Core Noise Reduction

Lennart S. Hultgren, NASA Glenn Research Center, Cleveland, OH 44135

Presented at the Acoustics Technical Working Group Meeting
Hampton, Virginia, October 18-19, 2011

Summary

This presentation is a technical summary of and outlook for NASA-internal and NASA-sponsored external research on core (combustor and turbine) noise funded by the Fundamental Aeronautics Program Subsonic Fixed Wing (SFW) Project. Sections of the presentation cover: the SFW system-level noise metrics for the 2015, 2020, and 2025 timeframes; turbofan design trends and their aeroacoustic implications; the emerging importance of core noise and its relevance to the SFW Reduce-Perceived-Noise Technical Challenge; and the current research activities in the core-noise area. Recent work[1] on the turbine-transmission loss of combustor noise is briefly described, two[2,3] new NRA efforts in the core-noise area are outlined, and an effort to develop CMC-based acoustic liners for broadband noise reduction suitable for turbofan-core application is delineated.

The NASA Fundamental Aeronautics Program has the principal objective of overcoming today's national challenges in air transportation. The reduction of aircraft noise is critical to enabling the anticipated large increase in future air traffic. The Subsonic Fixed Wing Project's Reduce-Perceived-Noise Technical Challenge aims to develop concepts and technologies to dramatically reduce the perceived aircraft noise outside of airport boundaries.

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[1] Hultgren, L. S., "Full-Scale Turbofan-Engine Turbine-Transfer Function Determination Using Three Internal Sensors," AIAA 2011-2912 (2011).
[2] NNC11TA40T, "Acoustic Database for Core Noise Sources," Honeywell International, 10/19/2011.
[3] NNX11AI74A, "Measurement and Modeling of Entropic Noise Sources in a Single-Stage Low-Pressure Turbine," U. Illinois, 6/15/2011.

National Aeronautics and Space Administration

Core Noise Reduction

…. *Quiet-Aircraft Discipline – Propulsion-Noise-Reduction Element*

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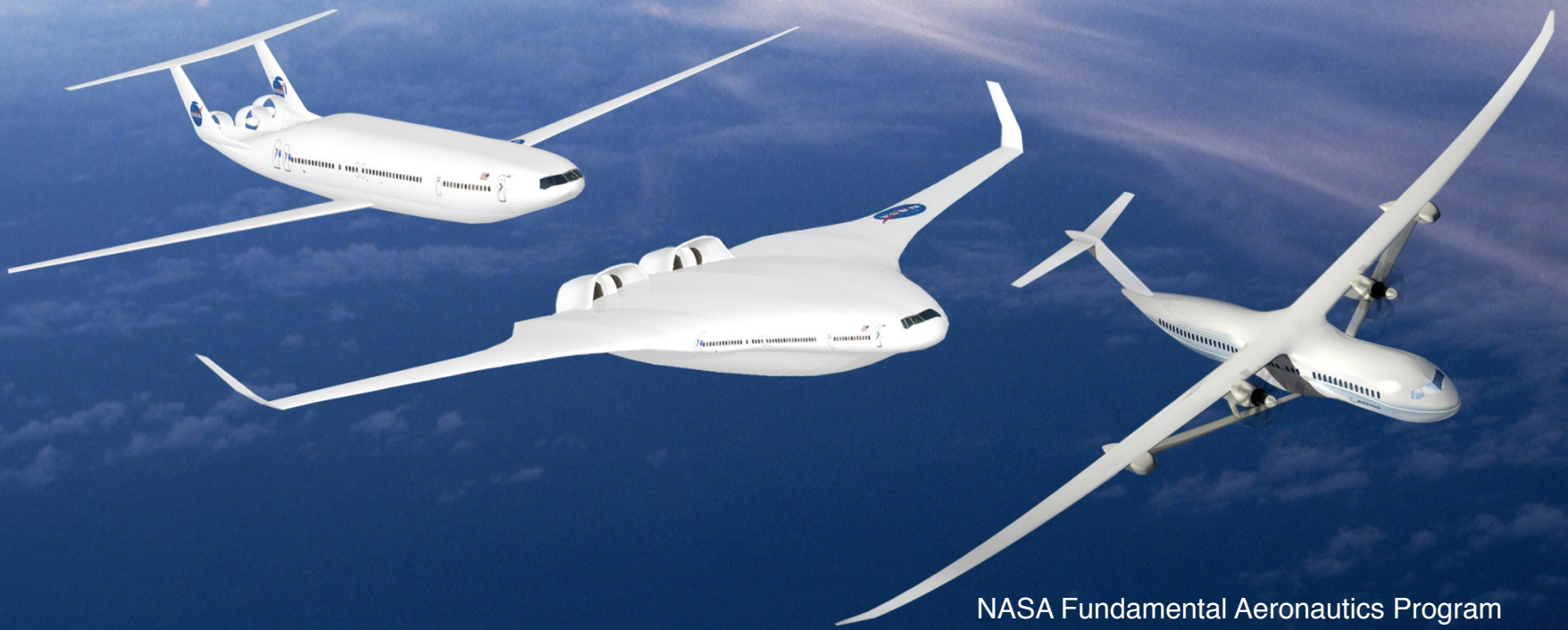


Acoustics Technical Working Group
Hampton, VA, October 18-19, 2011

NASA Fundamental Aeronautics Program
Subsonic Fixed Wing Project
Reduce-Perceived-Noise Technical Challenge

NASA FAP SFW Core-Noise-Reduction

…. outline

- Introduction
  - NASA Subsonic Fixed Wing Project Goals & Challenges
  - aeroacoustic implications of turbofan design trends
  - emerging importance of core (combustor & turbine) noise
  - current noise-prediction tools based on 1970-80s technology
- Core-Noise-Reduction Work
  - in-house research activities
  - 2 core-noise SFW NRA R5 efforts (GRC monitored)
    - Cooperative Agreement with U. Illinois/U. Notre Dame
    - Contract with Honeywell Aerospace, Phoenix, AZ
- Summary

Improve aircraft noise-prediction capability and noise-reduction technologies

NASA Subsonic Transport System Level Metrics

…. technology for dramatically improving noise, emissions, & performance

TECHNOLOGY BENEFITS*	TECHNOLOGY GENERATIONS (Technology Readiness Level = 4-6)		
	N+1 (2015)	N+2 (2020**)	N+3 (2025)
Noise (cum margin rel. to Stage 4)	-32 dB	-42 dB	-71 dB
LTO NOx Emissions (rel. to CAEP 6)	-60%	-75%	-80%
Cruise NOx 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 and mission. 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

