



Subsonic-Transport Core/Combustor Noise

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

Research in Support of Ultra-Efficient Subsonic Transports

NASA/GRC/LTV Branch Presentation
Cleveland, Ohio, March 2021

NASA Advanced Air Vehicles Program
Advanced Air Transport Technology Project

www.nasa.gov



WHY – WHAT – HOW

Why Worry About Core/Combustor Noise (Motivation)

- Subsonic-Transport Airport-Community-Noise Reduction
- Propulsion-Noise Source Strengths Are Changing
- Impact of Design Trends on Combustor Noise

What Is Combustor Noise

- Physical Mechanisms and Character
- Direct and Indirect Combustor Noise

How

- Prediction
- Measurement

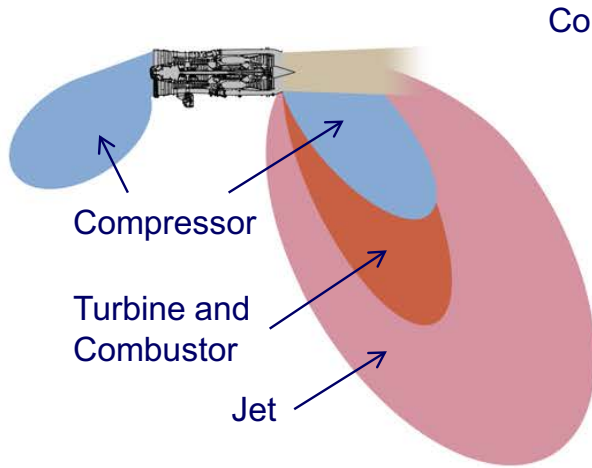


Takeoff and Landing Noise: an Airport-Environmental Impact Issue

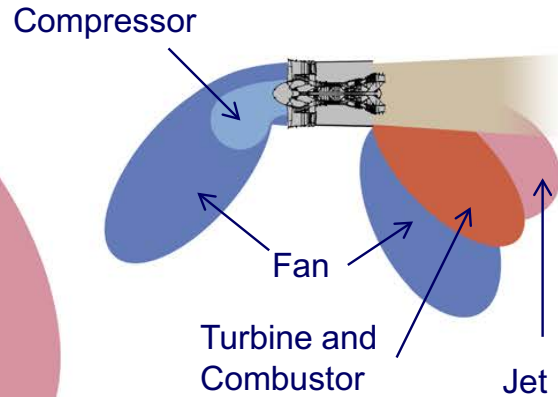


- Tremendous Progress Since 1960s
- Air Traffic Is Predicted to Increase
- Further Noise Reduction Is Essential
- Many Noise Sources
- Airframe and Propulsion Noise:
 - Slats, flaps, landing gear, wing and tail
 - Fan, core and jet
- Core Noise:
 - Compressor, combustor and turbine
 - Combustor noise likely a future issue

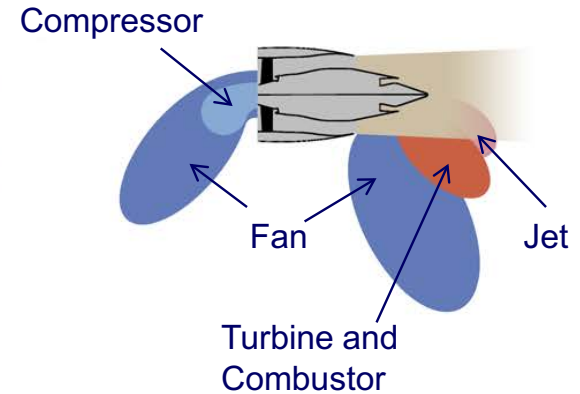
EVOLUTION OF PROPULSION NOISE SOURCES



1960s engine
1:1 BPR



1990s engine
6~8:1 BPR



2015 engine
12:1 BPR

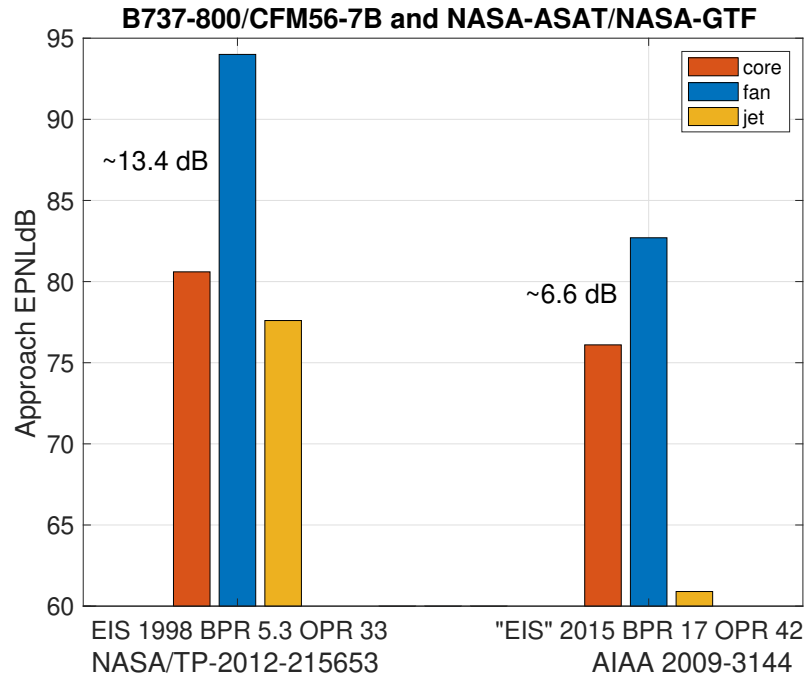
- Fan Noise Is Currently the Dominating Propulsion Noise Source
- Combustor Noise Can Make Contribution at Approach Conditions

PROPULSION-NOISE TRENDS ILLUSTRATION



Relative Strength of Propulsion-Noise Sources Are Changing

Illustrative Example



- Two NASA System Studies
 - Modern reference case: B737/CFM56-7B
 - Advanced NASA concept: ASAT/GTF
- BPR Increase Reduces Jet Noise
- Fan Is Dominant Noise Source:
 - Dominance halved between studies
 - Trends are likely to be continued
- Further Propulsion-Noise Reduction Is Essential Due to Traffic Increase
- Combustor a Future Limiting Issue

2035-EIS COMPACT-CORE CHARACTERISTICS



NASA Hybrid Thermally Efficient Core (HyTEC) Project

- Project Still in Development Stage – Early Pre-Formulation Requirements:✧

- 5% (absolute) increase in thermal efficiency, η_T
- Corrected core mass flowrate ≤ 2.5 lbm/s



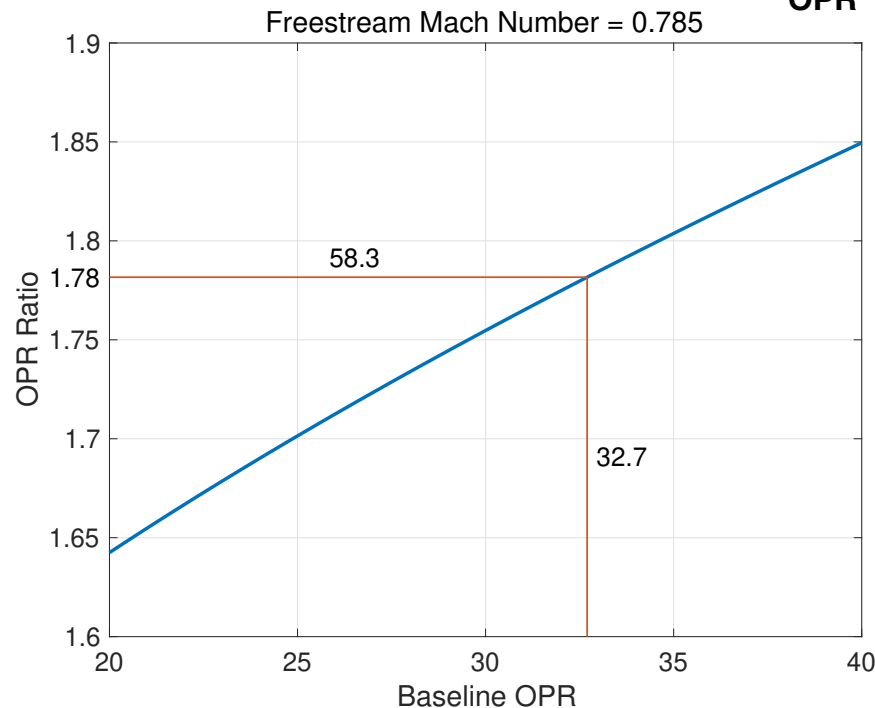
OPR

Thermal Efficiency (Ideal)

- $\eta_T = 1 - 1/(\tau_r \tau_c)$
 - Total-temperature ratio: $\tau = \pi^{(\gamma-1)/\gamma}$
 - Ram effect: $\tau_r = 1 + 0.5(\gamma-1)M^2$
 - Total-pressure ratio: $\pi_c = \text{OPR}$

