The Role of Analytic Methods in Computational Aeroacoustics

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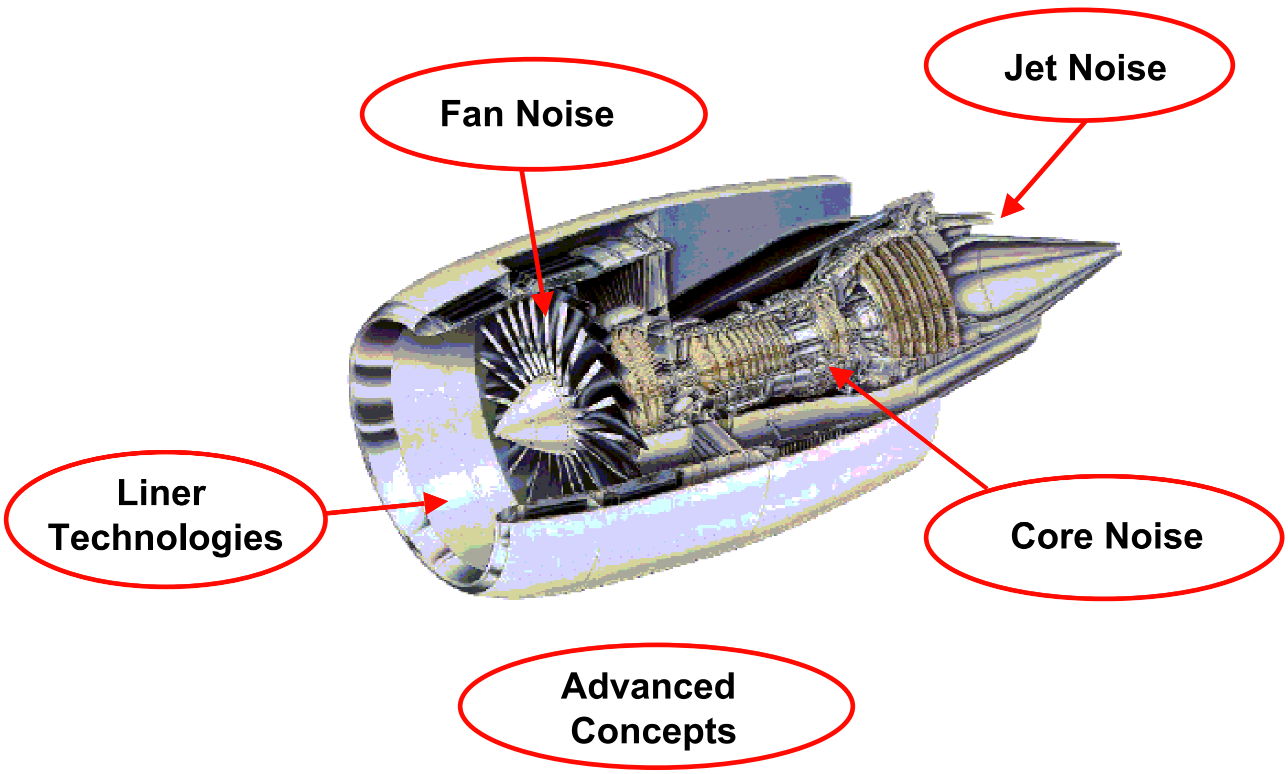
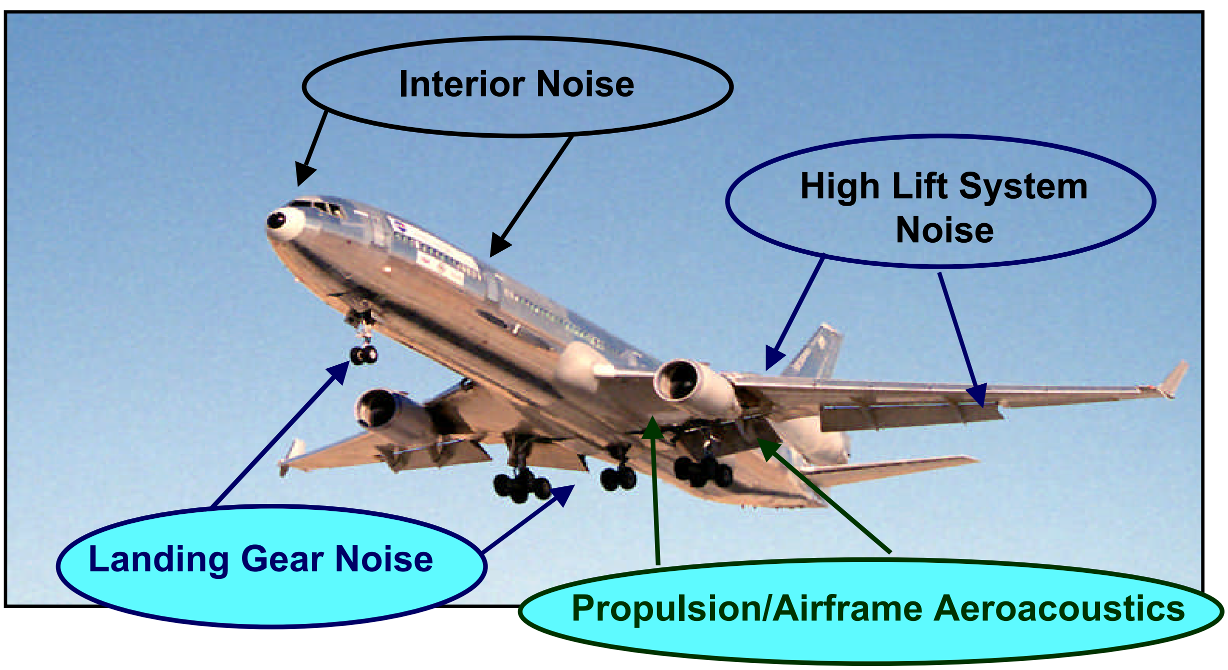
Outline