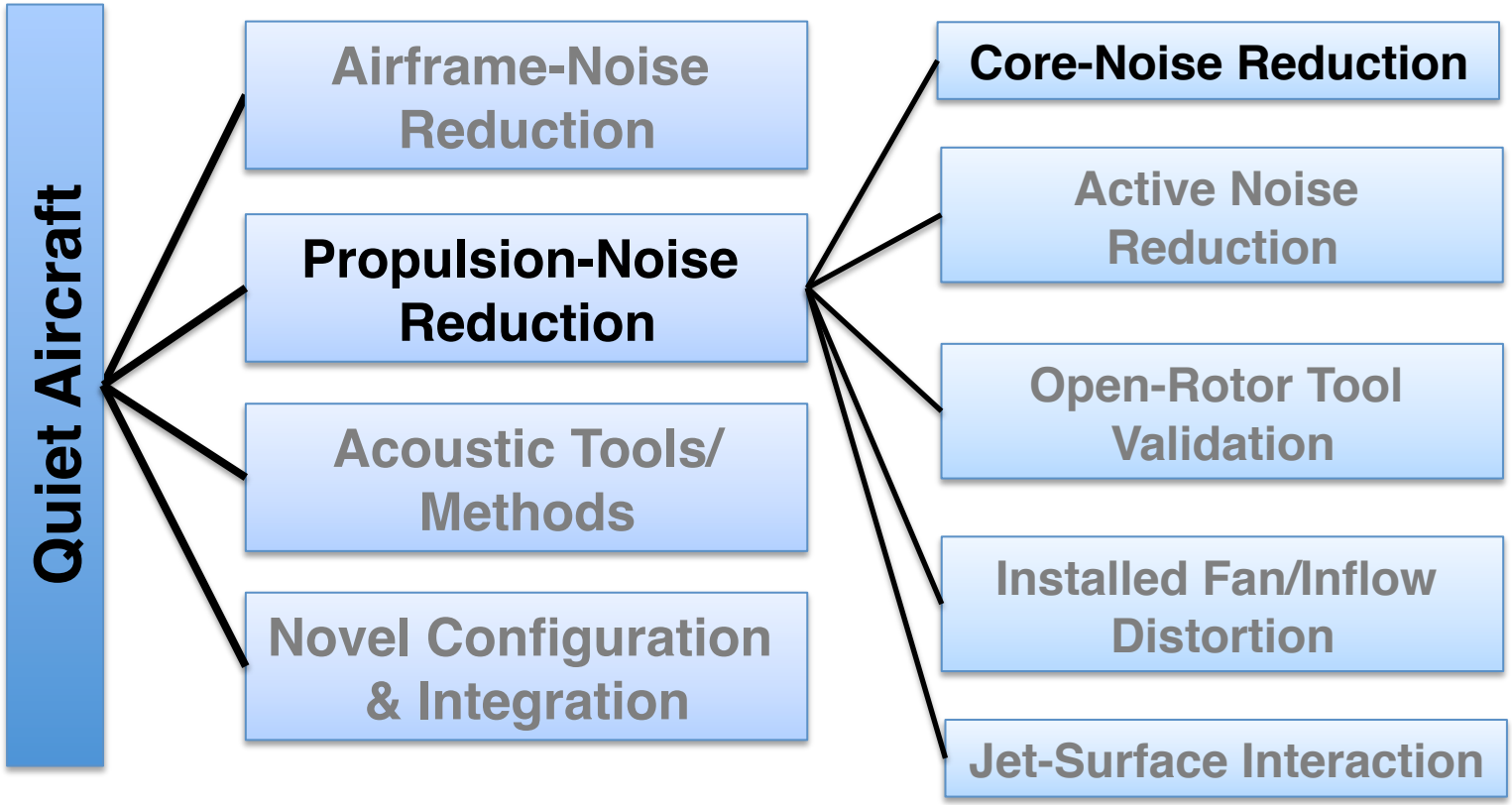
‡ CO_2 emission benefits dependent on life-cycle CO_{2e} per MJ for fuel and/or energy source used

Principal objective of the NASA FAP is to overcome today's national challenges in air transportation

Reduction of aircraft noise is critical for enabling the anticipated large increase in future air traffic

SFW Reduce-Perceived-Noise Technical Challenge

…. dramatically reduce perceived noise outside of airport boundaries



- Discipline, Elements and Tasks

Concepts and technologies to dramatically reduce the noise outside of airports

Turbofan Design Trends

…. overall cycle changes that will increase the relative importance of core noise

- Overall cycle changes:

BPR ↑ **FPR** ↓ **N1** ↓

Non-core propulsion-noise components will be reduced at all power levels

- High-power-density, low-emission cores:

COMBUSTOR

OPR ↑ T_4 ↑

TURBINE (LPT)

Blade Loading & Temperature ↑ **Blade Counts, Stages & Stage Spacing** ↓

Core-noise components will be increased at all power levels

High-Power-Density, Low-Emission Cores

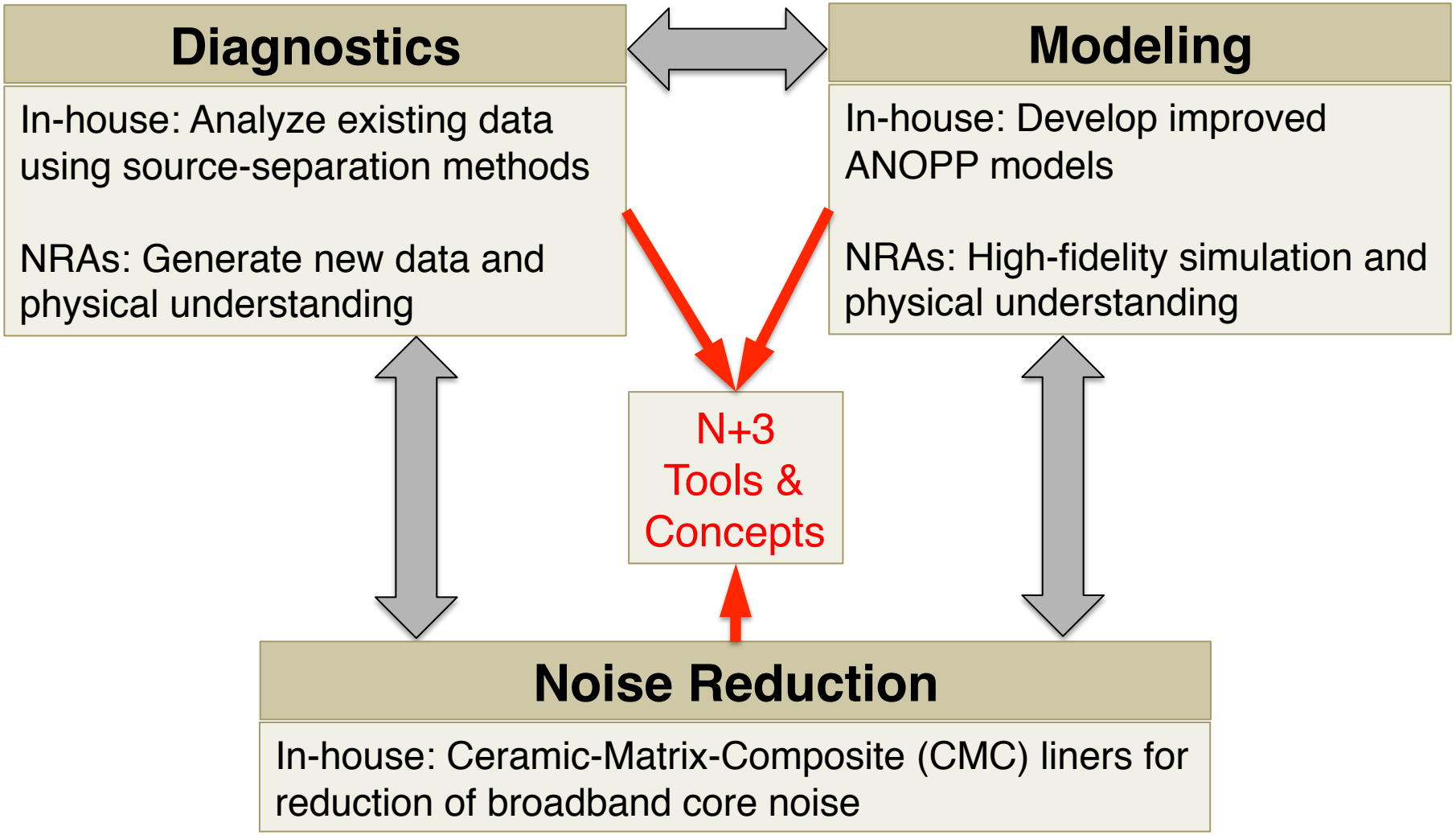
…. potential acoustic implications & why core noise is important

- Core noise traditionally a concern only at approach, but …
- Combustor noise increased due to
  - direct noise increases with $(OPR)^2$
  - low-emission designs could increase indirect noise
  - turbine design trends could lower transmission losses
  - implications from near-combustion-instability operation
- Low-Pressure-Turbine noise increased due to
  - stronger and more complex sources due to increased blade loading and decreased stage spacing
  - less attenuation due to decreased stage solidities
  - acoustic treatment more difficult due to increased temperatures

Emerging ultra-high-bypass-ratio engines with advanced high-power-density core components could make core noise a more significant component of the total engine noise signature at all power settings, which will need to be addressed to meet NASA noise goals

NASA FAP SFW QA Core-Noise Activities

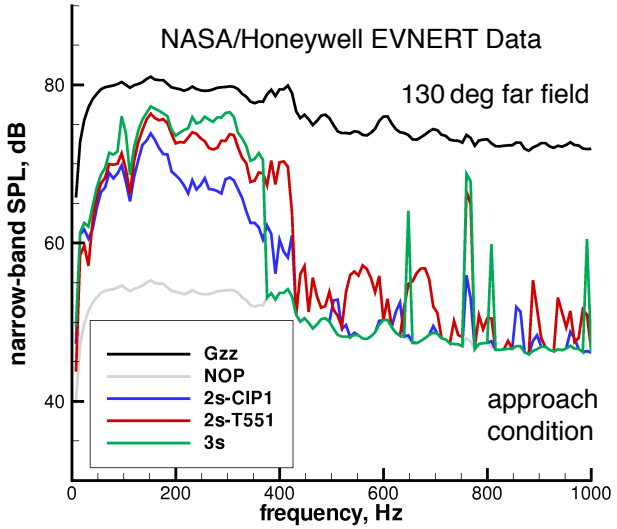
…. ongoing NASA research to enable tools and concepts for N+3 designs



