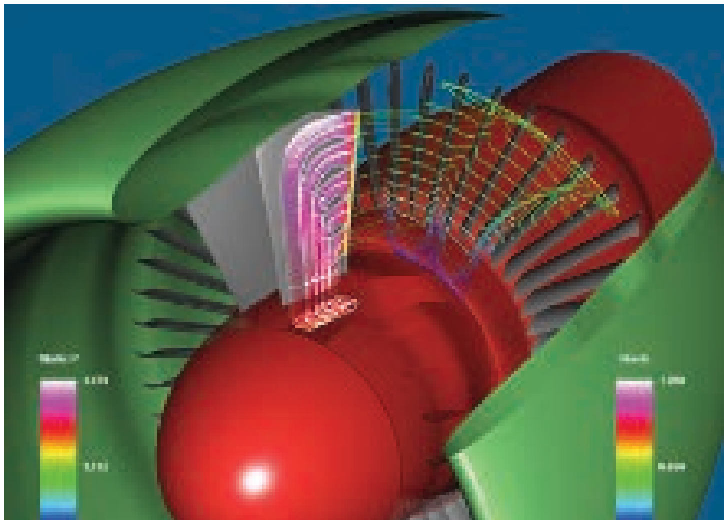
Over the Rotor Treatment

Soft Vanes





Fan Trailing Edge Blowing

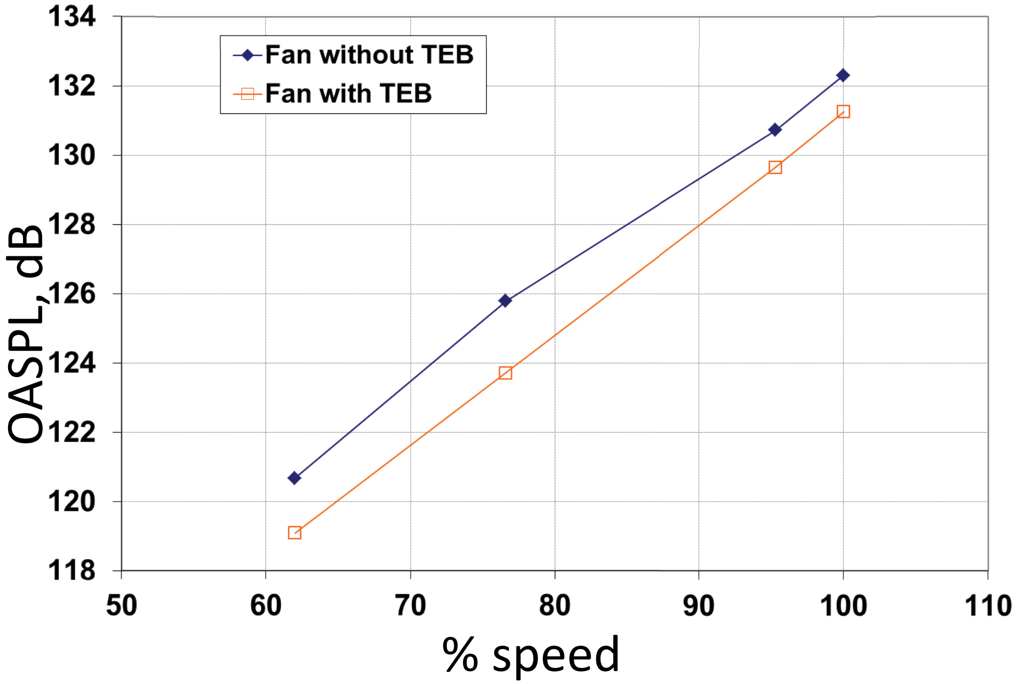


Objective: Characterize aero/acoustic performance of Fan Trailing Edge Blowing at moderate TRL

Approach: Design and test representative fans in low speed test rig and the 9x15 LSWT

Outcome:

- Tones and broadband impacted by TEB; @ takeoff -- 2BPF, -5dB; 3BPF, -1dB; 4BPF +.5 dB
- Thrust slightly higher for TEB (9x15)
- TEB efficiency 94.4% vs. 95.6% baseline (9x15)
- 2% blowing rate optimum, about 2db OASPL noise reduction relative to baseline across spectrum



