A Comparison of Combustor-Noise Models – AIAA 2012-2087

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Summary

The present status of combustor-noise prediction in the NASA Aircraft Noise Prediction Program (ANOPP)[1] for current-generation (N) turbofan engines is summarized. Several semi-empirical models for turbofan combustor noise are discussed, including best methods for near-term updates to ANOPP. An alternate turbine-transmission factor[2] will appear as a user selectable option in the combustor-noise module GECOR in the next release. The three-spectrum model proposed by Stone et al.[3] for GE turbofan-engine combustor noise is discussed and compared with ANOPP predictions for several relevant cases. Based on the results presented herein and in their report,[3] it is recommended that *the application of this fully empirical combustor-noise prediction method be limited to situations involving only General-Electric turbofan engines.* Long-term needs and challenges for the N+1 through N+3 time frame are discussed. Because the impact of other propulsion-noise sources continues to be reduced due to turbofan design trends, advances in noise-mitigation techniques, and expected aircraft configuration changes, the relative importance of core noise is expected to greatly increase in the future. The noise-source structure in the combustor, including the indirect one, and the effects of the propagation path through the engine and exhaust nozzle need to be better understood. In particular, the acoustic consequences of the expected trends toward smaller, highly efficient gas-generator cores and low-emission fuel-flexible combustors need to be fully investigated since future designs are quite likely to fall outside of the parameter space of existing (semi-empirical) prediction tools.

This work was carried out under the NASA Fundamental Aeronautics Program, Subsonic Fixed Wing Project, Quiet Aircraft Subproject. It is part of a NASA-internal and NASA-sponsored external research effort for the development and improvement of aircraft noise-prediction capability and tools, to enable a dramatic reduction of the perceived aircraft noise outside of airport boundaries. This noise reduction is critical in view of the anticipated future increase in air traffic.

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[1] Zorumski, W. E., "Aircraft Noise Prediction Program Theoretical Manual," NASA TM-83199-Pt-1&2,1982.
[2] Hultgren, L. S., "Full-Scale Turbofan-Engine Turbine-Transfer Function Determination Using Three Internal Sensors," AIAA Paper 2011-2912 (NASA TM-2012-217252), 17th AIAA/CEAS Aeroacoustic Conference, Portland, Oregon, 2011.
[3] Stone, J. R., Krejsa, E. A. and Clark, J. C., "Enhanced Core Noise Modeling for Turbofan Engines," NASA CR-2011-217026, 2011.

National Aeronautics and Space Administration

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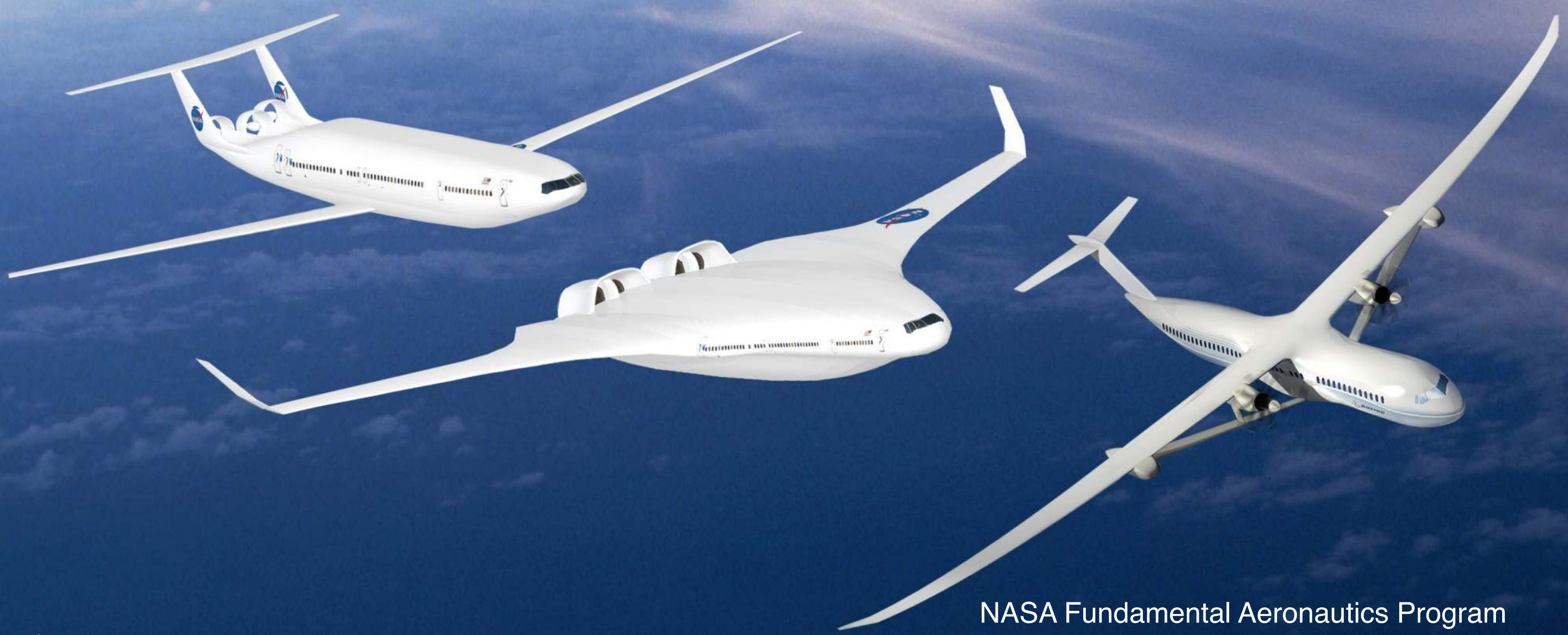

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NASA Fundamental Aeronautics Program
Subsonic Fixed Wing Project
Quiet Aircraft Subproject