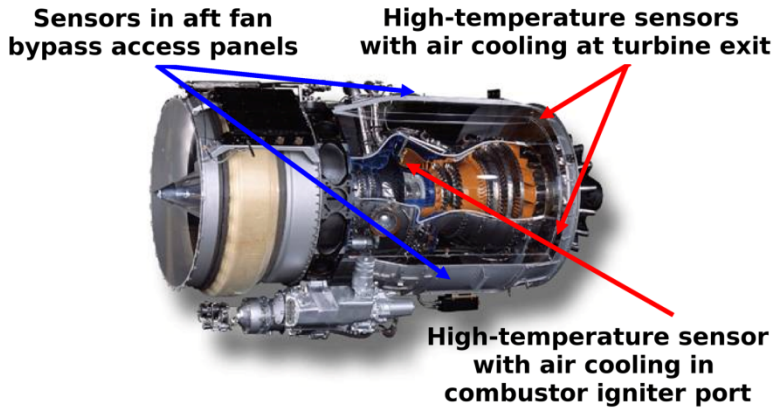
Current tools: dated and applicability to emerging N+3 designs unknown

NASA FAP SFW Core-Noise Activities

…. ongoing in-house NASA research efforts under Quiet-Aircraft Discipline



Honeywell TECH977 Turbofan



- Presence of jet noise makes measurement difficult
  - combustor noise masked by jet noise during static engine test
- Assessment and development of source separation methods
  - necessary aid in developing improved reduced-order models
  - applied to real engine data
    - new additional discriminator for three-signal method

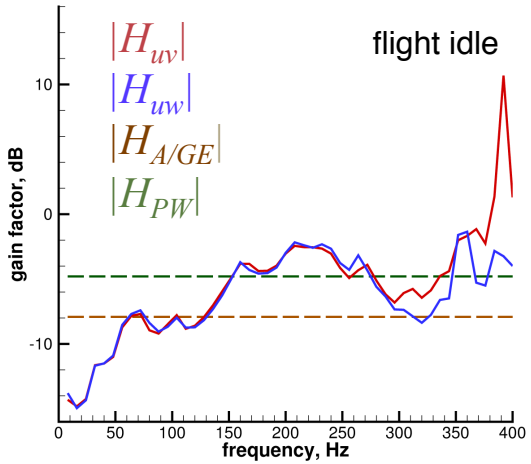
      L. S. Hultgren & J. H. Miles: AIAA 2009-3220
    - turbine-transfer function for TECH977 engine

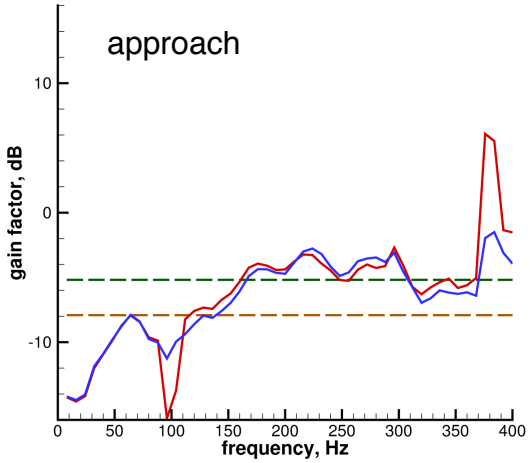
      L. S. Hultgren: AIAA 2011-2912

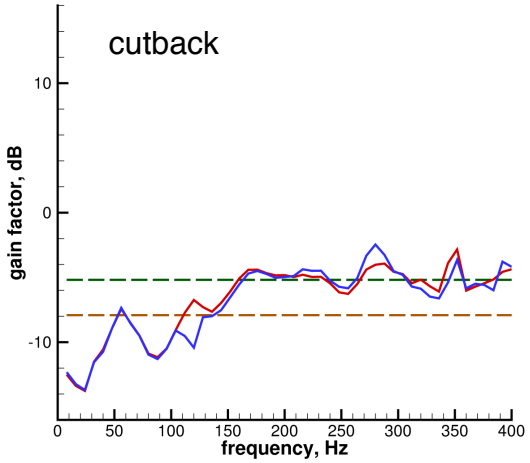
Source-separation techniques applied to real-engine data to aid modeling

Combustor-Noise Turbine-Transfer Function

…. narrowband (8 Hz) gain factors from NASA/Honeywell EVNERT TECH977 data



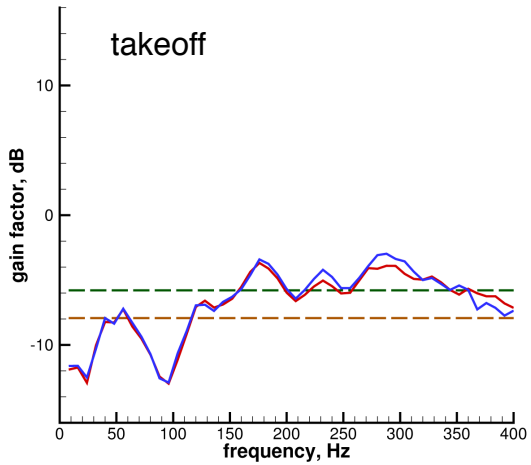




- Empirical turbine loss formulas
  - ANOPP/GE: $|H(f)_{A/GE}|^2 = (\Delta T_{des}/T_{ref})^{-4}$
    - depends on design-point temperature drop
    - independent of operating point
  - Pratt & Whitney:
    - simplified formula
    - impedance ratio

$$|H(f)_{PW}|^2 = \frac{(1+\zeta)^2}{0.8\zeta}$$

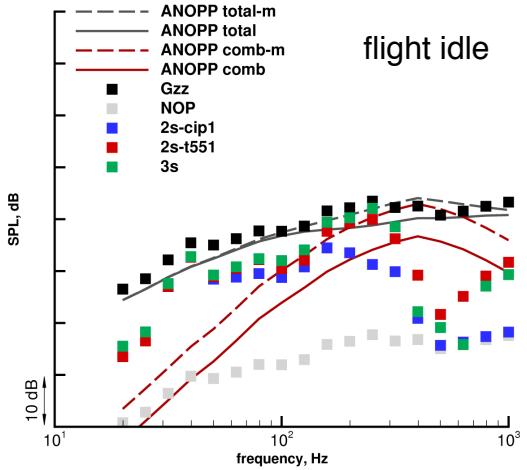
$$\zeta = \rho_{te} c_{te} / \rho_{ti} c_{ti}$$

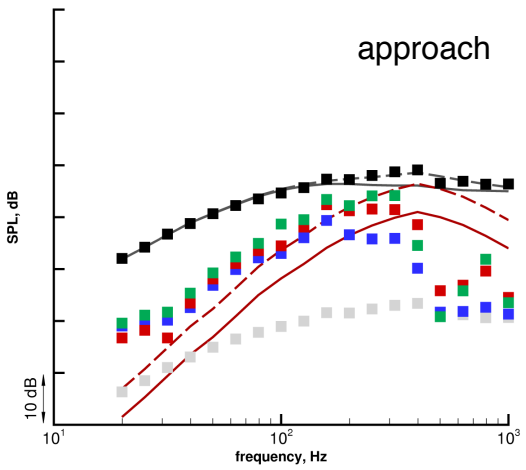


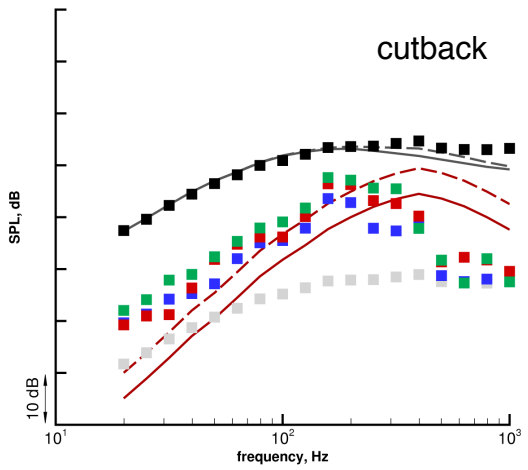
Simplified P&W formula a better fit above 150 Hz (more significant region)