CFM56-7B Baseline★ for Estimates

- OPR = 32.7 @ ADP (TOC, 10.668 km)
- $M = 0.785$, BPR = 5.3 & FPR = 1.55



ILLUSTRATIVE PARAMETRIC ESTIMATES



Ideal Parametric Turbofan Model Results (**Baseline** and **“Design”**)

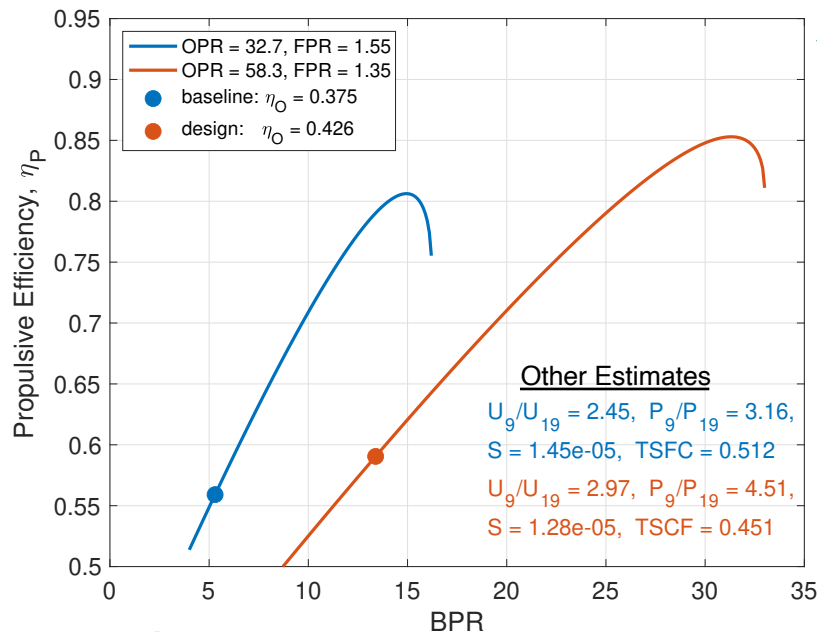
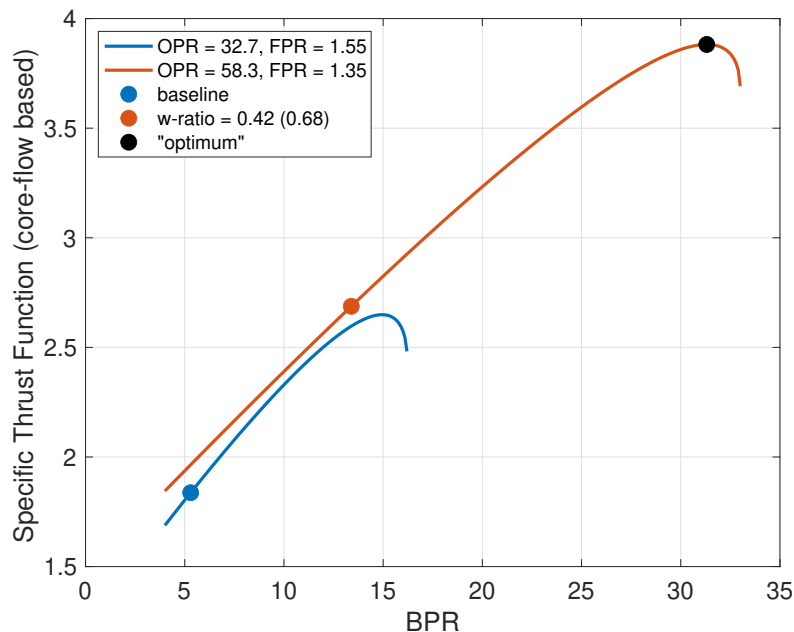
- OPRs as Determined – Core Mass Flowrate Reduced From ~ 6 to 2.5 lbm/s
- Specific-Thrust Model Determines BPR $\Rightarrow$ Other Results Follow from Model



BPR



W_{3c}



ACOUSTIC-POWER-SCALING INSIGHTS



Combustor Acoustic Power Based on Existing Direct-Noise Model

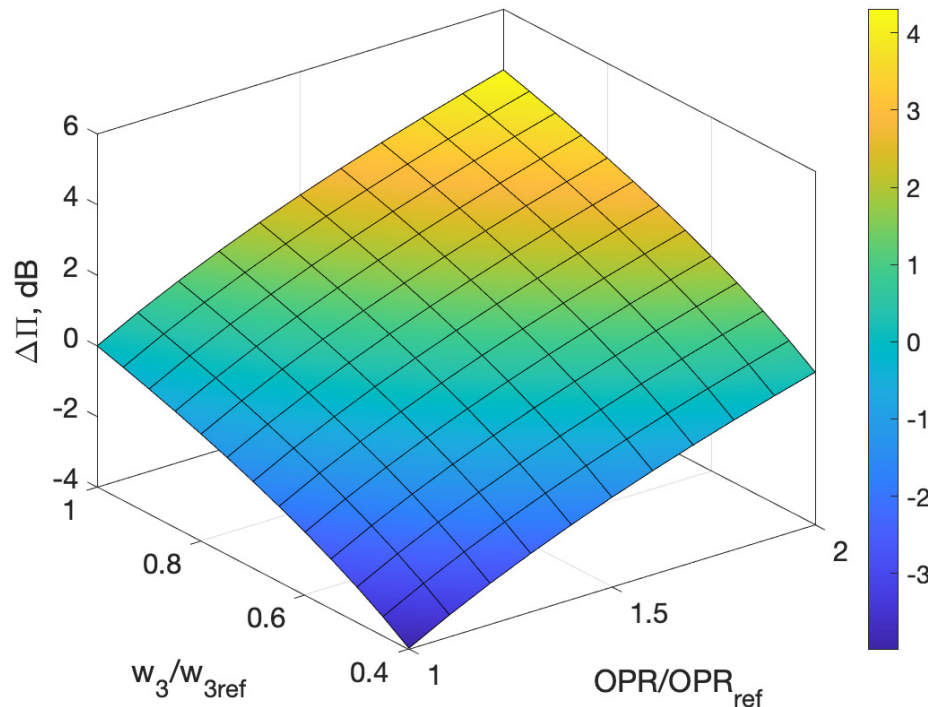
- Acoustic Power: $\Pi \sim w_3 \times (\Delta T)^2 \times (OPR)^{5/3.5}$ with ΔT essentially unchanged

Combustor-Noise Impact

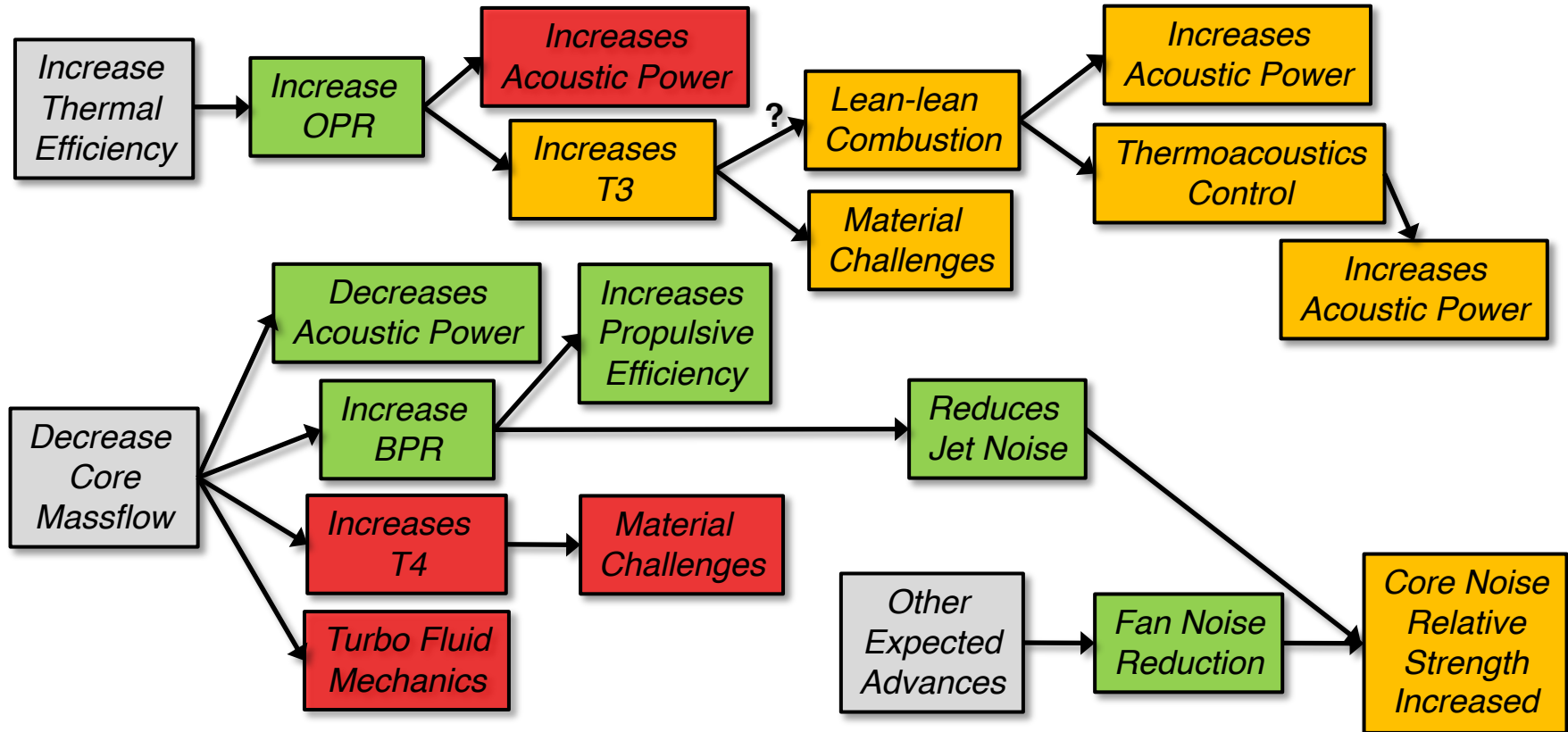
- Increase, $\Delta \Pi \sim$ 0 dB to +4 dB
- Essentially Unchanged at Best
- Not Good Enough If Further Noise Reduction Is Desired