A Comparison of Combustor-Noise Models

…. introduction and outline

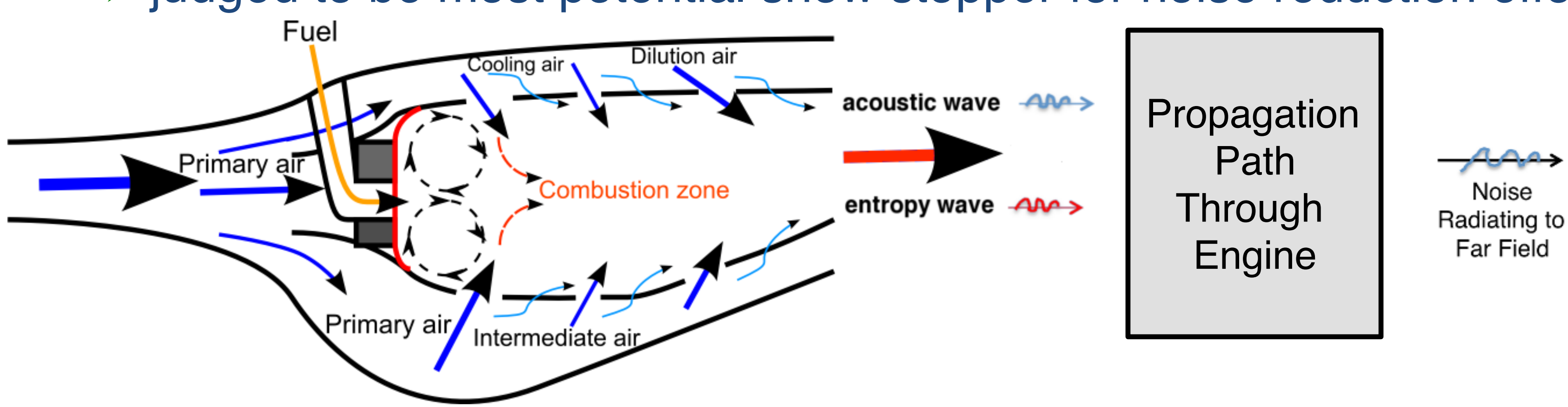
- Current combustor-noise prediction tools
  - based on empiricism and rooted in 1970s technology
    - some updates in 1990s & 2000s
  - dated and of unknown applicability to emerging N+3 core designs
  - core noise must be addressed to meet N+3 goals
- Outline
  - what is core noise
  - increasing importance of core noise due to turbofan design trends
  - high-efficiency, small gas generator – N+3 subsystem research
  - current combustor-noise models in ANOPP
  - multi-component empirical models – past and present
- Summary
  - future needs and challenges

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

Core Noise

…. what are its components?

- Engine-Internal Propulsion Noise Other Than Fan and Jet
  - compressor noise – tonal in blade-passing frequency range (kHz)
  - combustor noise – low frequency (< 1 kHz) broadband
  - turbine noise – tonal in blade-passing frequency range (kHz)
- Combustor and Turbine Noise Most Important
- NASA SFW Emphasis on Combustor Noise
  - limited resources
  - judged to be most potential show stopper for noise reduction effort



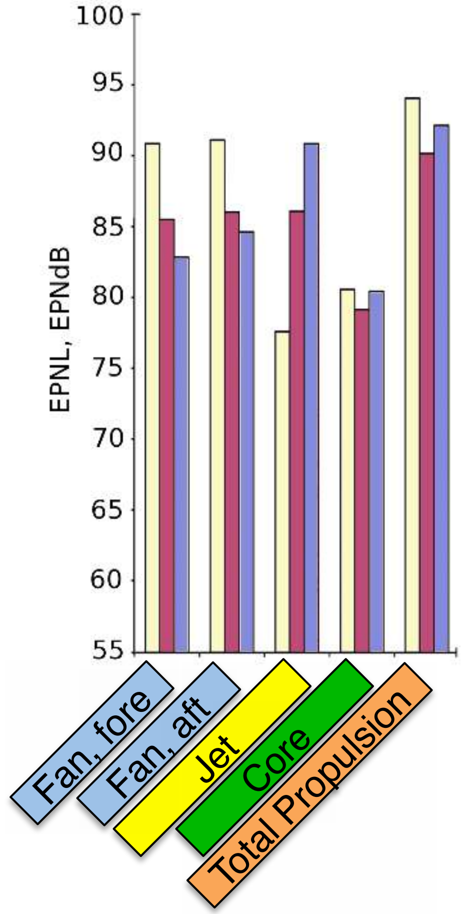
Must fully understand noise-source structure in combustor and the effects of propagation path through engine

Predicted N & N+1 Airplane Certification Levels

…. core noise becoming an important component of the total

B737-800/CFM56-7B
Burley et al. NASA/TP-2012-215653

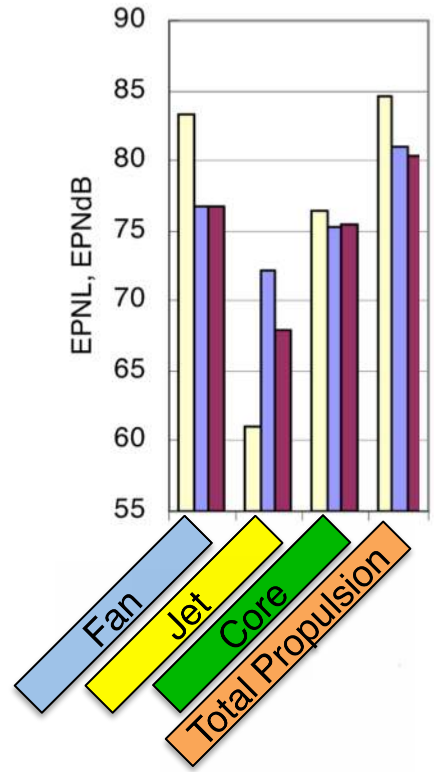
26,300 lbf
BPR = 5.1
FPR = 1.65
OPR = 32.8