130 Degree Far-Field Comparison With ANOPP

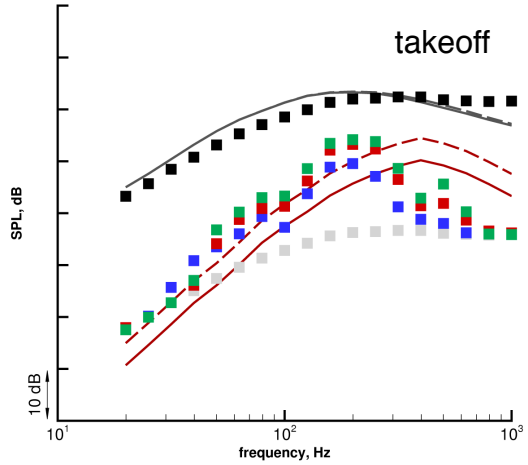
…. total and combustor-component 1/3-octave SPL (EVNERT TECH977)







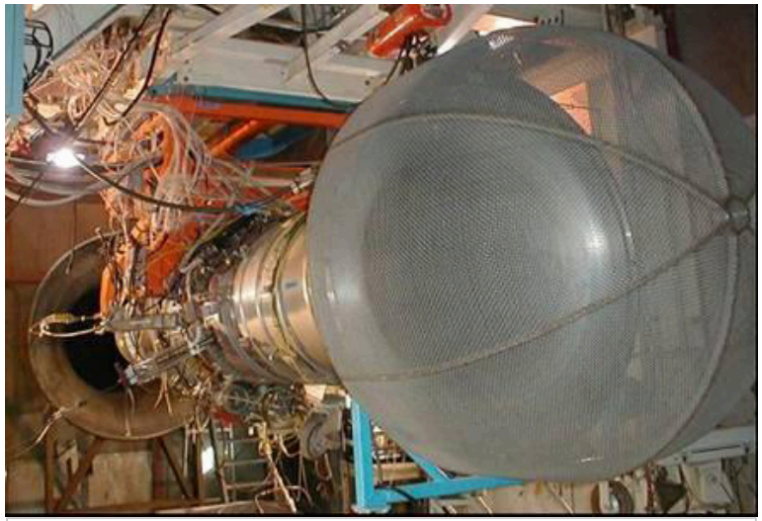
- AIAA 2011-2912 & AIAA 2009-3220
  - 2009: three source-separation methods
  - 2011: total and combustor component post-corrected to use simplified P&W formula
  - modified predictions are clear improvement
    - in particular for total noise signature



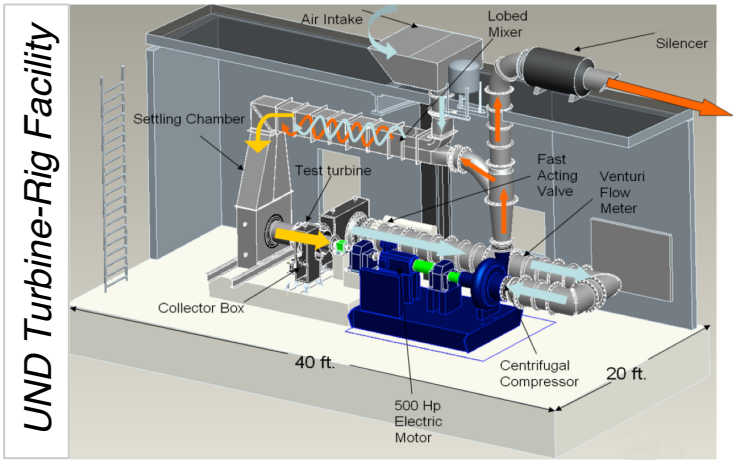
Substitution of simplified P&W formula improves ANOPP predictions

NASA FAP SFW QA NRA Round 5 Core-Noise Work

…. NASA sponsored research efforts for tool development and improvement



Honeywell TECH977 Turbofan in Test Cell

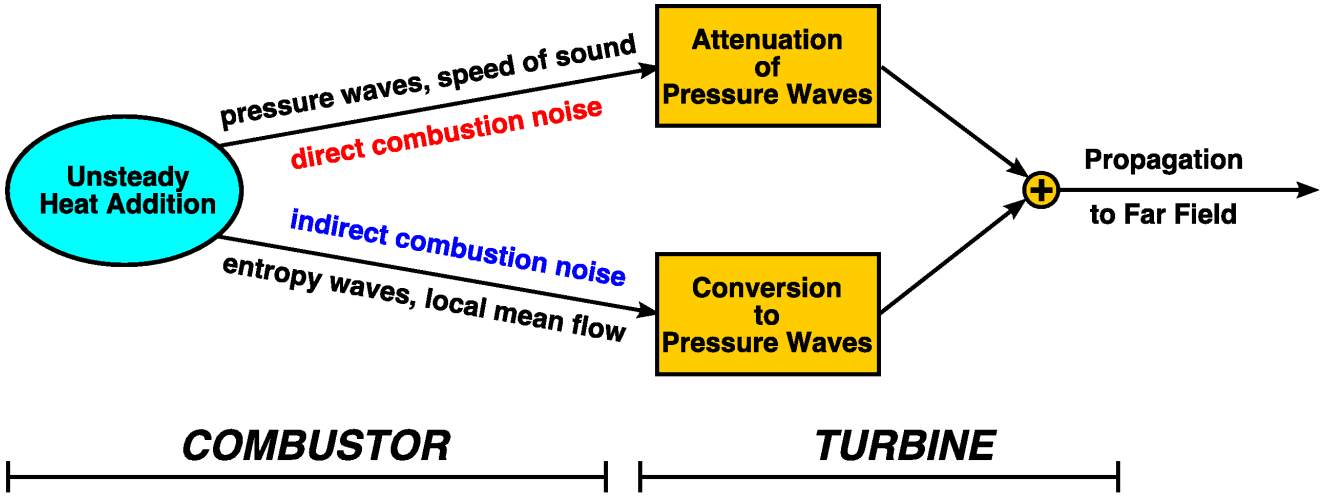


- 2 three-year efforts starting up
- Honeywell, Phoenix, AZ
  - unsteady temperature and pressure measurements inside TECH977 engine
- U. Illinois Urbana-Champaign with U. Notre Dame
  - measurement, simulation and modeling of scattering of entropy fluctuations into noise
  - indirect combustor noise
  - UND: single-stage turbine rig
  - UIUC: high-fidelity LES & models
- Both: indirect combustor noise

Acoustic databases for core noise and improved physical understanding

NASA FAP SFW Combustor-Noise Activities

…. ongoing NASA research efforts under Quiet-Aircraft Discipline



- Direct and indirect contributions to combustor noise
  - same low frequency range
  - relative importance uncertain
  - source-separation analysis: indirect noise present in real-engine data

    J. H. Miles: AIAA 2008-0050; J. Propulsion and Power **25** (1), 2009;
    J. Propulsion and Power **26** (2&5), 2010
  - both NRA R5 efforts designed to yield significant physical insight

Dual paths of combustor noise (direct & indirect)

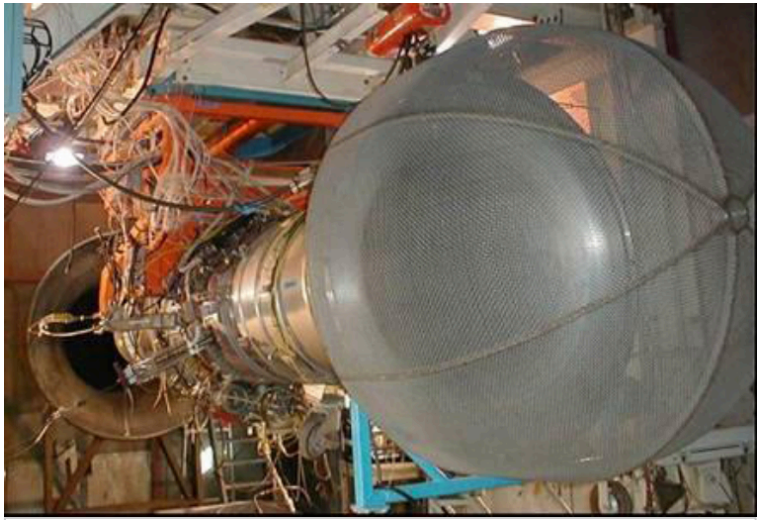
ACOUSTIC DATABASE FOR CORE NOISE SOURCES