Other Uncertainties

- Turbine Attenuation Change
- Indirect-Noise Increase
- Thrust-Class Effects



HIGH-EFFICIENCY COMPACT CORE IMPACT



COMBUSTOR NOISE – WHAT IS IT



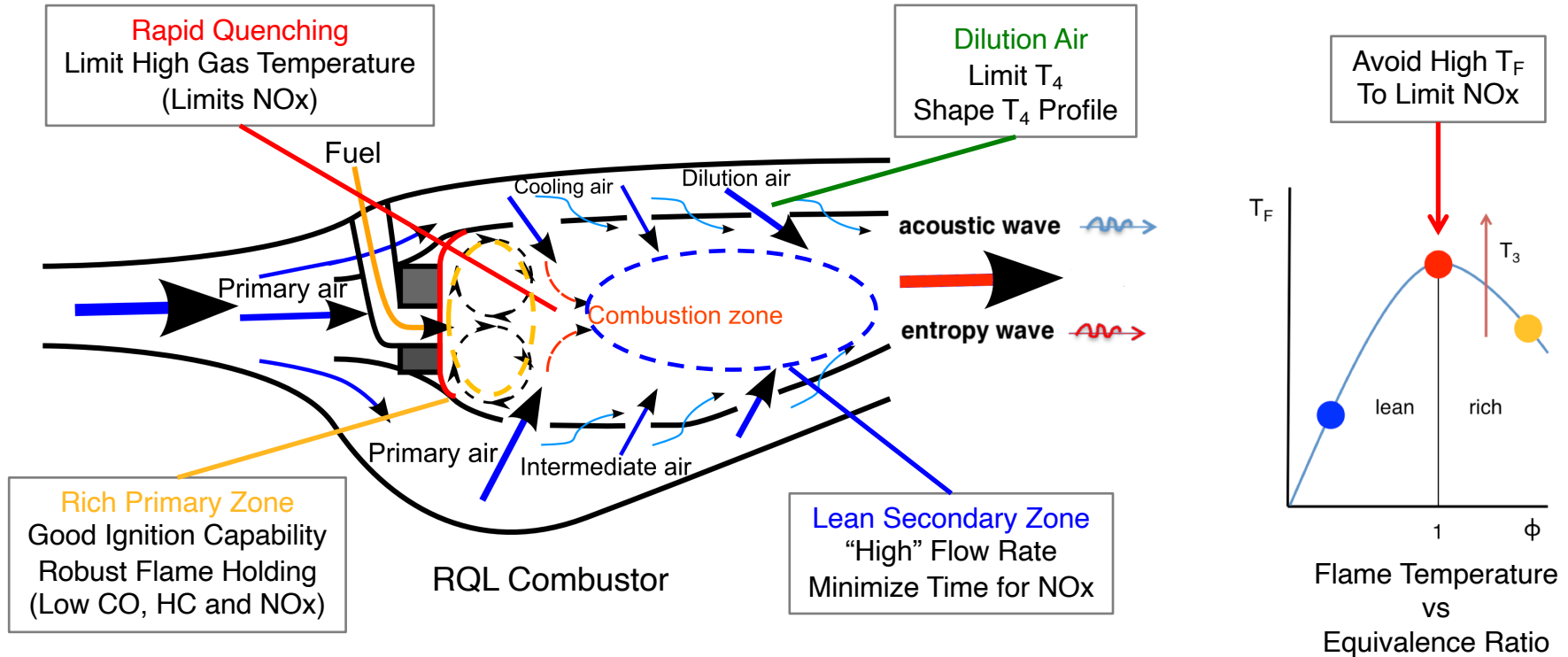
Combustor-Noise Character

- Aft-Radiated Low-Frequency Broadband Noise
- Normally Peaks in the 400 Hz 1/3-Octave Frequency Band
- Dominated by Jet Noise For Current Turbofans – Particularly During Static Tests
- Can Make a Contribution at Low-Power (Approach) Conditions
- Design Trends Likely to Make Combustor Noise Important at All Conditions

Combustor-Noise Physical Mechanism(s)

- Originates From Low-Mach-Number Unsteady Combustion Process
- Modified by Passage Through Engine Internal Flow Path
- Direct- and Indirect-Noise Components

RICH-QUENCH-LEAN (RQL) COMBUSTOR

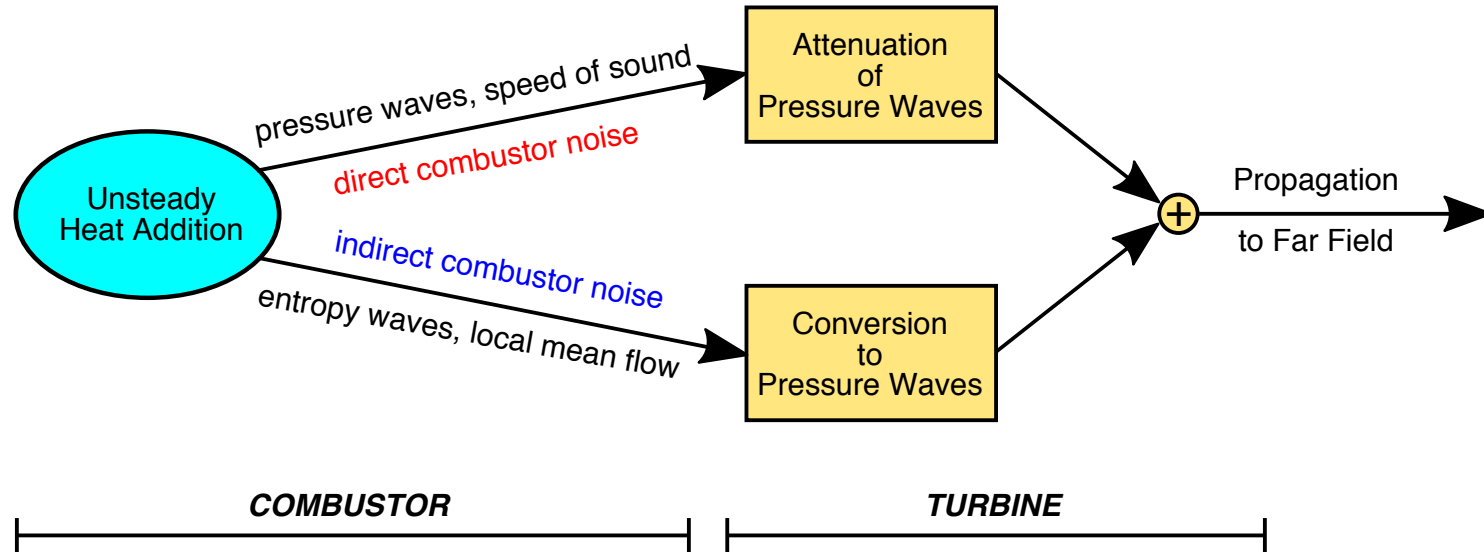


- Acoustic and Entropy Disturbances Generated by Unsteady Heat Release

COMBUSTOR-NOISE SOURCE MECHANISMS

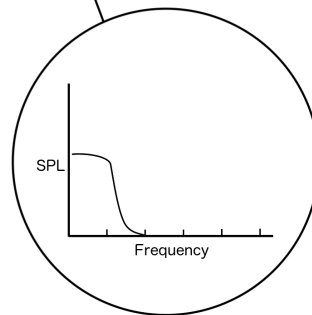
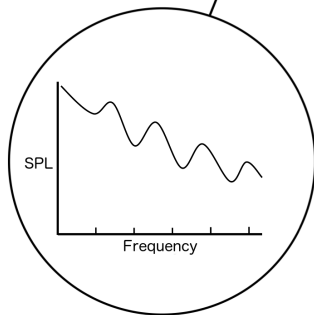
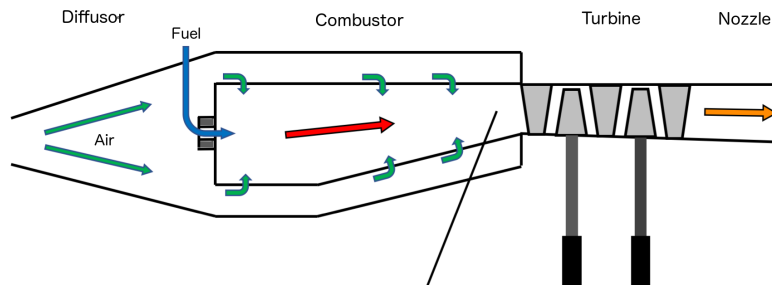