Approach
Sideline
Flyover

Notional N+1 Aircraft
Berton et al. AIAA 2009-3144

23,000 lbf
BPR = 16
FPR = 1.3
OPR = 32



Relative importance of core noise is increased from N to N+1 generation

N+3 High-Efficiency Small Gas Generator

…. versatile core applicable to variety of N+3 propulsion systems/installations

NASA Research Objective

Explore and develop technologies to enable advanced, small, gas-turbine generators with high thermal efficiency

Benefit/Pay-off

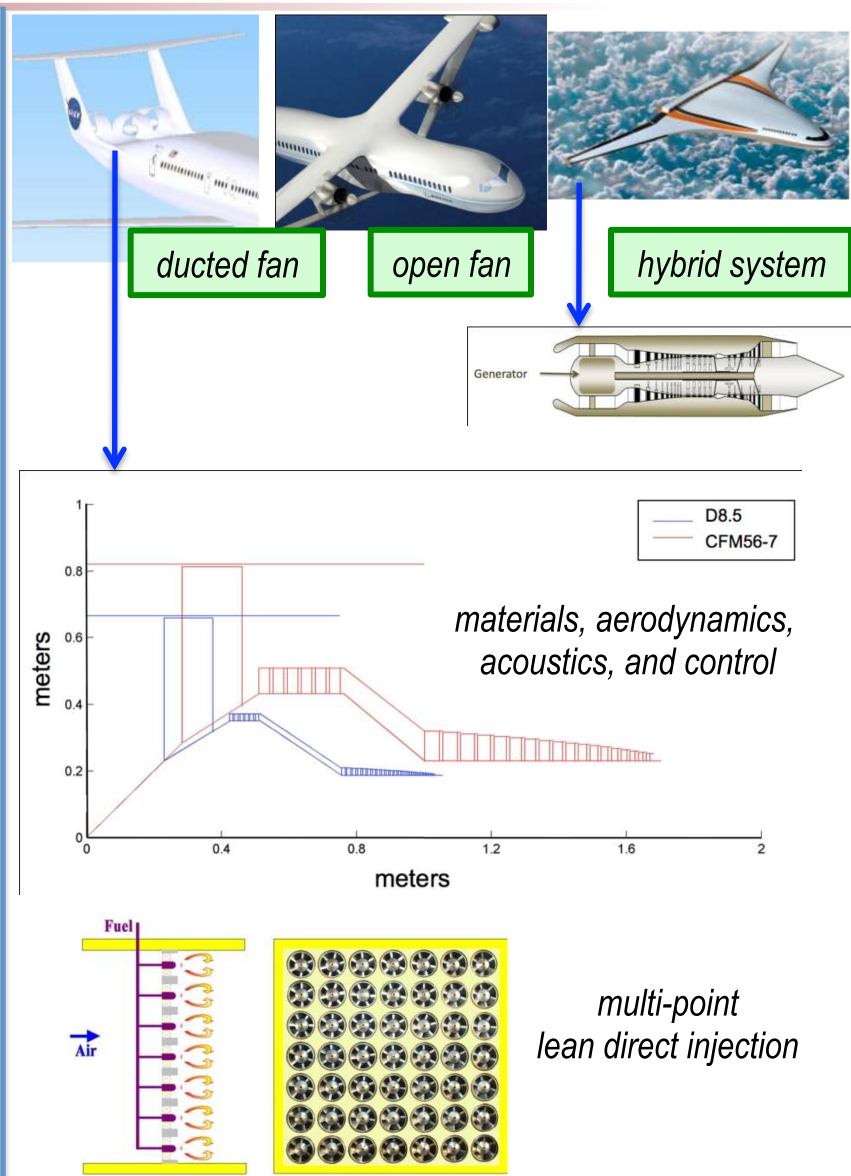
- BPR *20+ growth by minimizing core size*
- *Low emission, fuel-flexible combustors with NOx reduction of 80% below CAEP6*

Acoustic Challenge

Core Noise

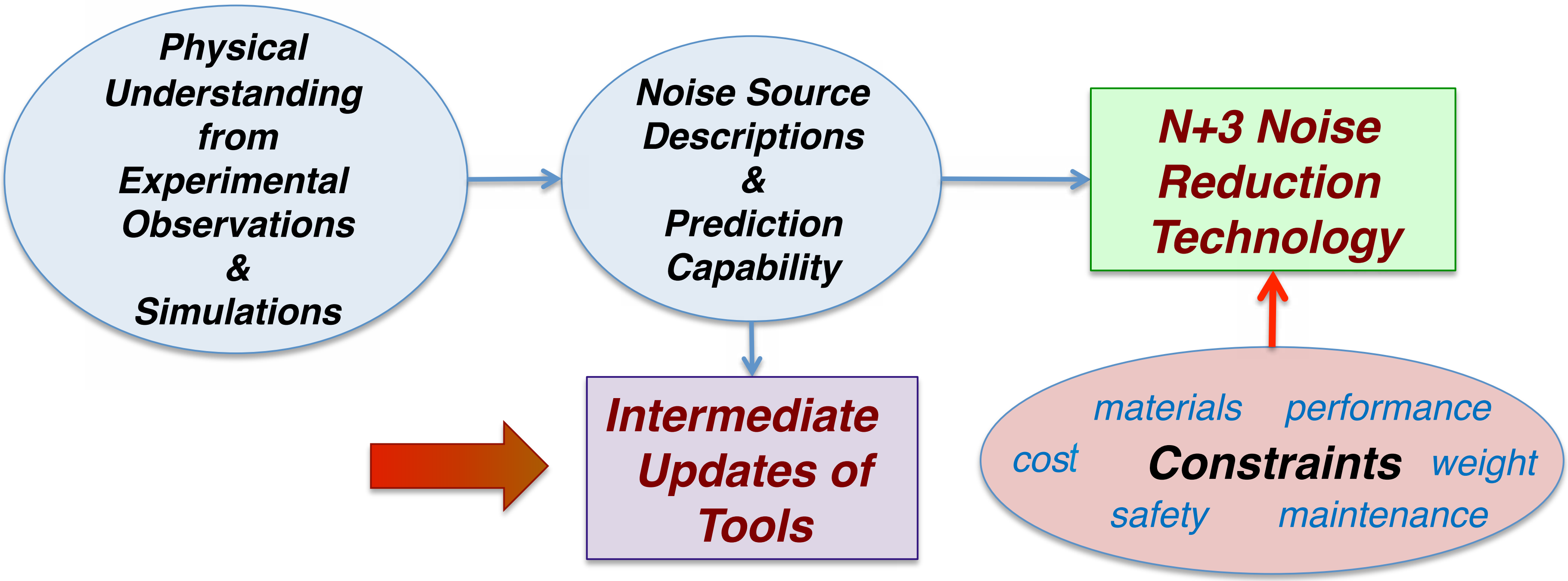
- *Understand and mitigate source noise*