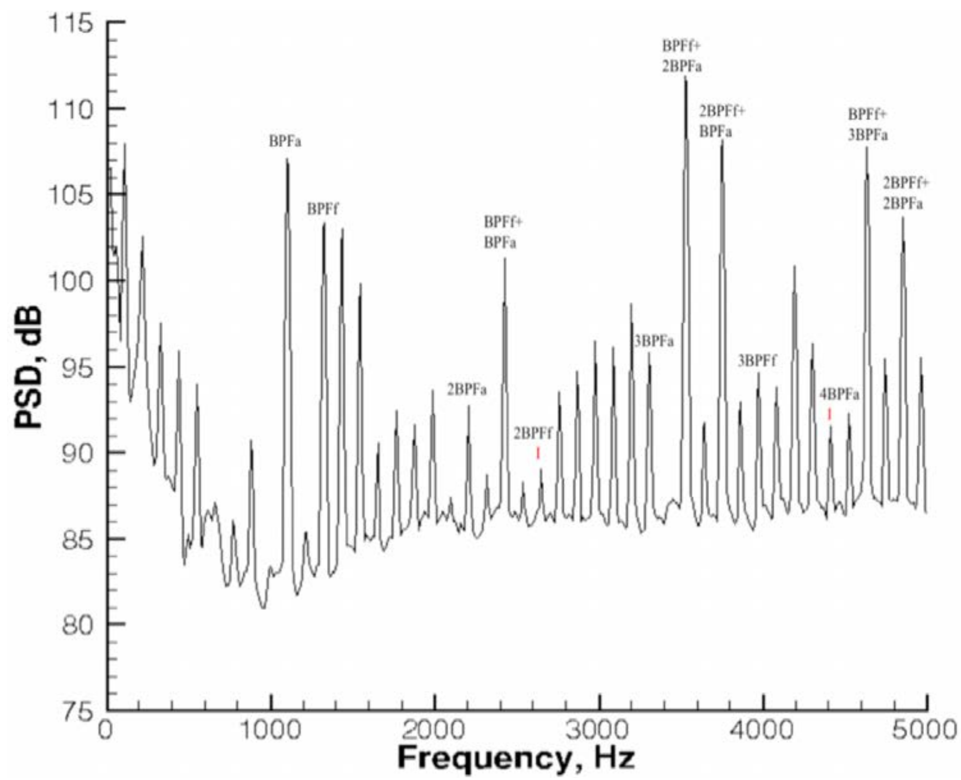
Open Rotor Test Entry

Objective: Reduce counter rotating open rotor noise using advanced blade designs

Approach: Test blade design concepts in 9x15 LSWT on open rotor drive rig

Outcome:

- Test of Baseline and multiple advanced blade sets
- Angle of Attack effects
- Pylon wake noise characterization
- Data used for system studies of aircraft noise comparison versus ducted engines
- Obtained large database of open rotor blade acoustics for pitch angle, angle of attack, pylon wake



Rotor Alone Nacelle System

Objective

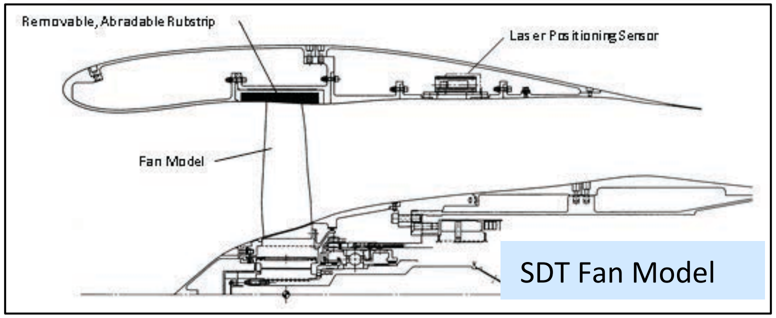
- Identify and characterize isolated rotor noise sources

Approach

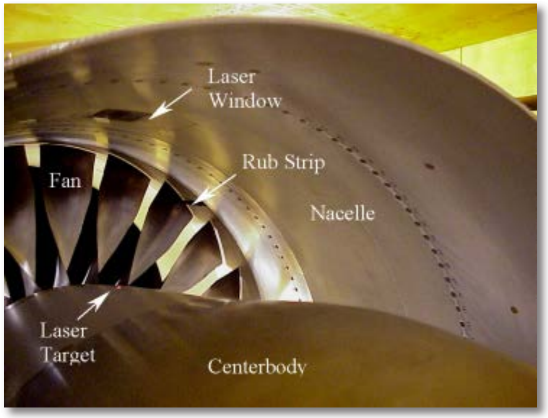
- Develop propulsor simulator that eliminates internal structures and isolates rotor within nacelle while maintaining operating characteristics and performance