Direct and Indirect Combustor Noise



- Low-Mach-Number, Essentially Constant-Pressure, Combustion Process
- Acoustic and Entropy Disturbances Generated by Unsteady Heat Release
- Entropy Disturbances Converted to Pressure Waves in Turbine

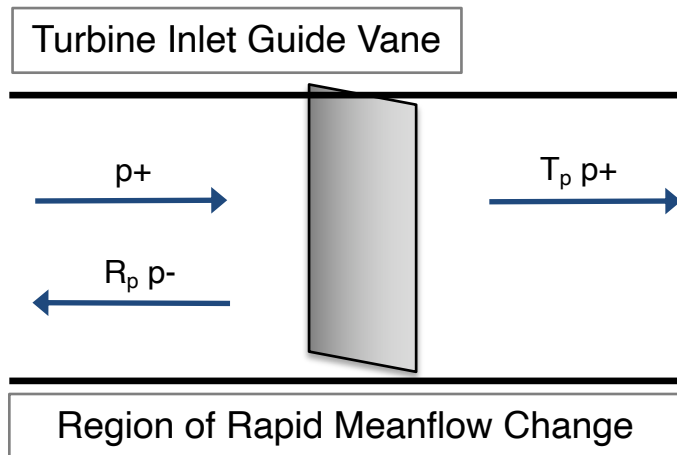
DIRECT COMBUSTOR NOISE



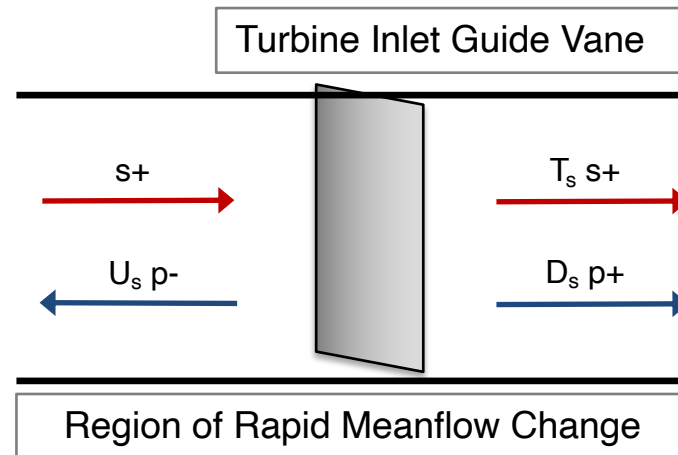
- Low-Frequency Broadband Noise
- Relevant Frequency Range $< 1,600$ Hz
- Acoustic Pressure Field Inside Combustor Is Affected by Confinement
 - Multitude of Modes (m,n)
 - Each Mode Dominant at Cut-On (Karchmer, 1983)
- Propagation Through Engine-Internal Flow Path
 - Most Modes Are Cut-Off
 - Mainly Plane Wave at Exit

- On an 1/3-Octave Basis, *SPL* Spectrum Peaks Around 300–600 Hz
- Directivity Has Maximum at About 120° Polar Direction (Aft Quadrant)

INDIRECT COMBUSTOR NOISE



- Incoming pressure wave $p+$ transmitted and reflected
- Low-Frequency Actuator-Disk Theory



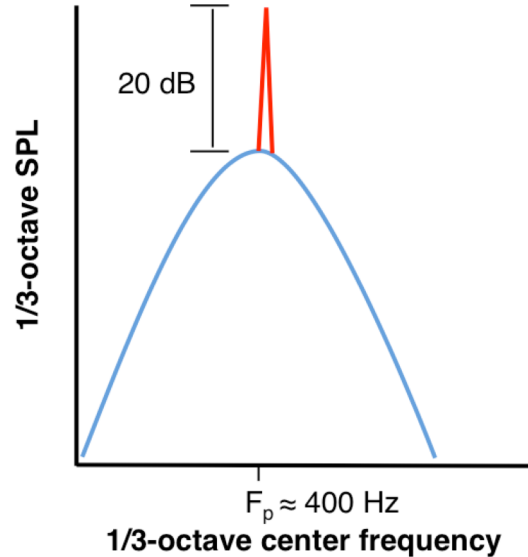
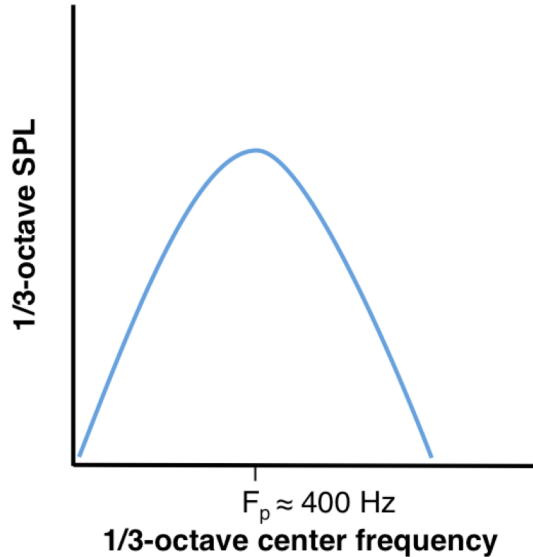
- Incoming entropy wave $s+$ transmitted
- Upstream/downstream acoustic waves created
- $D_s p+$ is indirect noise propagating to farfield
- Combustor rumble: upstream acoustic waves interact with injector flow (low frequency tones)
- Dynamic instability: acoustic feedback on combustion – tones ~ 20 dB above background

COMMUNITY NOISE VS. DYNAMIC INSTABILITY



Typical Combustor Noise Spectrum

– with Thermoacoustic Instability



Dynamic Instability is
a Serious Issue for
Combustor Design

- Life Cycle
- Operability
- Safety

- Assume Not an Issue – Problem Fixed Before Hanging Engine on Wing
- Only Incoherent Broadband Noise for Airport-Community Impact of Combustor



Combustor-Noise Prediction

- Semi-Empirical Models for Prediction – NASA ANOPP GECOR Module
- Current Engineering Models Developed in 1970s/1990s + Some Later Updates
- Fully-Compressible Reacting LES Still in Its Infancy (~ 5 Years)
- LES for Turbine-Transmission of Combustor Noise
- NASA: In-House Work on Engineering Methods – NRA Support for LES in Past

For More Modeling Info: NASA/TM-2018-220041 & Tam et al. CEAS Aeronautical J (2019)10(1)

Combustor-Noise Measurement

- Real-Engine Static Tests Are Most Meaningful
- Masked by Other Propulsion-Noise Sources – Not Straightforward Measurement
- Core, Burner or Burner-Section Rig-Tests Can Also Provide Important Insights
- Provide Source Understanding and Insights for Mitigation Techniques



ANOPP-GECOR Semi-Empirical Model

- Acoustic Power:

$$\Pi = 10^{K/10} w c_0^2 [(T_4 - T_3)/T_3]^2 (P_3/P_{s0})^2 \times F_{TA}$$

- $K = -60.53$ SAE, $K = -64.53$ SmE
- Turbine attenuation factor: F_{TA} (2 options: GE || P&W)
- 3 differences from original SAE method: '0' denotes ambient not SLS, 2nd value for K, 2nd choice for F_{TA}