Future core designs likely outside of current noise-model parameter space



NASA Core-Noise Activities

…. research in support of N+3 goals



- Core Noise Must Be Addressed to Ensure N+3 Goals
- Focused Research Is Carried Out to Enable Advanced Subsystems That Meet NASA's N+3 Technical Challenges
- Noise-Prediction Tools Are Updated As Understanding Improves

Reduce perceived community noise attributable to aircraft with minimal impact on weight and performance

Current ANOPP Combustor-Noise Models

…. SAE method and small-engine (SmE) method

- Mean square pressure in 1/3-octave band (b)

$$< p^2 >^{(b)} = \frac{\rho_\infty c_\infty \Pi D(\theta) S(f^{(b)})}{4\pi r_s^2}$$

static-engine conditions

- normalization

$$\int_0^\pi D(\theta) \sin\theta \mathrm{d}\theta = 2 \qquad \sum_b S(f^{(b)}) = 1$$

- total acoustic power

$$\Pi = \int_A \frac{\sum_b < p^2 >^{(b)}}{\rho_\infty c_\infty} \mathrm{d}A \qquad \mathrm{d}A = r_s^2 \sin\theta \mathrm{d}\theta \mathrm{d}\phi$$

Total acoustic power depends on engine operational conditions – directivity and spectral function are universal

Current ANOPP Combustor-Noise Models

…. semi-empirical models with roots from the 1970s

SAE and small-engine (SmE) methods

$$\Pi = 10^{K/10} c_\infty^2 \dot{m}_{core} \left(\frac{T_{t,ce} - T_{t,ci}}{T_{t,ci}} \right)^2 \left(\frac{P_{t,ci}}{P_\infty} \right)^2 \times F_{TA}$$

- K = -60.53 in SAE method; K = -64.53 in SmE method
- SAE: Huff et al 1974, Emmerling et al 1976, Ho & Doyle 1979
- small-engine: Hough & Weir 1997
- turbine attenuation factor, Motsinger 1972,

$$F_{TA} = \left(\frac{\Delta T_{des}}{T_\infty} \right)^{-4}$$

ANOPP/GE attenuation formula

Total acoustic power depends only on engine operational conditions – only change in constant K between SAE and SmE methods (4 dB)

Current ANOPP Combustor-Noise Models

…. intermediate narrow-band model Schuster and Lieber 2006

- Narrow-band (n) mean square pressure

$$< p^2 >^{(n)} = \frac{\rho_\infty c_\infty \Pi D(\theta, f_n) S(f_n)}{4\pi r_s^2}$$

can account for tailpipe resonance

frequency dependent directivity

  - normalization

$$\int_0^\pi \sum_n D(\theta, f_n) S(f_n) \sin\theta d\theta = 2$$

  - total acoustic-power Π formula identical to SAE and SmE cases

  - mean square pressure in 1/3-octave band

$$< p^2 >^{(b)} = \sum_{n \in b} < p^2 >^{(n)}$$

Total acoustic power accounts for engine operational conditions

Updated Turbine-Attenuation Factor

…. NASA/Honeywell EVNERT TECH977 engine-internal unsteady data

- EVNERT Program Full-Scale Turbofan Time-Series Data
  - true combustor-noise turbine-transfer function for TECH977 engine determined by using three engine-internal pressure sensors
  - updated turbine attenuation factor

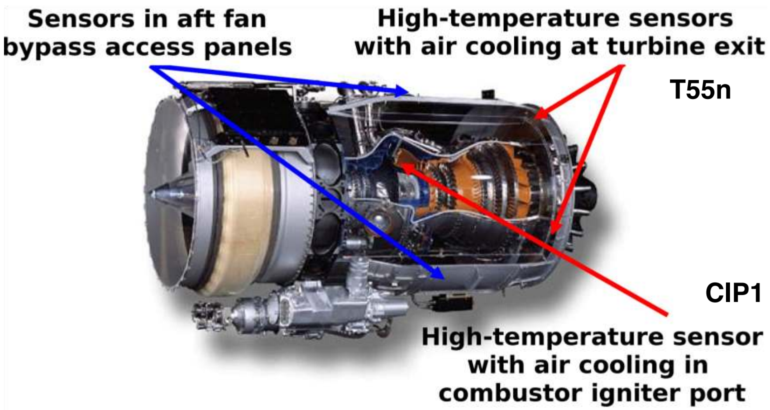
$$F_{TA} = \frac{0.8\zeta}{(1+\zeta)^2}$$

simplified Pratt & Whitney formula

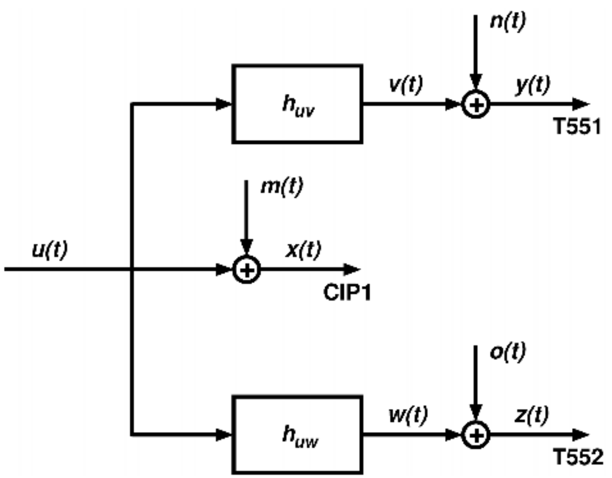
$$\zeta = \rho_{te}c_{te}/\rho_{ti}c_{ti}$$