…. Honeywell International, PI: Craig Goodrich, Co-I: Bill Shuster & Don Weir

- Contract awarded 10/19/2011

Key Research Points

- test and evaluate sensors that will significantly advance state-of-the-art for unsteady temperature measurements at real-engine conditions, high T & P – Phase I
- obtain unsteady temperature and pressure measurements in a TECH977 engine core – Phase II



Honeywell TECH977 Turbofan in Test Cell

Potential Impact

- knowledge of unsteady T & P will lead to understanding of direct versus indirect combustor noise
- better understanding of sources
- updates to ANOPP core module
- theory and model validation

Challenges

- unsteady temperature is very difficult to measure
  - sufficient frequency range
  - dual fine-wire thermocouples and thin-film or ultra fine wire resistance thermometry
- builds on EVNERT program

Acoustic database for core noise and improved physical understanding

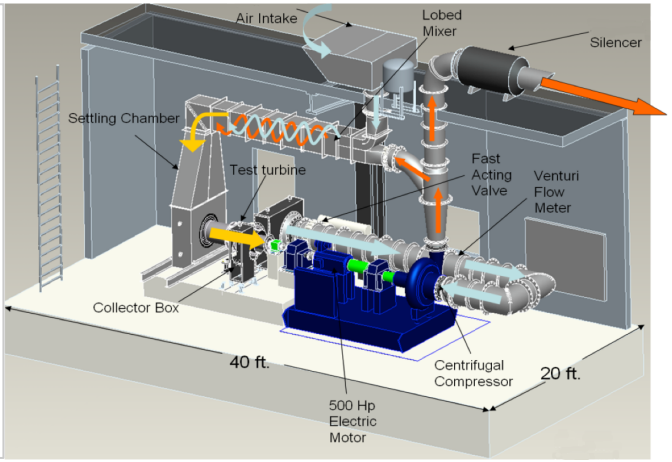
MEASUREMENT & MODELLING OF ENTROPIC NOISE SOURCES IN A SINGLE-STAGE LPT – *PI: Daniel Bodony, UIUC; Co-I: Scott Morris, UND*

- Coop. Agreement: 6/15/2011

Key Research Points

- turbine-rig test with controlled temperature perturbations
- steady and unsteady temperature and pressure through a realistic advanced-design turbine stage
- advancing testing state-of-art
- high-fidelity computations (LES) on the same geometry
- very high degree of synergy between experiment and computation

UND Turbine-Rig Facility



Potential Impact

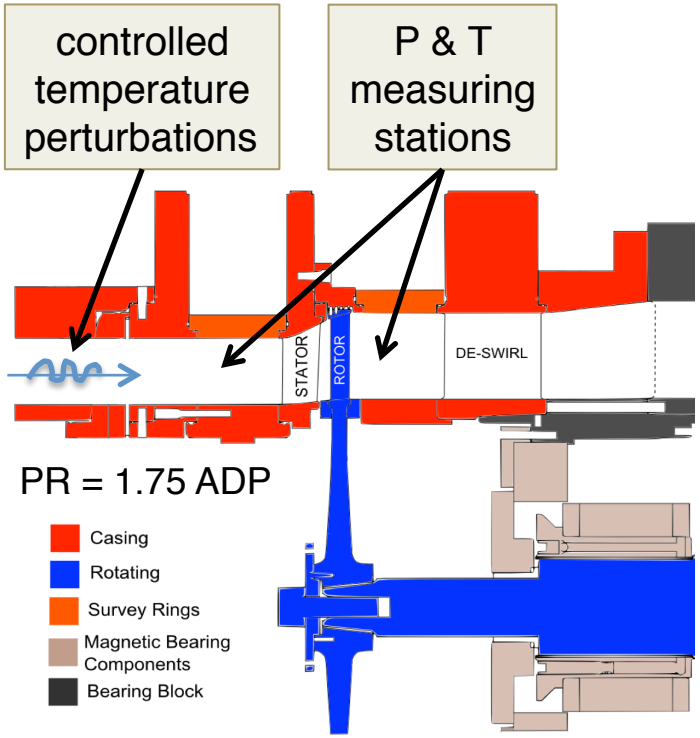
- experimental data will help identify direct versus indirect noise-source mechanisms
- comparison with computations will validate LES approach for core-noise analysis and design
- experimental and computational data will aid in development and validation of improved reduced-order models

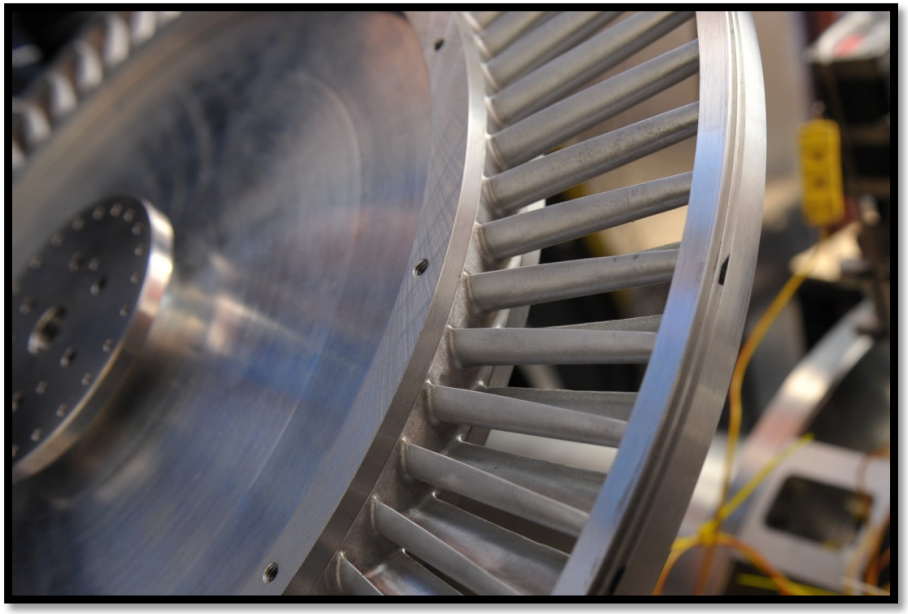
Acoustic database for core noise and improved physical understanding

NOTRE DAME TRANSONIC AXIAL TURBINE FACILITY

…. UIUC/UND NASA SFW Round 5 NRA

- flexible & low-cost operation
- 1000 hp compressor
- 5,000 – 15,000 rpm
- magnetic bearings