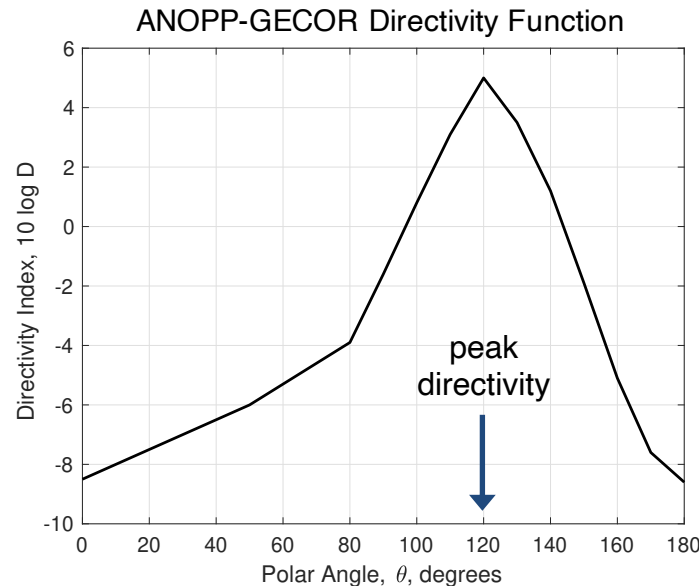
- Sound Pressure Level:

$$SPL = 10 \log_{10} [\rho c \Pi D(\theta) S(f) / 4\pi r^2 (P_{ref})^2]$$

- Universal directivity & spectrum: $D(\theta)$ & $S(f)$

Acoustic-Power Scaling Law

$$\Pi \propto w (\Delta T)^2 (OPR)^{5/3.5} \quad \text{with} \quad \Delta T \sim \text{constant} \quad (\text{fuel heating value } h_{PR} \text{ dependent})$$

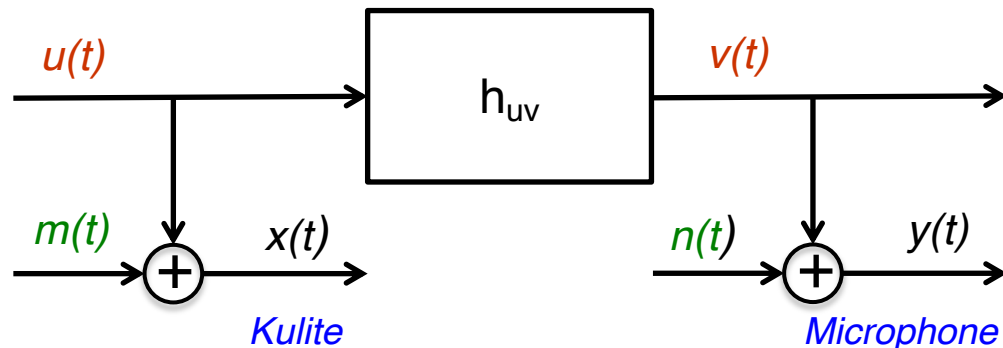


COHERENCE TECHNIQUES



- Direct Measurement of Core/Combustor Noise Difficult Due to Jet Noise
- Coherence Techniques Identify the **Core-Noise** Component

$u(t)$ & $v(t)$: coherent signals
 $m(t)$ & $n(t)$: uncorrelated signals
 $x(t)$ & $y(t)$: measurable signals



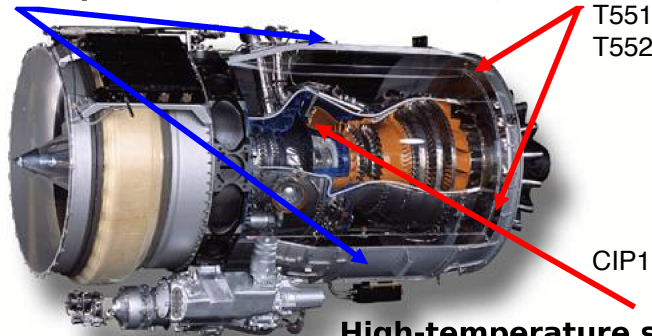
- Coherence Function: $\gamma_{\alpha\beta} = |G_{\alpha\beta}| / (G_{\alpha\alpha} G_{\beta\beta})^{1/2}$; Theoretically: $0 \leq \gamma_{\alpha\beta}(f) \leq 1$
- Finite Data Series – Estimated Coherence Always Non-Zero: $\varepsilon \leq \gamma_{\alpha\beta}(f) \leq 1$
 - $\varepsilon = [1 - (1-P)^{1/(M-1)}]^{1/2}$; P = confidence interval & M = number of independent segments
 - If estimated coherence is less than ε , the signals are independent with probability P
- Two-Signal or Coherent-Power Method: $G_{vv}(f) = [\gamma_{xy}(f)]^2 G_{yy}(f)$

SOURCE-SEPARATION – EVNERT DATA



Sensors in aft fan
bypass access panels

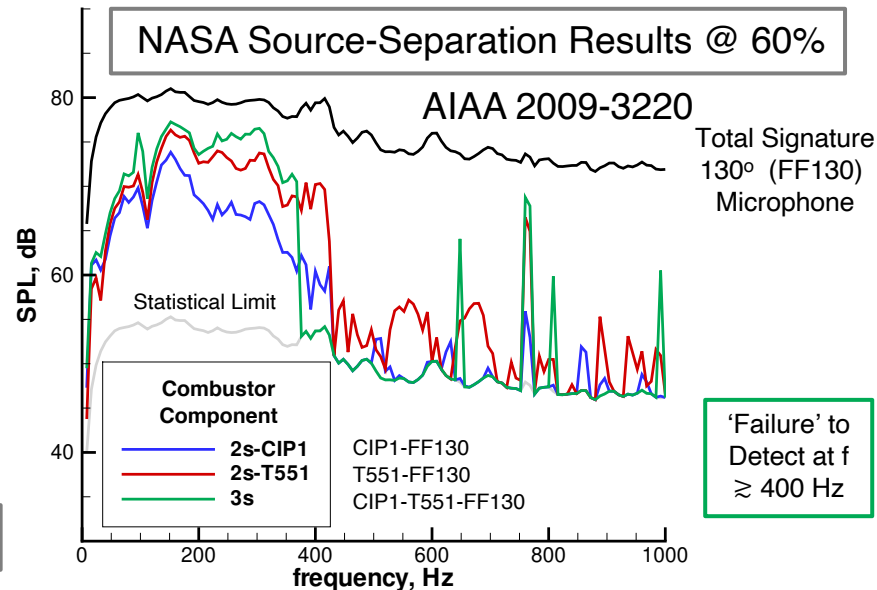
High-temperature sensors
with air cooling at turbine exit



NASA/CR-2008-215225

High-temperature sensor
with air cooling in
combustor igniter port

TECH977 Research Turbofan Internal Instrumentation



- NASA/Honeywell 2005–2007 Outdoor (San Tan Facility) Static Engine Test Data
- Engine-Internal Sensors and Ground-Based Microphones at 100 ft
- 2s-CIP1 Method Robust but Shows Gradual Underestimation Due to Bias Error

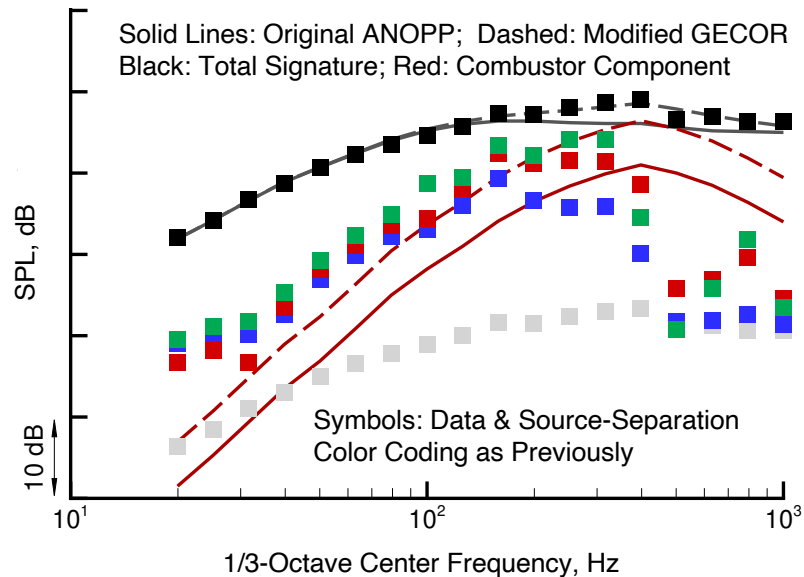


Evaluation of Various Methods

- 2s-CIP1 Results Suffers Since Non-Planar Modes Become Important in Combustor as Frequency Increases
- 2s-T551 Results Rapidly Suffers Because of Other Coherent Signals
- 3s-Method Can Handle Two Coherent Sources but In Practice Quite 'Fragile'
- NASA/TM-2016-219419: 2s, 3s & 4s
- Mendoza et al. AIAA 2008-2009: 5s