impedance ratio across turbine

  - Hultgren AIAA 2011-2912
  - option in next release of ANOPP



Honeywell TECH977 Turbofan

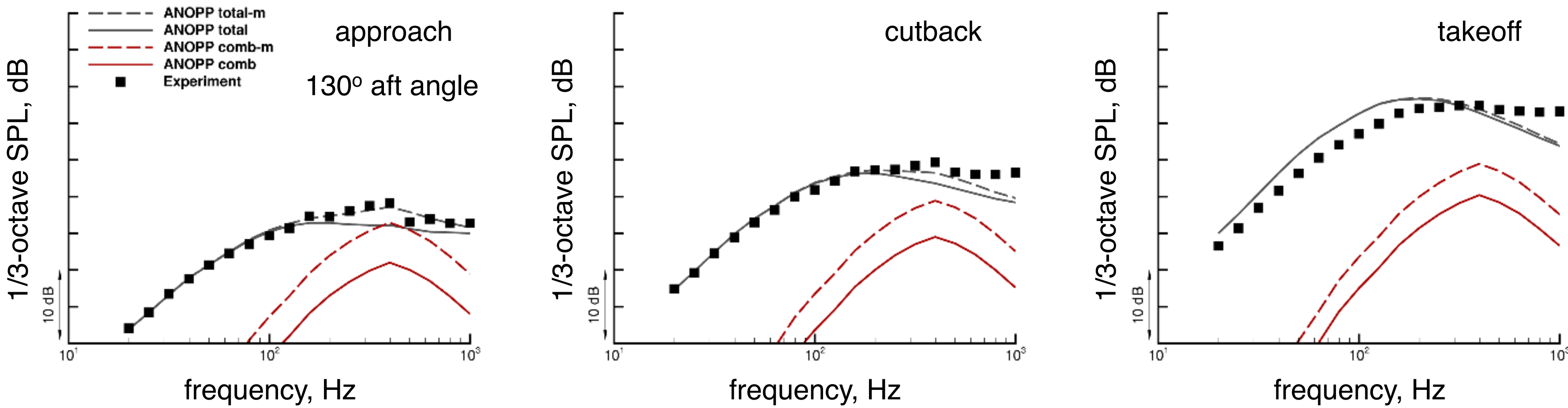


Source-Diagnostic Schematic

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

Far-Field Comparison With ANOPP Predictions

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



- AIAA 2011-2912 & AIAA 2009-3220
  - predictions post-corrected to use simplified P&W formula
  - modified predictions (dashed lines) are clear improvement
- New ANOPP/GECOR Module Attenuation-Formula Option

GE-option: $F_{TA} = \left(\frac{\Delta T_{des}}{T_\infty}\right)^{-4}$ PW-option: $F_{TA} = \frac{0.8\zeta}{(1+\zeta)^2}$

Substitution of simplified P&W formula improves ANOPP predictions

General Multi-Component Model

.... in case of several independent combustor-noise sources

- 1/3-octave-band (b) mean-square pressure

$$< p^2 >^{(b)} = \frac{\rho_\infty c_\infty \sum_{k=1}^{N_c} \Pi_k \mathcal{D}_k(\theta, f_b)}{4\pi r_s^2}$$

combined frequency and directivity function

- Overall mean-square pressure

$$< p^2 > = \sum_b < p^2 >^{(b)} = \frac{\rho_\infty c_\infty \sum_{k=1}^{N_c} \Pi_k D_k(\theta)}{4\pi r_s^2} = \frac{\rho_\infty c_\infty \Pi D(\theta)}{4\pi r_s^2}$$

  - component directivity: $D_k(\theta) = \sum_b \mathcal{D}_k(\theta, f_b)$
  - overall directivity: $D(\theta) = \sum_{k=1}^{N_c} \Pi_k D_k(\theta)/\Pi$
  - power: $\Pi = \sum_{k=1}^{N_c} \Pi_k$

Acoustic power accounts for engine operational conditions

Empirical Multi-Component Models

…. based on static engine testing

- von Glahn & Krejsa – NASA TM-83012 (1982)
  - YF102, JTD15, and CF6-50 turbofan engines
  - single-, two-, and four-segment spectra examined
- Gliebe et al. – NASA CR-2000-210244 (2000)
  - CF6-80C2 & CFM56-5B/7B engines with SAC
  - GE90 & CFM56-5B/7B engines with DAC
  - SAC: three-segment spectrum with peaks at 63, 160 & 630 Hz
  - DAC: two-segment spectrum with peaks at 160 & 500 Hz
- Stone et al. – NASA CR-2011-217026 (2011)
  - CF6, CF34, CFM56, and GE90 turbofan engines
  - three-component spectrum

Fully empirical methods for combustor-noise prediction

Stone et al Empirical Combustor-Noise Model

…. empirical three-spectral-component model with roots in the QAT program

- Stone et al. procedure – OASPL at 90 degree polar angle

$$OASPL_k(\theta = 90^o) = C_k + 10\left[\alpha_k \log Q - \beta_k \log n_f - \log(4\pi r_s^2)\right]$$

  - combustion-noise parameter

$$Q = \dot{m}_{core} T_\infty^2 \left(\frac{T_{t,ce} - T_{t,ci}}{T_{t,ci}}\right)^2 \left(\frac{P_{t,ci}}{P_\infty}\right)^2$$