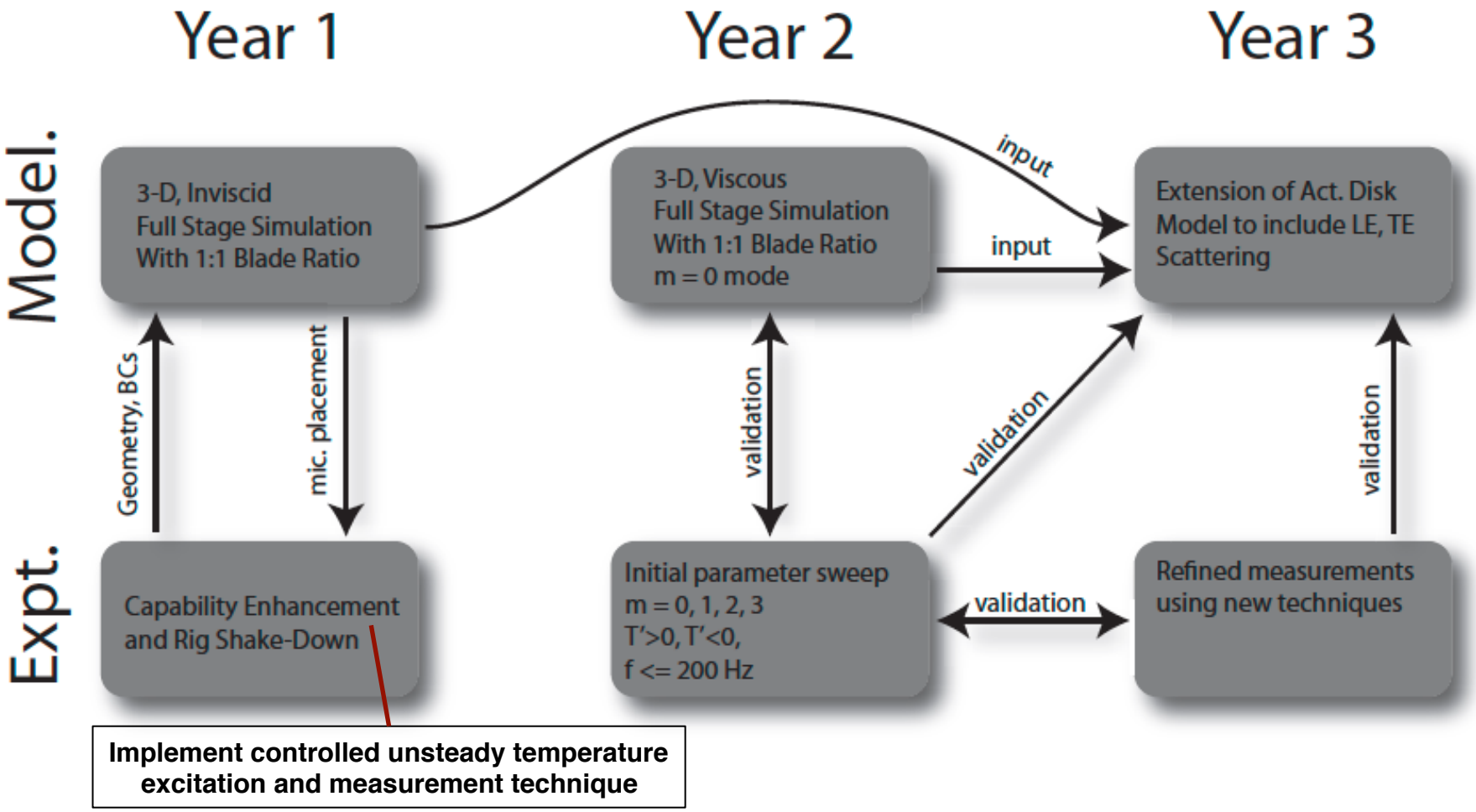


- continuous transonic operation
- range of HPT and LPT stages
- relevant pressure ratio, stage loading, flow coefficient and Mach numbers for LPT/HPT

Existing, modern and unique facility well suited for core-noise research

UIUC/UND NASA SFW R5 NRA PLAN

…. combined experimental and numerical campaign

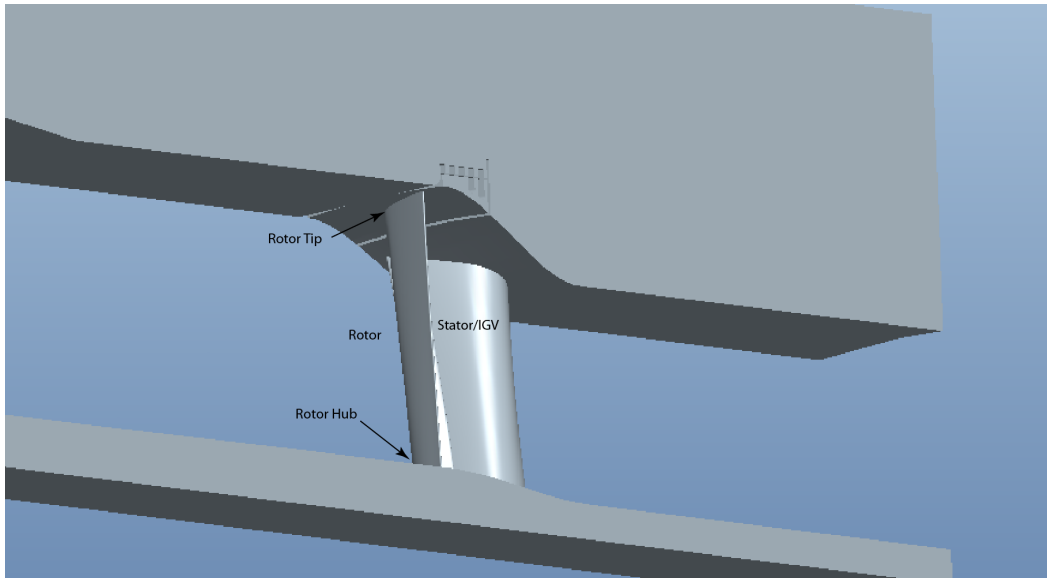


Very high degree of synergy between experiment and computation

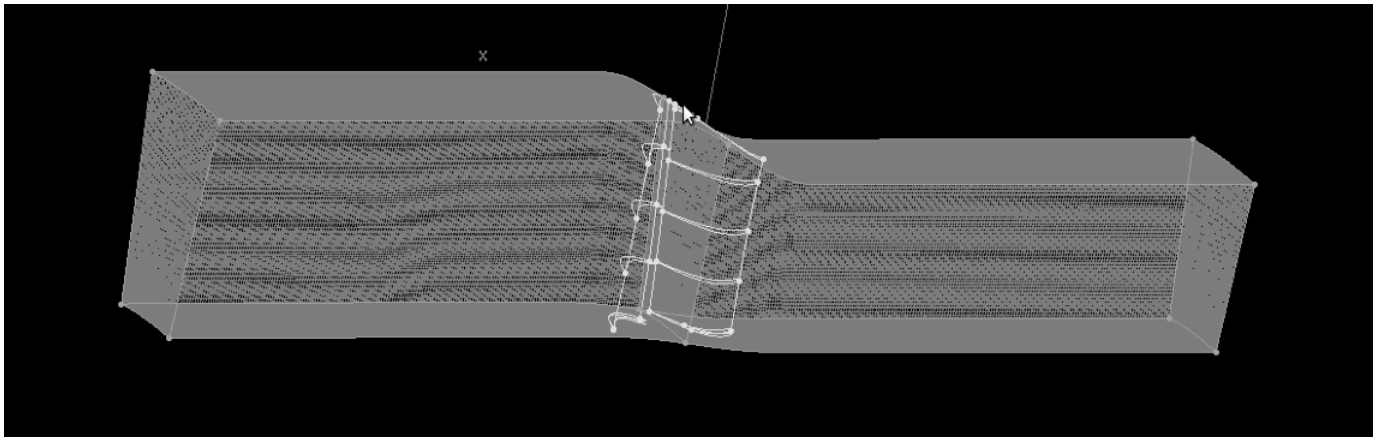
UIUC/UND FLOW PATH AND GRID

…. UIUC/UND NASA SFW Round 5 NRA

Flow Path in UND Rig



Preliminary Grid for Rig

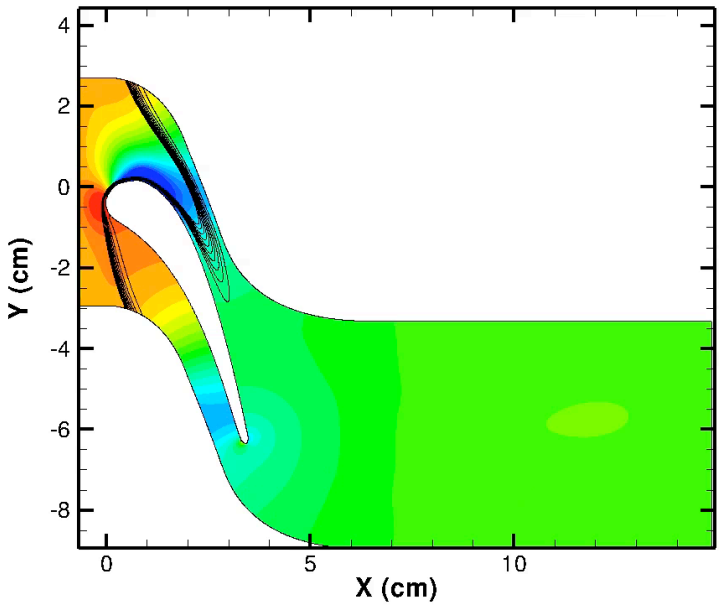


3-D inviscid full-stage year one – 3-D viscous full-stage year two+

ACTUATOR-DISC THEORY VS SIMULATION

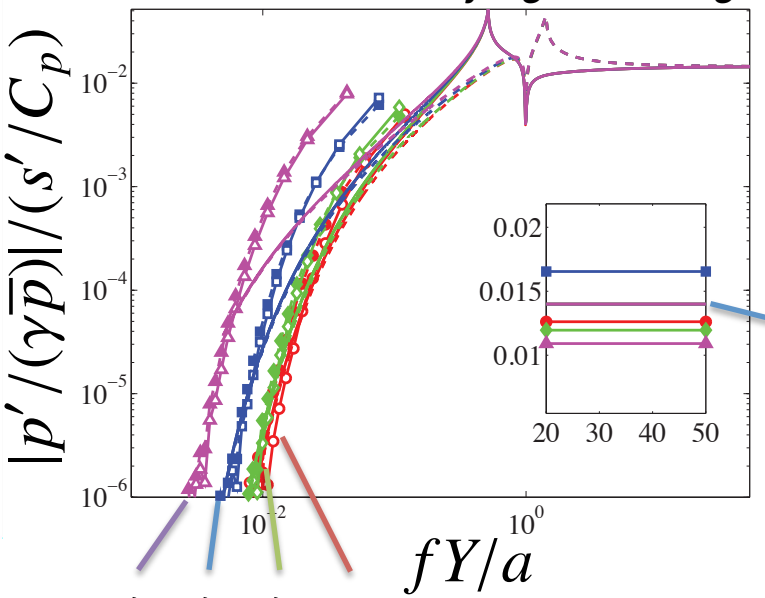
…. begun under Stanford Round 1 NRA – now UIUC/UND Round 5 NRA