⇒ **There Is No Magic Bullet**

ANOPP-GECOR F_{TA} Update

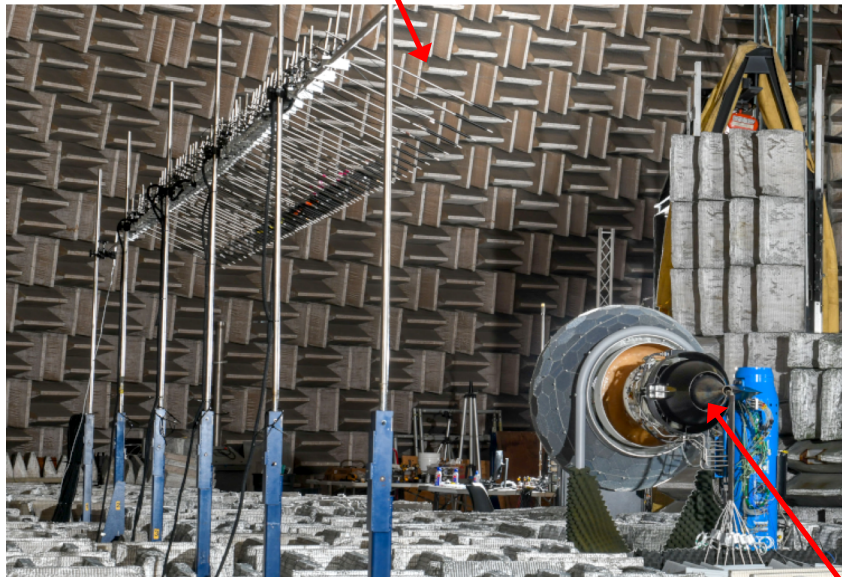


- Turbine-Transfer Function Obtained
- P&W Attenuation Formula Better Fit

2019 DART SOURCE-DIAGNOSTIC TEST



AAPL Overhead Microphone Array[↑] &
Linear Sideline Microphone Array Used



DART Testbed in AAPL (Anechoic) Facility
Boyle et al. GT2020-14194, JEGTP 143(5) 2021

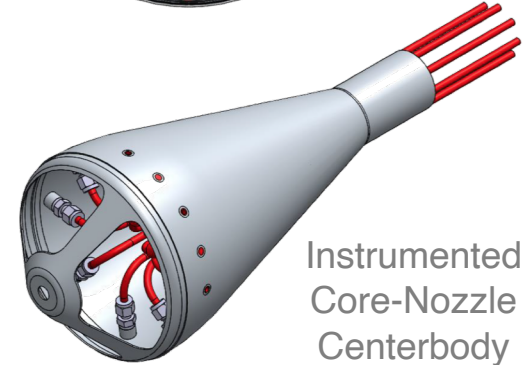
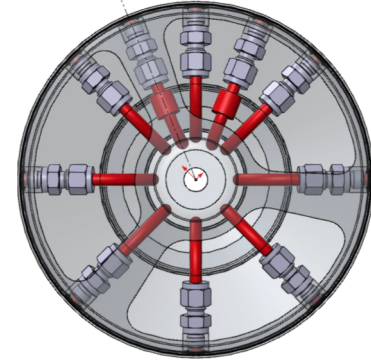
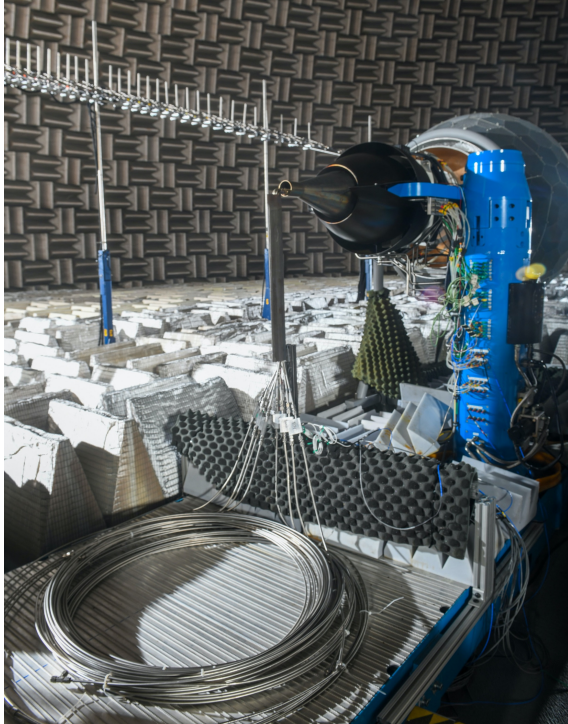
NASA Advanced Air Vehicles Program
Advanced Air Transport Technology Project

- NASA GRC DGEN Aeropropulsion Research Turbofan (DART) Testbed
 - DGEN 380 – 500-lbf-thrust-class GTF
 - BPR = 7.6 & fan-gear-ratio = 3.32
 - Small, but relevant aeroacoustics
- NASA GRC Aero-Acoustic Propulsion Laboratory (AAPL)
 - Anechoic dome – wedges on walls and floor
- Combustor-Source Characterization and Noise Propagation to Farfield
- Method Development/Validation
- Mitigation Research Preparation
- Circumferential Sensor Array at Core Nozzle Exit