- ✈ Current aeroacoustic problems
- ✈ Characteristics of good noise prediction methods
- ✈ Why analytic methods?
- ✈ History of CAA at NASA Langley
- ✈ Examples of recent work
- ✈ Concluding remarks

Propulsion Noise Research



Airframe System Noise Considerations



Current Aeroacoustic Problems

– **Subsonic and Supersonic Jet Noise Prediction:**
  multiple jets, 3-D nozzle designs

– **Ducted Fan Noise Prediction:**
  generation, propagation and radiation w/ effects of liners & nacelle geometry

Current Aeroacoustic Problems (cont.)

- **Airframe Noise Prediction:**

  flap, slat, cavity, landing gear,B/L, interior

- **Rotating Blade Noise Prediction:**

  helicopter main & tail rotors, propellers, windmills, industrial rotating machinery

- **Propagation and Scattering:** wing & fuselage scattering, long range prop. and absorption

Good Noise Prediction Methodology

– includes physics with least approximation

– incorporates realistic modeling of geometry and kinematics

– is robust and accurate

– executes quickly and uses minimum computer resources; i.e., efficient

Why analytic methods?

Methodology = mathematical model + computer algorithms and code that give numbers as output.

Efficiency depends on mathematical model as well as computer algorithms.

Purely numerical methods are mostly algorithmic.

Combining numerical and analytic methods can produce highly efficient codes.

Why analytic methods? (cont.)

Analytic methods often eliminate problems of grid generation, spatial & temporal grid size limitations, numerical stability, numerical dissipation & dispersion, and satisfaction of far field boundary conditions.

Therefore, whenever possible, we should use analytic methods for noise prediction.

Recommended Noise Prediction Practices

- Use a hybrid code, i.e., FD, FE or analytic method, as appropriate, in different regions.
- Know when to stop an analytic study and go to a computer for numerical results.
- Symbolic manipulation software, e.g., Mathematica and Maple, is most helpful in deriving analytic results.

Useful Analytic Methods in CAA

– **Wave propagation in uniform media**

- ✓ **Green's function technique for the wave and Helmholtz equations: FW-H method, boundary integral equation method**

– **Wave propagation in nonuniform media**

- ✓ **Geometrical acoustics: ray acoustics**
- ✓ **Parabolic approximation method**
- ✓ **Method of characteristics**
- ✓ **Variational methods: finite element method**
- ✓ **Adjoint method: linearized Euler equation**

CAA at Langley Using Analytic Methods

Many solutions of Ffowcs Williams-Hawkings (FW-H) eqn.