Pressure p' (color) and Density ρ'



Euler calculation for NASA CERTS Stator
M = 0.15 inflow & M = 0.8 exit
Plane wave incident entropy waves of
400 – 1100 Hz

open symbols: DNS left-running
close symbols: DNS right-running
solid line: theory left-running
dashed line: theory right-running



Planar mode ($Y \to \infty$)

400 Hz
700 Hz
1000 Hz
1100 Hz

All pressure waves are evanescent for fY/a < 1

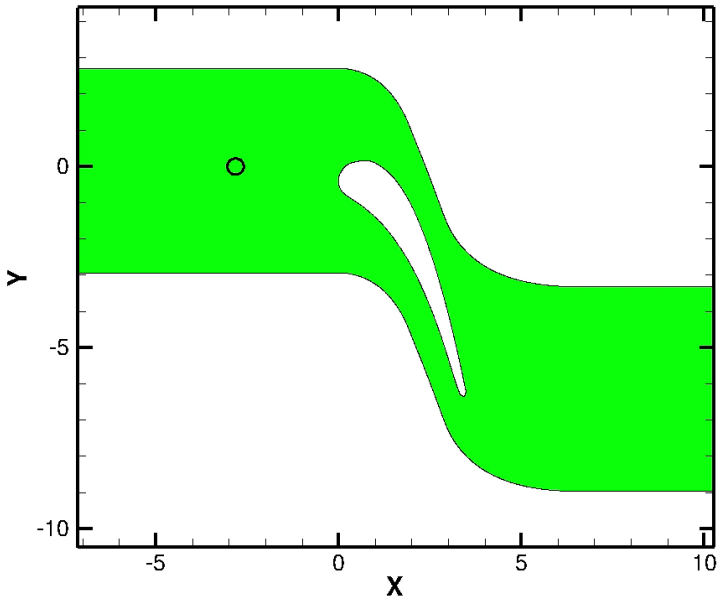
Insert: propagating plane mode

ADT does a good job at low frequencies

ACTUATOR-DISC THEORY VS SIMULATION

…. begun under Stanford Round 1 NRA – now UIUC/UND Round 5 NRA

Pressure p' (color) and Density ρ'



open symbols: DNS left-running
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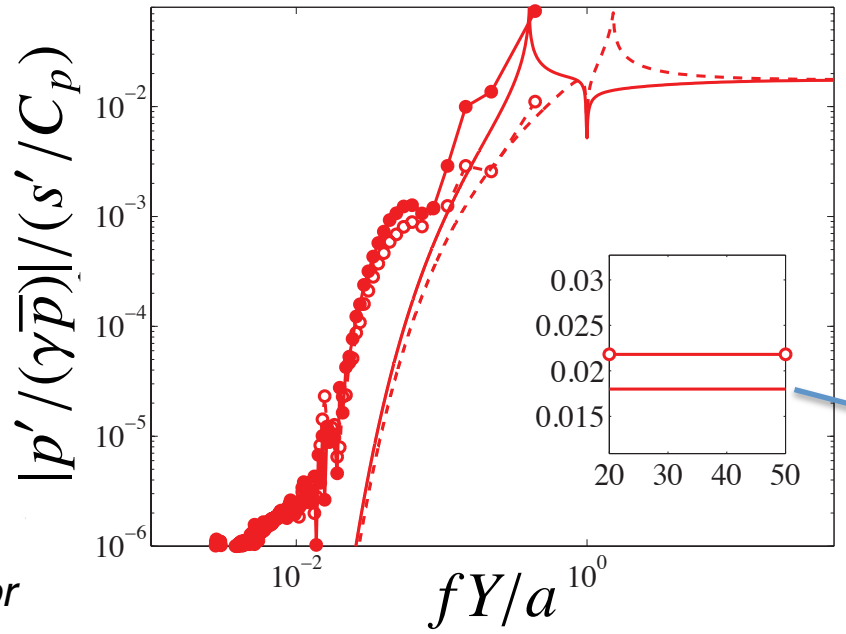


Planar mode ($Y \rightarrow \infty$)

Euler calculation for NASA CERTS Stator
M = 0.15 inflow & M = 0.8 exit
Localized incident entropy disturbance
(> 5 kHz)

All pressure waves are evanescent for fY/a < 1

Insert: propagating plane mode

ADT fails to predict decaying modes – propagating plane wave result OK

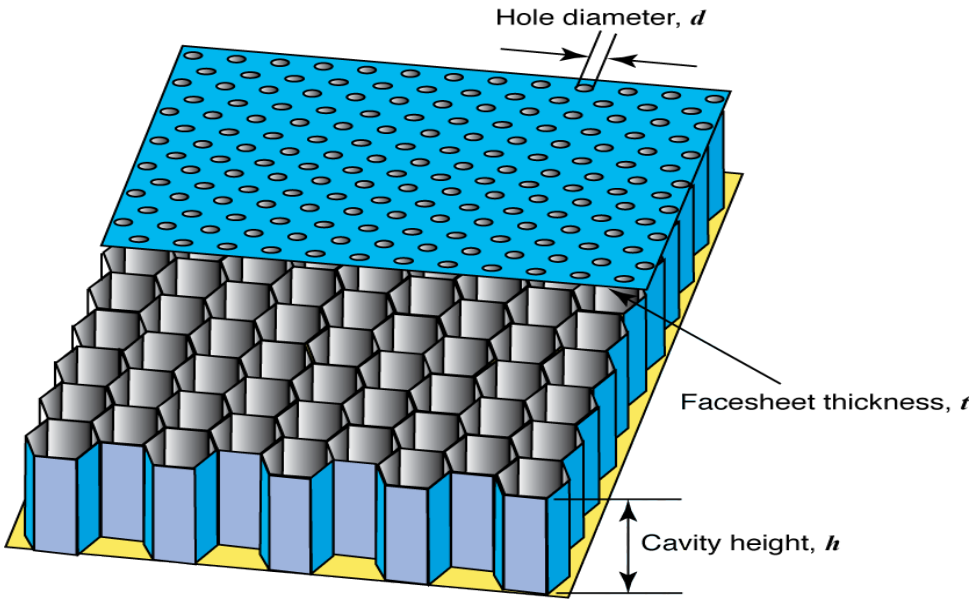
CMC LINERS FOR CORE-NOISE REDUCTION

…. NASA GRC and LaRC joint in-house research effort

- NASA GRC and NASA LaRC are teaming to develop a compact, lightweight, oxide/oxide CMC-based acoustic liner containing channels of different lengths to provide broadband noise reduction over a typical range of 400 Hz to 3 kHz suitable for core application
- The channels (0.375” to 0.5” wide CMC honeycomb cells) will need to range in effective length from about 1.5” to 12”

A thin perforated CMC facesheet will cover the cells. The honeycomb cell geometry is preferred because it provides excellent strength