CORE-NOZZLE-EXIT 8-ITP ARRAY



8 Differential Kulite Sensors in Infinite-Tube-Probe Arrangement

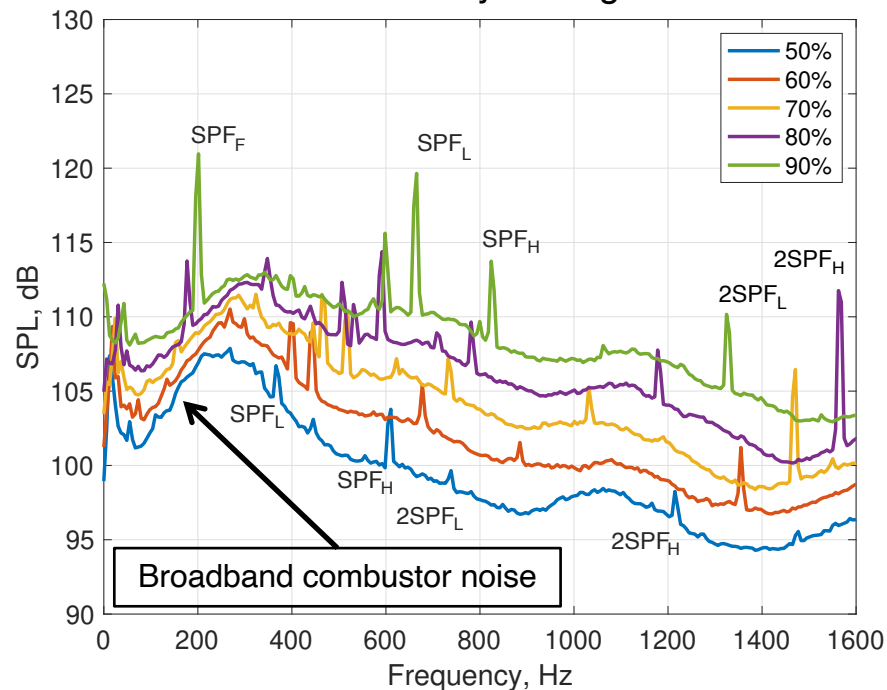


Instrumented
Core-Nozzle
Centerbody

CORE-NOZZLE-EXIT ITP SPL

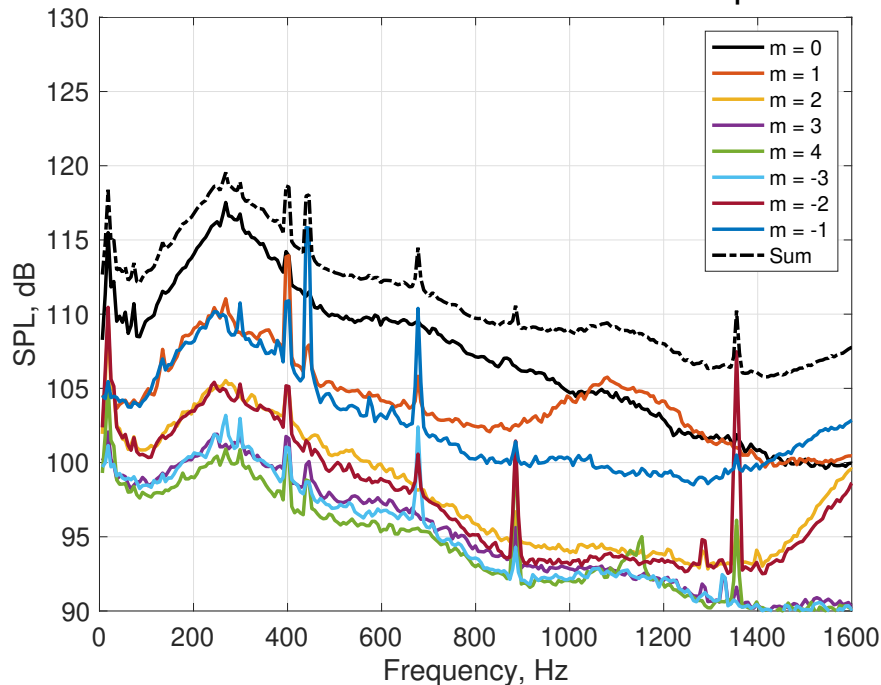


Circumferentially averaged *SPL*



- Broadband and SPF Tones

Modal *SPL* contribution at 60% fan speed

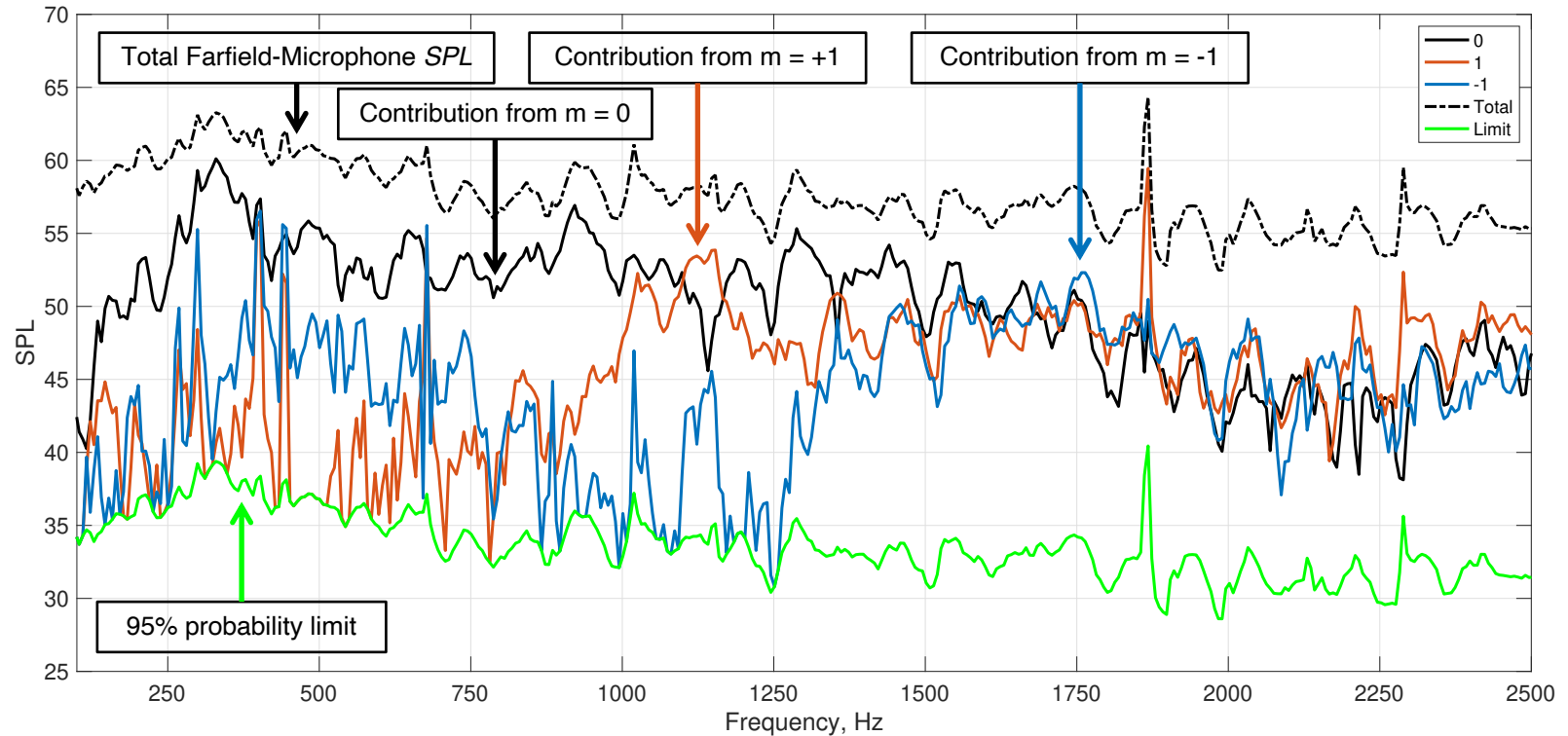


- Plane Wave Dominates Below ~ 1 kHz

MODAL-BASED COP – 120° FARFIELD @ 60%



20190801-tp003 - Modal-Based COP - FF019 (preliminary)

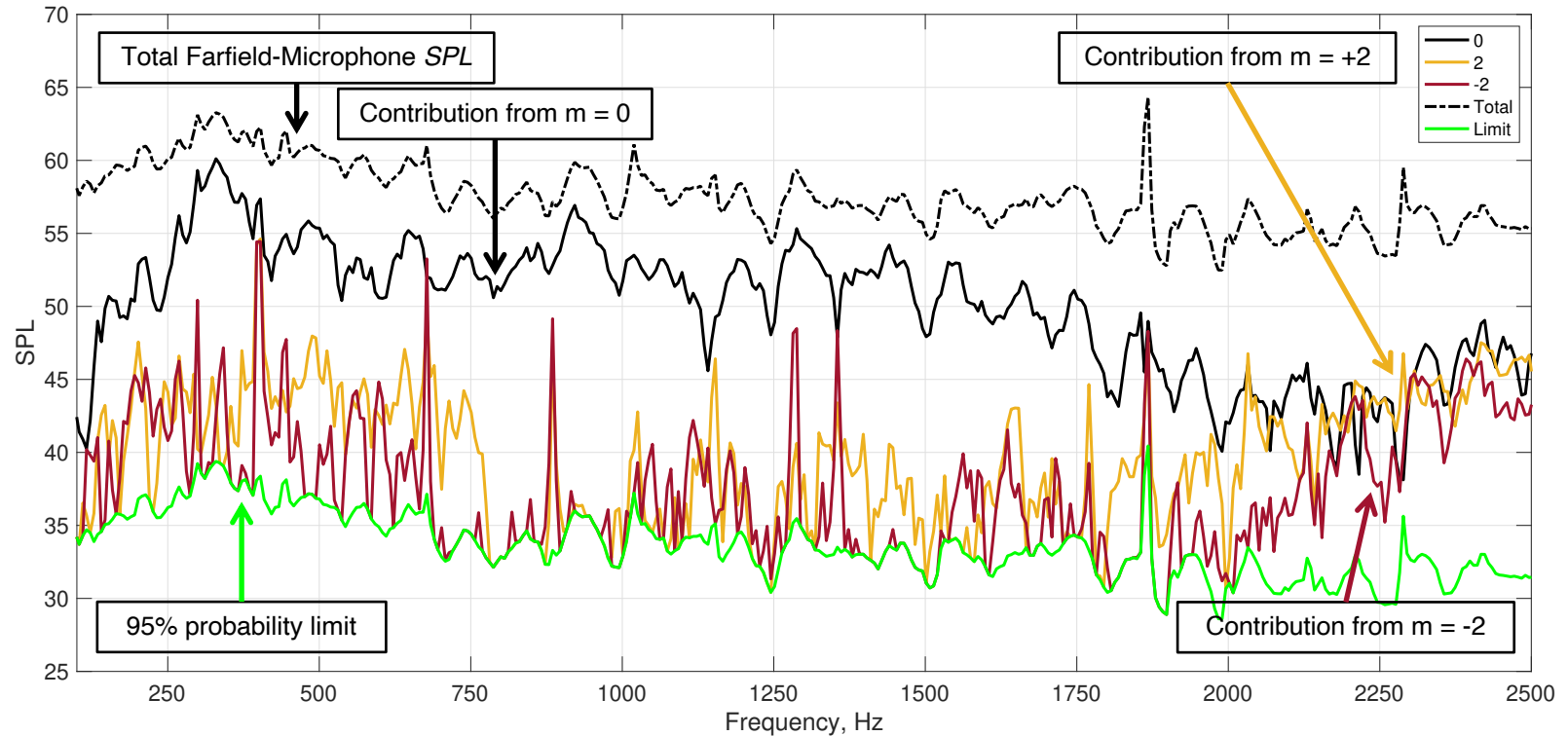


Only $m = 0$ and $m = \pm 1$
contributions are shown

MODAL-BASED COP – 120° FARFIELD @ 60%



20190801-tp003 - Modal-Based COP - FF019 (preliminary)



Only $m = 0$ and $m = \pm 2$
contributions are shown

MODAL-BASED COHERENCE METHODS

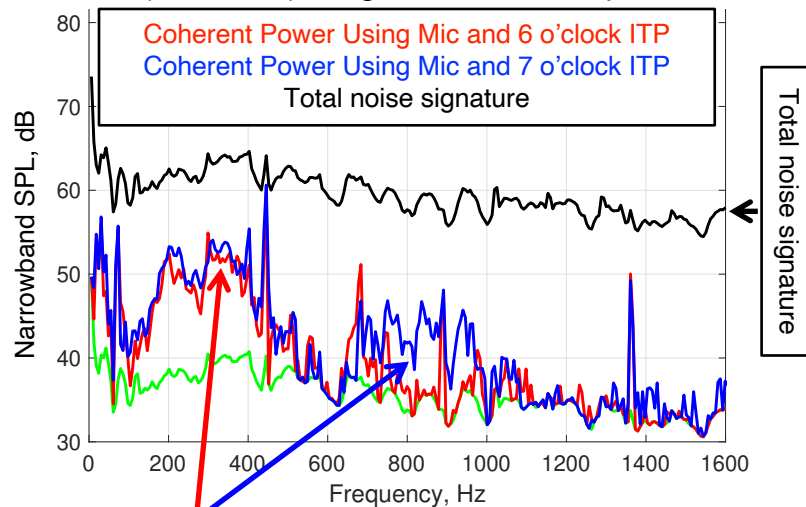


Advantage Of Modal Approach

- Modes Originating in the Combustor Are Statistically Independent ($m, n=0$)
- The Modal Decomposition Allows Individual Study of Each Mode
- Turbine-Generated Modes Generally Have $|m| \gg 1$
- COP Method Bias Problem Minimized
- Building on Ideas from Davis & Bennett, AIAA 2011-2825