  - parameters obtained through data fit involving jet-noise model

Modified Stone et al. Constants

	$k=1$	$k=2$	$k=3$
C_k	89.69	71.30	53.93
α_k	0.7	1.0	0.9
β_k	1.4	1.8	0.0

C_k values depend on units used

  - low-, mid-, and high-frequency components

Stone et al Empirical Combustor-Noise Model

…. empirical three-spectral-component model with roots in the QAT program

- Stone et al. 1/3-octave band *SPL$_k$* and *OASPL$_k$*

$$SPL_k^{(b)} = OASPL_k(\theta = 90^o) + \mathcal{I}_k(\theta, St_k^{(b)})$$

$$OASPL_k = OASPL_k(\theta = 90^o) + \Delta OASPL_k(\theta)$$

$$\Delta OASPL_k(\theta) = 10 \log \left[\sum_b 10^{\mathcal{I}_k(\theta, St_k^{(b)})/10} \right]$$

directivity and frequency index

  - Strouhal numbers

$$St_1 = f_b d_{cn}^{(h)} / c_\infty \, ,$$

$$St_k = f_b d_c / c_{ce} \quad k = 2, 3$$

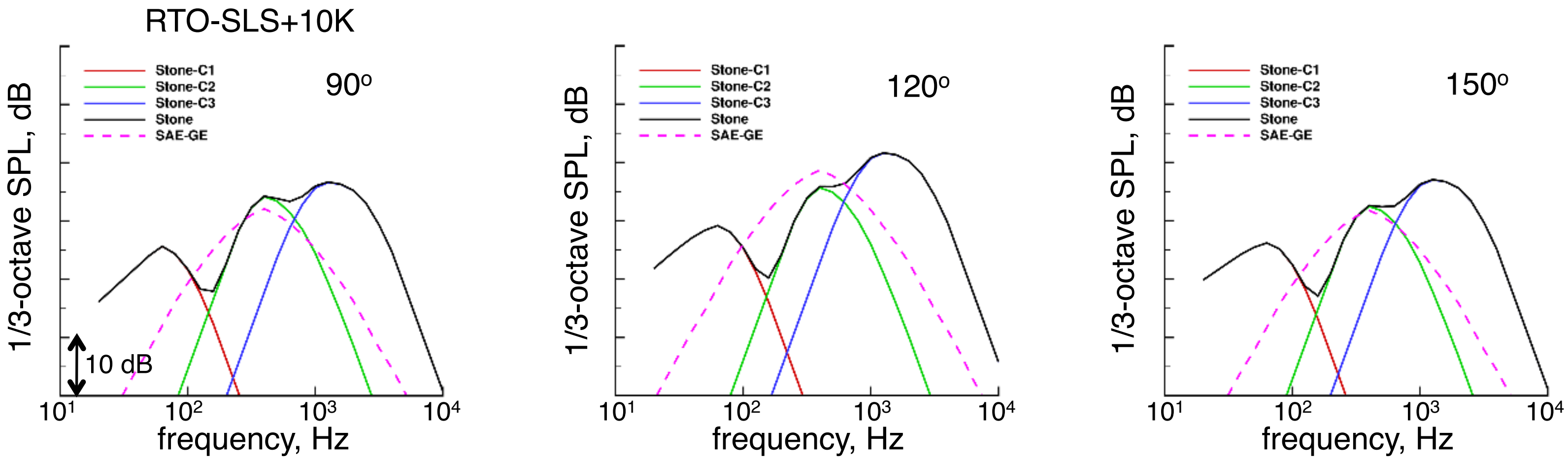
core-nozzle hydraulic diameter & ambient speed of sound

combustor diameter & combustor-exit speed of sound

- Method works well within dataset used for development

Comparison of Stone et al. With SAE-GE Predictions

…. GE90-94B takeoff engine-power setting – RTO-SLS+10K

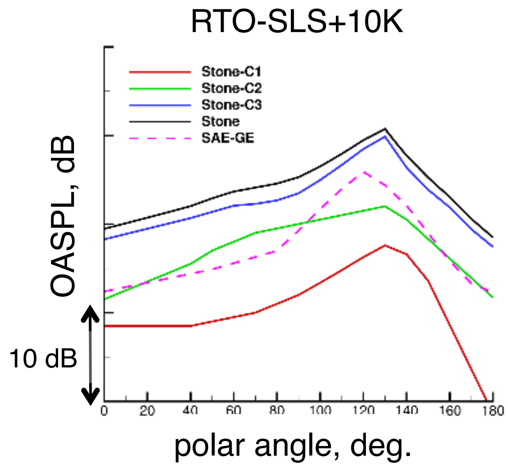


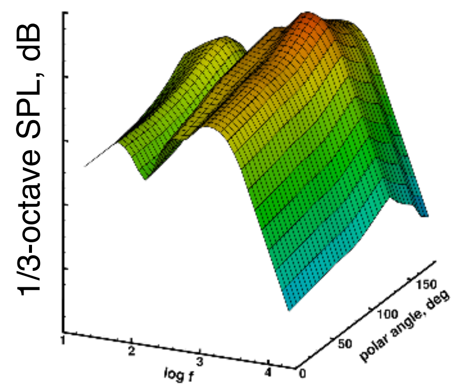
- Methods implemented in MATLAB scripts
  - in absence of acoustic data – will compare method predictions
  - NASA CR-2011-217026 ➔ reasonable predictions by Stone method
- One foot lossless data for takeoff condition
  - SAE-GE and Stone mid-frequency component peaks are comparable
  - Stone high-frequency component has highest peak level