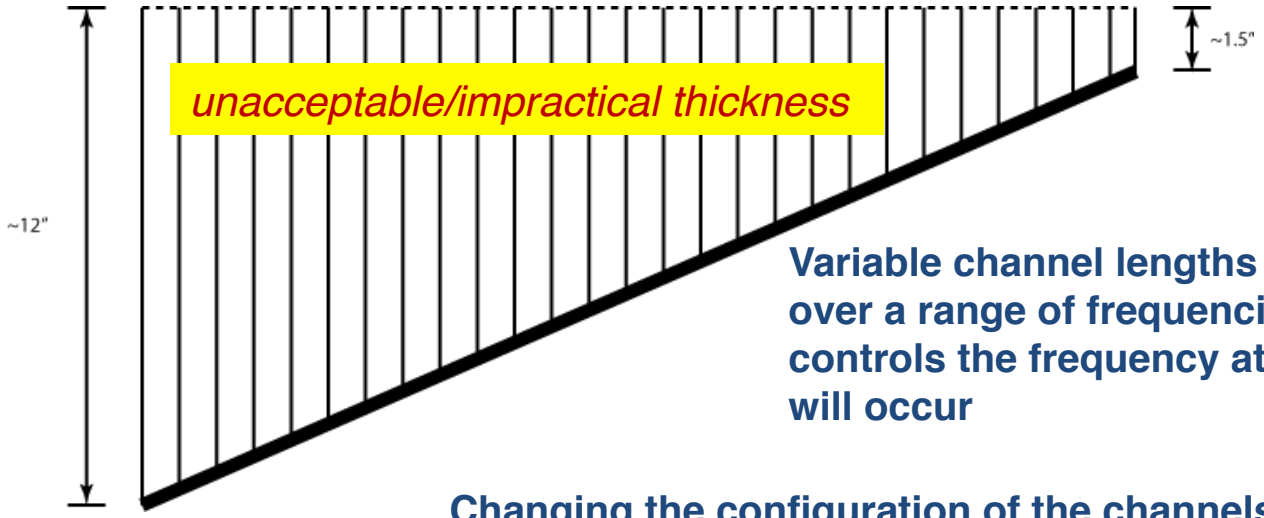
The oxide/oxide CMC has a density of 2.8 g/cc (vs. the 8.4 g/cc density of IN625), potentially offering component weight reduction and reduced fuel consumption



High-temperature capability, weight reduction & broadband noise reduction

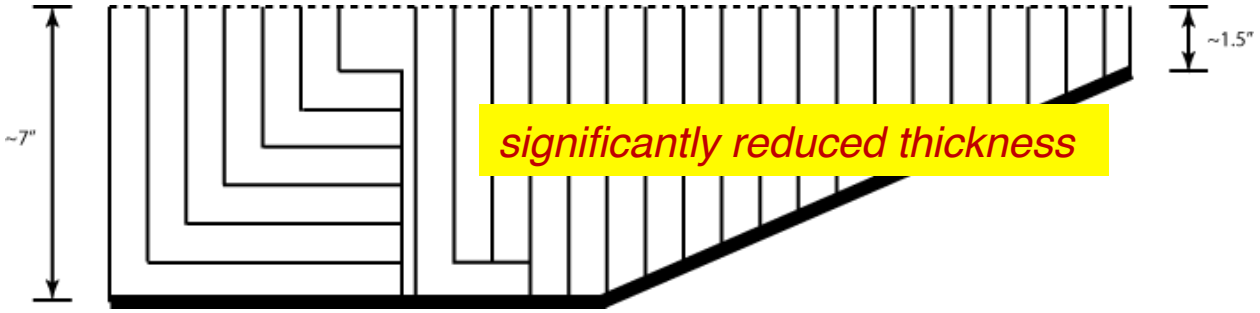
CMC LINERS FOR CORE-NOISE REDUCTION

…. NASA GRC and LaRC joint in-house research effort



Variable channel lengths can provide noise reduction over a range of frequencies, because the cavity height controls the frequency at which maximum absorption will occur

Changing the configuration of the channels by angling the cells or using curved or bent cells with the required effective length can reduce the liner depth to around 7”, while still providing nearly the same performance



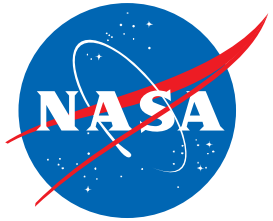
NASA Team:
Doug Kiser/GRC
Mike Jones/LaRC
J. E. Grady/GRC
L. S. Hultgren/GRC
C. J. Miller/GRC

Feasibility increased by using non-straight channels

Summary

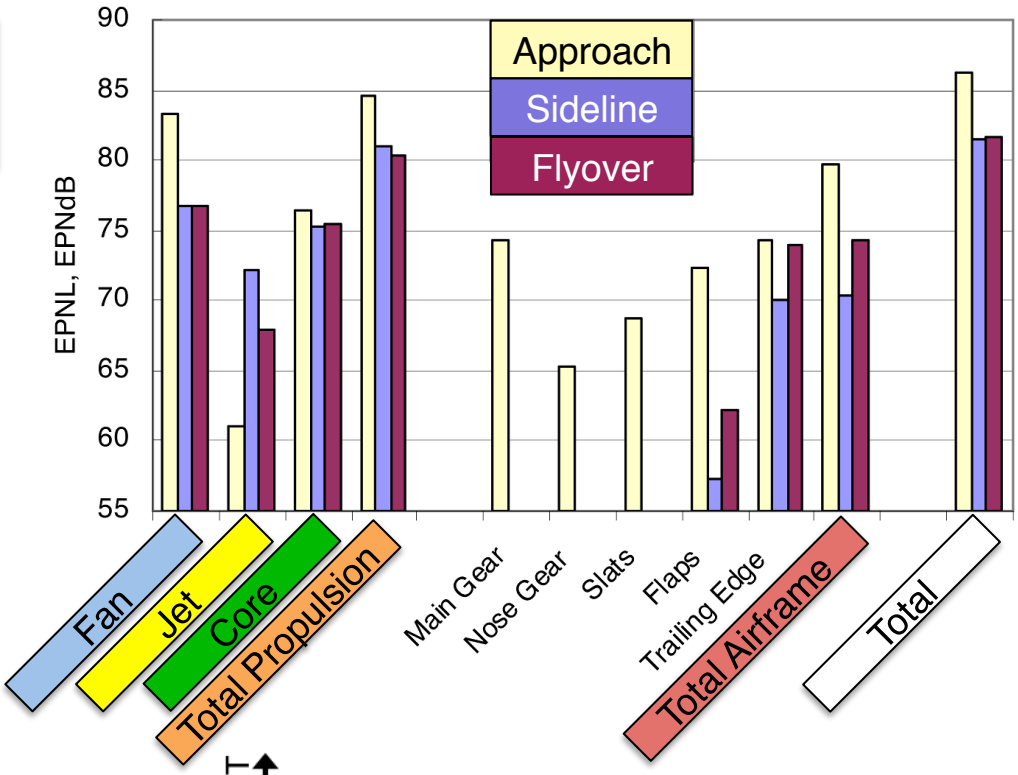
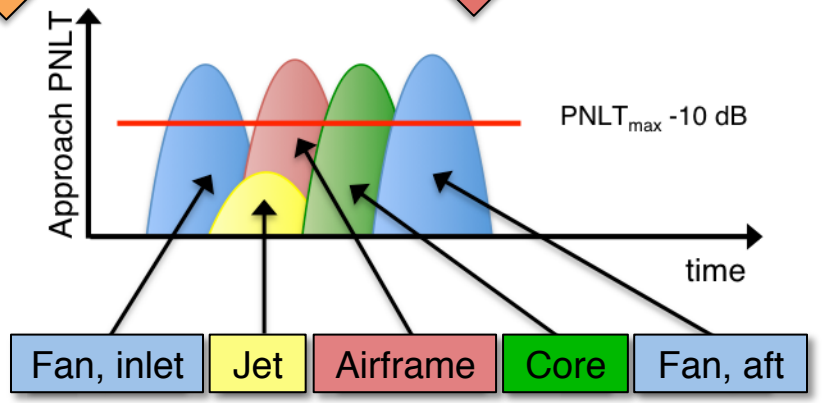
…. NASA FAP SFW QA Core-Noise Reduction Task

- Background
  - existing prediction capability for core (combustor & turbine) noise is based on empiricism and is outdated for N+3 requirements
  - core noise needs to be addressed to meet N+3 noise goals
- Three focus areas
  - addressed through in-house research and two NRAs
- Core-noise diagnostics
  - in-house: analyze existing data
  - NRAs: new data and increased understanding
- Core-noise modeling
  - in-house: develop improved reduced-order models for ANOPP
  - NRAs: high-fidelity simulation, understanding, and modeling
- Core-noise reduction
  - GRC/LaRC: CMC broadband acoustic liner


NASA

Predicted N+1 Airplane Certification Levels

…. Jeffrey J Berton, Edmane Envia & Casey Burley – AIAA 2009-3144

Thrust = 23,000 lb; BPR = 16; FPR = 1.3; OPR = 32

- The N+1 predictions by Berton, Envia & Burley show that core noise is significant for takeoff and cutback conditions
- At approach:
  - fan-noise dominates EPNL due to tone penalties and duration
  - total-airframe then core-noise OASPL peaks are the largest