Classical Coherence Method

Farfield (37ft, 131°) 2-signal coherent output @ 60%



Broadband combustor noise

- 2017 Baseline DART Test
- Only Two Sensors at Core Exit

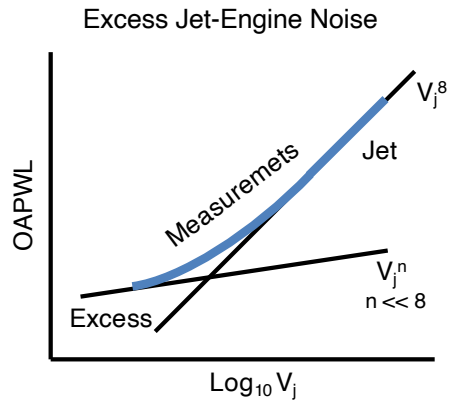


Boyle et al. AIAA 2018-3281

INDIRECT-COMBUSTOR-NOISE DEBATE



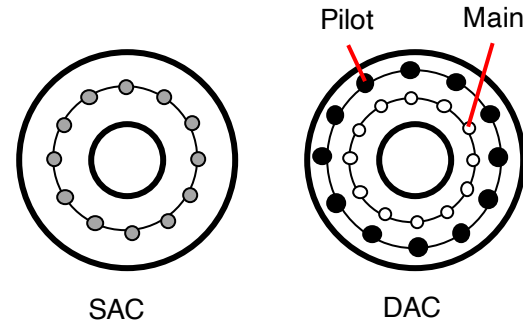
- Importance of Combustor Noise
First Realized in the Early 1970s



Observation by Cumpsty 75-GT-61

- Vigorous Direct/Indirect Debate
- Industry Practitioners Generally in the Direct Camp

- Mathews et al. (1977) FFA-RD-77-3 Model Showed Indirect Noise 20dB Below Known Levels for P&W Engines
- Much More Noise at Approach for Early Low-Emission (~1995) DAC Than SAC



- Attributed to Indirect Combustor Noise
- Fixed by Changing Firing Pattern

INDIRECT-COMBUSTOR-NOISE PREDICTION



- Simple Formula for Direct-Noise Prediction – ANOPP GECOR
- In Contrast, Predicting Indirect Noise Is More Involved
- First, The Entropy, or Temperature, Disturbance Field at The Combustor Exit Must Be Known – Including Some Length Scales
 - Entropy is not directly measurable
 - Very hard to measure unsteady temperature fluctuations in the hostile engine environment
- Second, The Interaction With and Propagation Through The Turbine Stages Must Be Computed
 - Use a sequence of transfer matrices based on actuator-disk theory (common approach)
 - LES or suitable linearized CAA code
 - Some commercial CFD codes may now also have the required capability (?)
 - No in-house NASA GRC activity at present, but NRA support in the past for LES

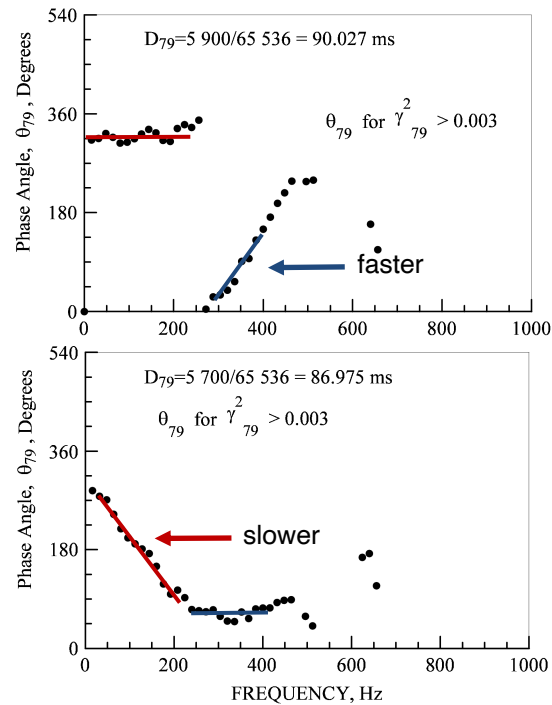
INDIRECT-NOISE EVIDENCE – EVNERT DATA



Time-Delay Analysis of Direct and Indirect Combustor Noise

Miles AIAA 2008-2912 & JPP (2009) 25(1)

- Need to Account for Time-of-Flight Between Sensors When Using Coherence Methods
- Time Delay Determined by Maximizing Coherence: $\max [IG_{xy} / (G_{xx} G_{yy})^{1/2}]$
- Or, Adjust Delay: $\arg(G_{xy}) = \text{constant}$
- Coherent Signal < 200 Hz Took 3 ms Longer Time Than 200–400 Band
- $\Rightarrow$ Mean-Flow Travel in Combustor
- < 200 Hz Associated with Indirect Noise
- Direct Noise at Peak ~ 400 Hz



EVNERT TECH977 – CIP1:FF130 Sensors

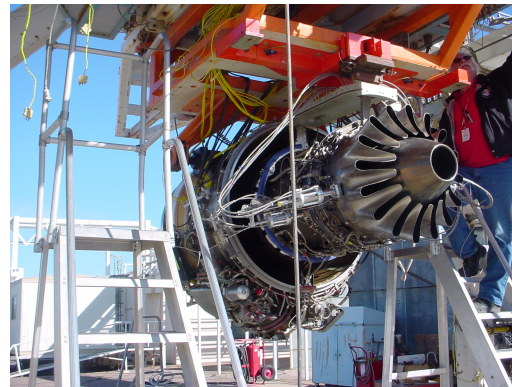
OTHER RELEVANT WORK



NRA 2011–2014 Honeywell Aerospace, Phoenix, AZ

NASA/CR– 2015-218879/VOL1 & AIAA 2015-2819

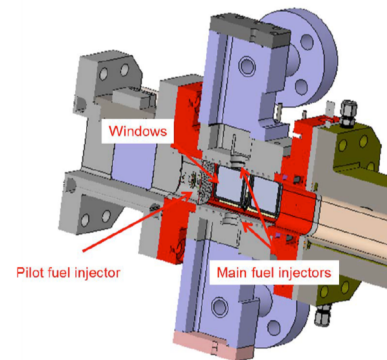
- Database of Unsteady Pressures and Temperatures Inside the TECH977 Turbofan
- In Combustor, Inter-turbine Duct and Turbine Exit
- One of the First Studies, If Not the Very First Study, Available in the Open Literature



NRA 2016–2019 UTRC East Hartford, CT

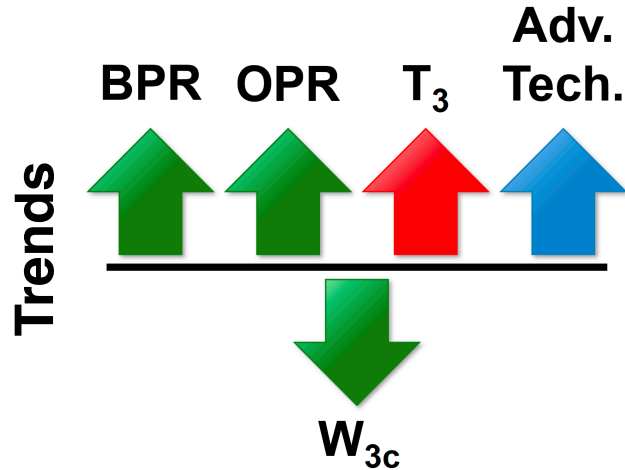
NASA/CR– 20205011099/VOL1

- Database of Detailed Unsteady Measurements Characterizing Noise Sources of Advanced (N+3) Low-Emissions Aero-Combustors





IMPACT OF DESIGN TRENDS ON CORE NOISE



- High BPR and OPR for Performance
 - Compact high-OPR core
- High OPR Implies High T₃ – Impacts Emissions
 - Lean-Lean, Fuel-Flexible Combustors
- Lean Combustion – Thermo-Acoustic Instability Risk
 - Advanced Technologies for Suppression
- Highly-Loaded, Low-Solidity Turbine Stages
- Low FPR and Advances in Fan-Noise Mitigation

- Impact**
- Reduction of Other Propulsion-Noise Sources
 - Potential Increase in Combustor-Noise Source Strengths
 - Less Combustor-Noise Attenuation by Turbine