Outcome

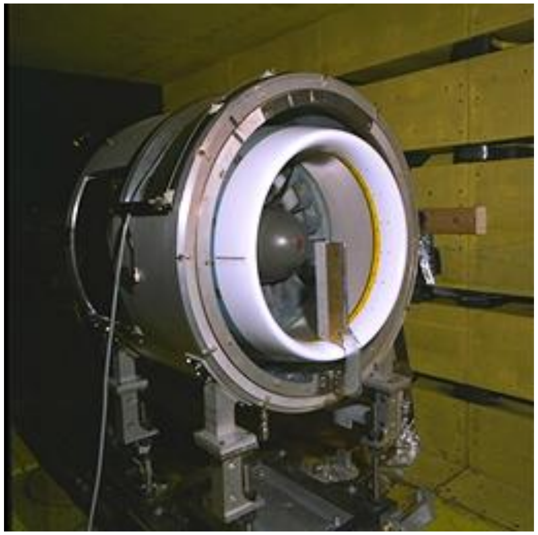
- New test technique successfully developed and tested
- Fan tip clearance held to 0.005" with active nacelle positioning system; fan performance maintained
- Isolated rotor noise sources identified and characterized



SDT Fan Model

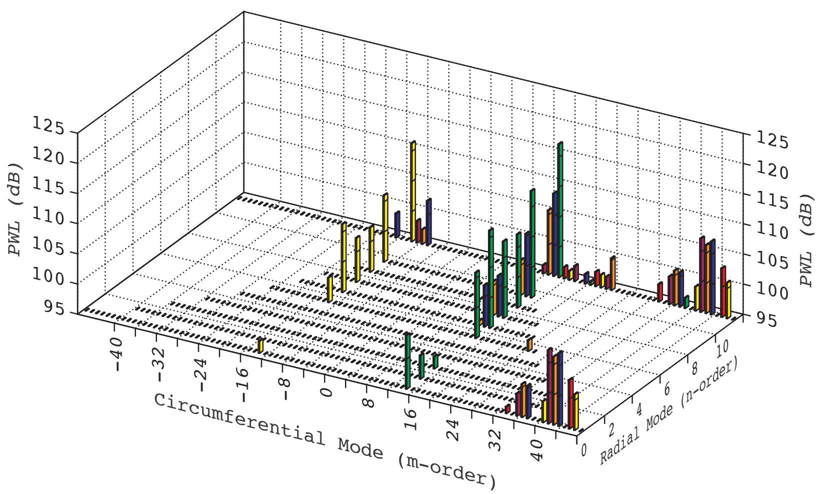


Rotating Rake



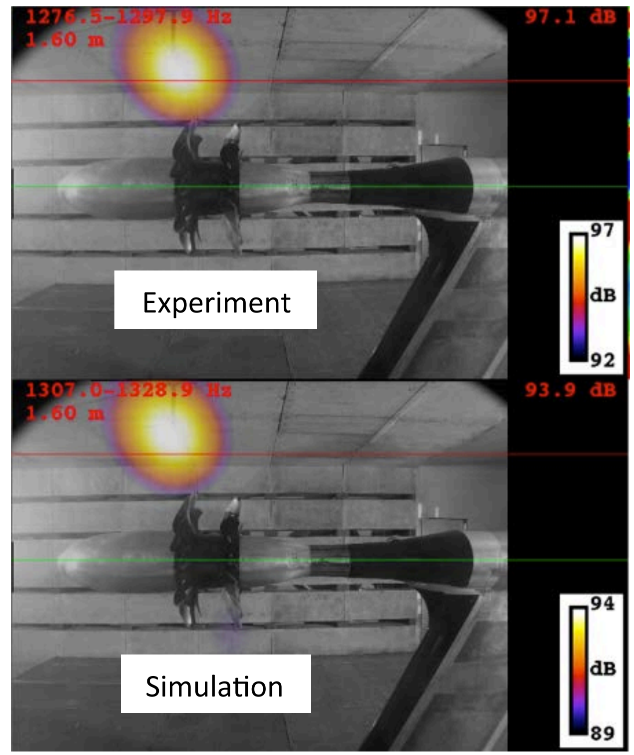
- Extensive fan noise database for a variety of fans covering a full range of fan pressure ratios and tip speeds.
- Includes noise data from research fans, prototype fans, and production engines.
- *<u>Only</u>* combined in-duct and farfield noise database for low speed fans.

SIGNIFICANCE: The Rotating Rake is a one-of-a-kind measurement system that provides a complete map of turbofan duct modes (magnitude & phase). This measurement system has contributed to development of engine noise reduction technology.



Phased Array Measurements

Used to locate noise sources, relies heavily on tailored data processing techniques, e.g. beamforming



Questions?