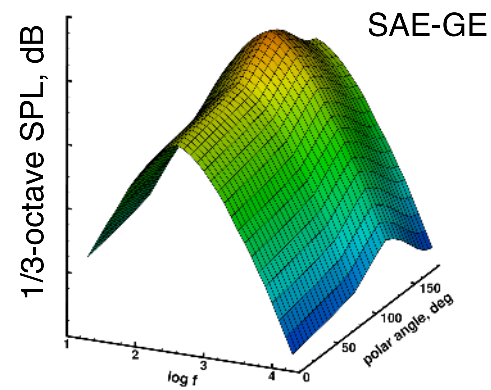
GE90-94B

Comparison of Stone et al. With SAE-GE Predictions

…. GE90-94B takeoff engine-power setting – RTO-SLS+10K





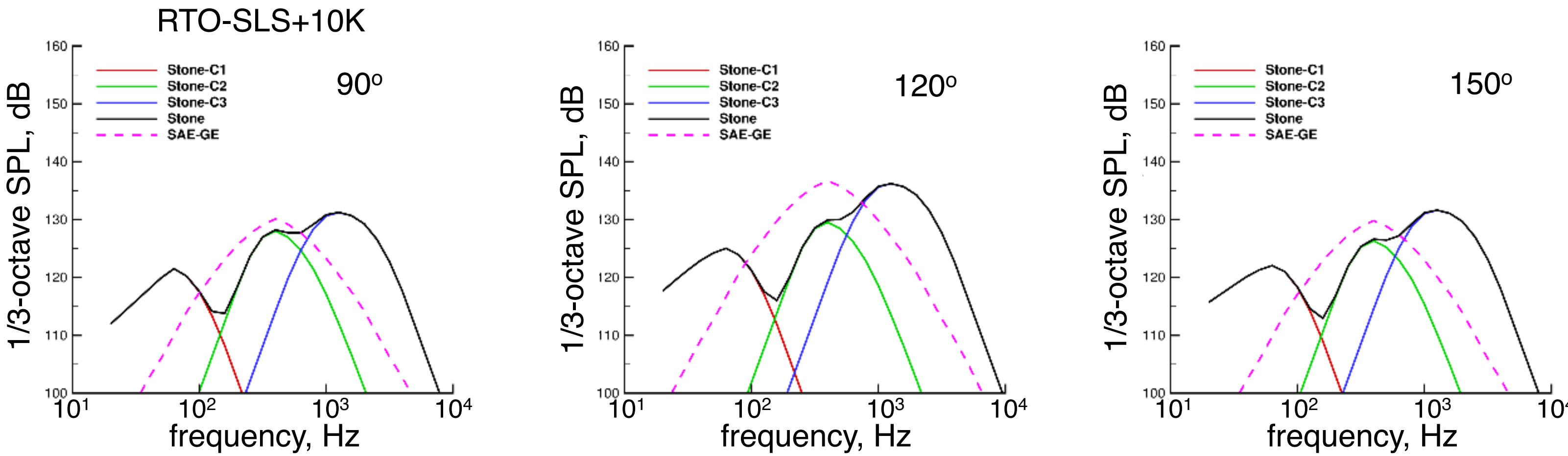


- Total Stone OASPL levels are higher than SAE-GE levels
  - peak level is about 5 dB higher
  - peak occurs at a shallower angle with respect to downstream axis
- Surface plots of 1/3-octave SPL as function of frequency and polar angle

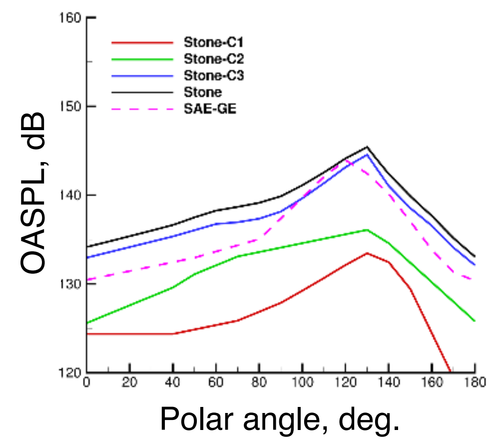
GE90-94B

Comparison of Stone et al. With SAE-GE Predictions

.... E^3 engine takeoff engine-power setting – RTO-SLS+10K



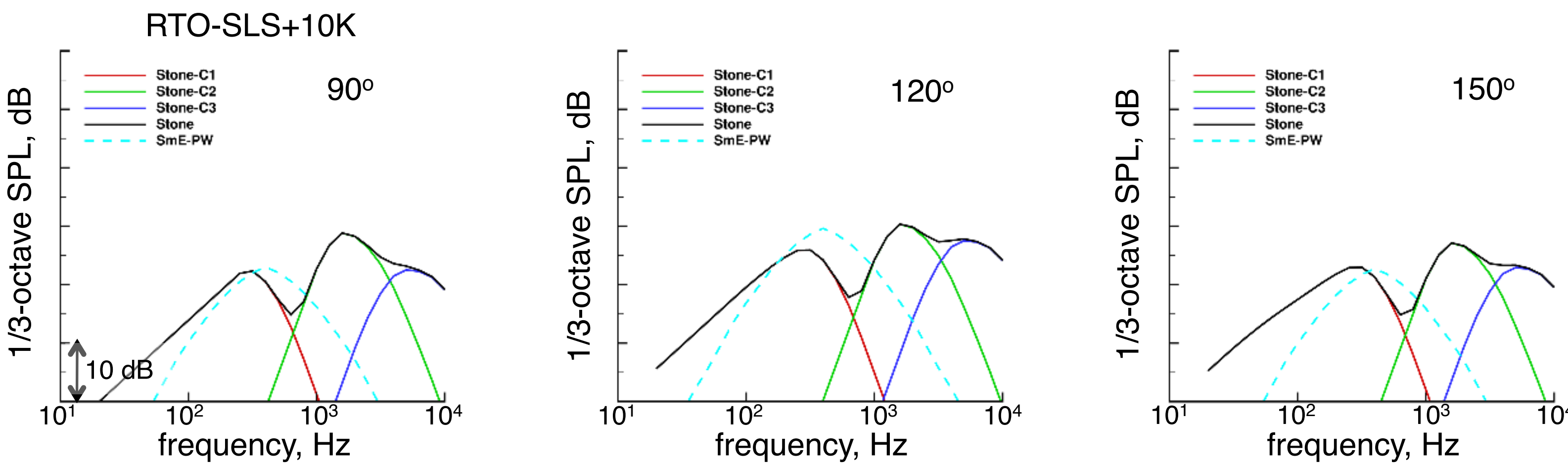
- E^3 engine at takeoff conditions
  - not used in Stone method development
  - considered part of GE turbofan family
  - SAE-GE and mid-frequency component peak frequencies coincide
  - OASPL peak levels are comparable



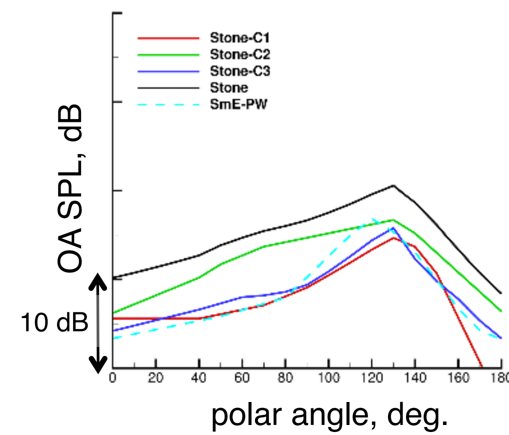
Energy Efficient Engine (E^3) Program demonstrator engine

Comparison of Stone et al. With SmE-PW Predictions

…. TECH977 engine takeoff engine-power setting – RTO-SLS+10K



- TECH977 acoustics well understood
  - data analyzed by several investigators
  - AIAA 2011-2912 ➔ SmE-PW works well
- Stone method: significant amount of combustor noise for freq. > 1 kHz
  - method not suitable for TECH977

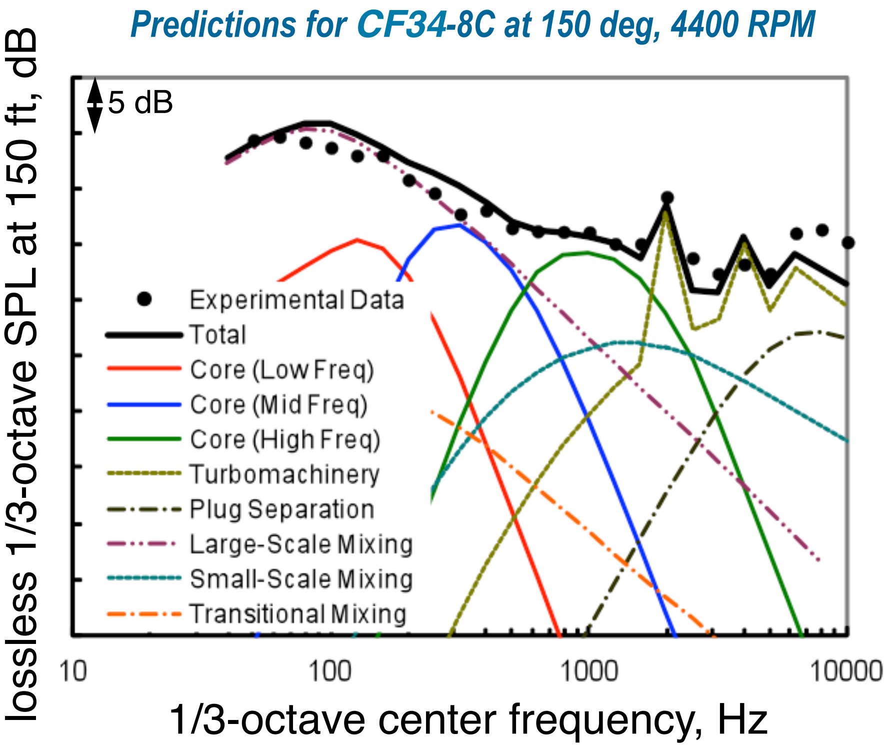


Honeywell TECH977 research turbofan engine

Stone et al. Empirical Combustor-Noise Model

…. empirical three-spectral-component model with roots in the QAT program

- NASA CR-2011-217026
  - model developed using CF6, CF34, CFM56 & GE90 static-engine data
  - multiple (3) spectral components assumed
  - frequency scaling based on combustor and core-nozzle dimensions



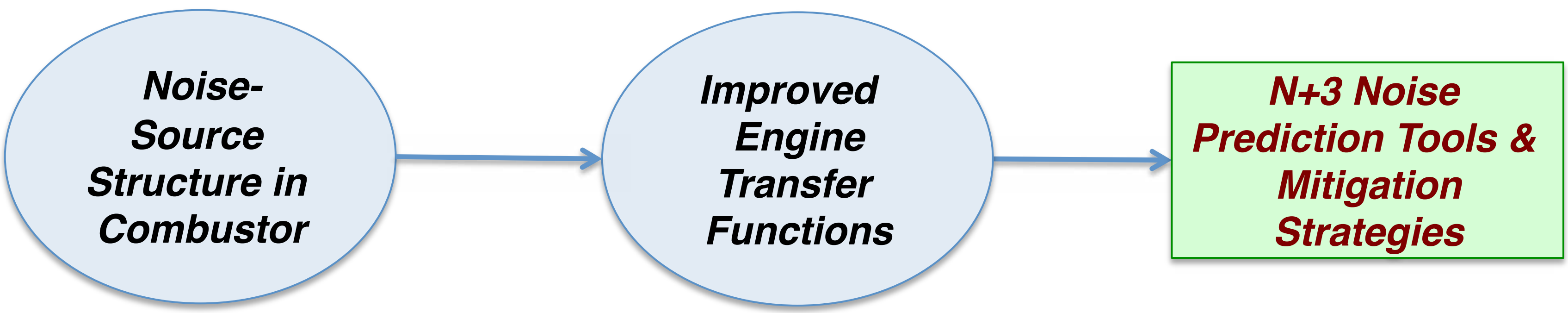
- Works well within development data set – outside not certain
  - potential improvement in prediction capability for GE (only) turbofans
- LaRC – future separate ANOPP module for combustor noise

Incremental improvements to ANOPP as understanding increases

Summary

…. core-noise research in support of N+3 goals

- Current Core-Noise Prediction Tools Are Dated
- Core Noise Must Be Addressed to Ensure N+3 Goals
- Prediction Tools Are Updated As Understanding Improves
- Need to understand impact of combustor-design changes
  - lean direct injection and other low-emission designs
  - alternate fuels
- Need Improved Turbine & Exit-Nozzle Transfer Functions
  - Schuster & Lieber 2006; Karchmer 1983
  - physics-based approach – holds more promise than empiricism



NASA