with and without quadrupoles

for subsonic and supersonic source motion

Prediction codes developed - examples

- **WOPWOP (helicopter rotors, several versions)**
- **ASSPIN (subsonic and supersonic propellers)**
- **ANOPP-PAS (GA propellers)**
- **JET3D (installed jets)**

Examples of Recent Work

Prediction methods for:

1. **Broadband noise from an airfoil**
2. **Ducted fan noise - CDUCT-LaRC**
3. **Installed jet noise - Jet3D**

First Example:

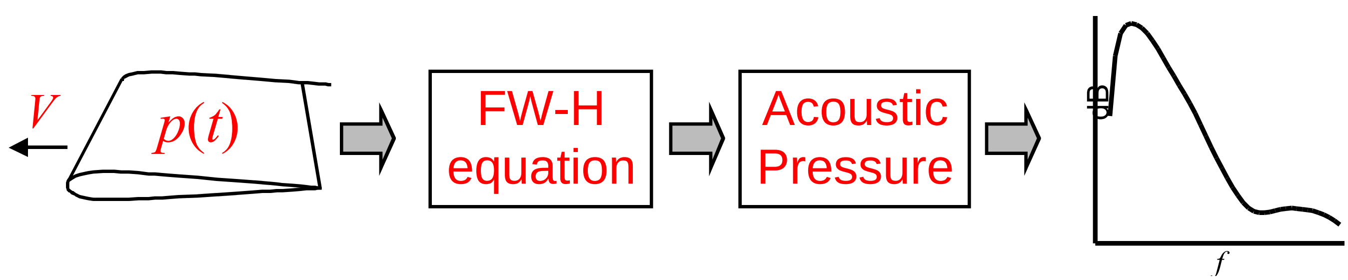
A New Time Domain Formulation for Broadband Noise Predictions

J. Casper and F. Farassat

International Journal of Aeroacoustics
Vol. 1, No. 3, 2002, 207-240

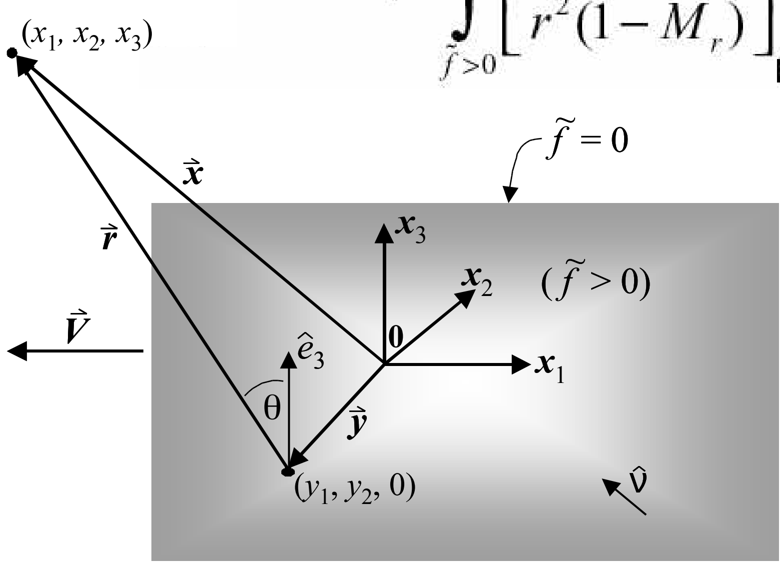
New Aeroacoustic Formulation

- Broadband Noise Prediction Tools for Airframe noise
- Time Domain Approach
  - New solution of Ffowcs Williams-Hawkings equation
  - Decouples aerodynamics from acoustics
  - Input from CFD or experiment
- Formulation 1B (F. Farassat)
  - Extremely simple for distant observer, low Mach no.
  - Applies to accelerating and rotating motion
  - Highly suitable for statistical analysis of broadband sources



Formulation 1B

$$4\pi p'(\vec{x},t) = \int_{\tilde{f}>0} \left[\frac{(\partial p/\partial\tau - V\partial p/\partial s)\cos\theta}{c_0\, r(1-M_r)}\right]_{\text{ret}} dS + \int_{\tilde{f}>0}\left[\frac{p\cos\theta}{r^2(1-M_r)}\right]_{\text{ret}} dS - \int_{\tilde{f}=0}\left[\frac{M_\nu\, p\cos\theta}{r(1-M_r)}\right]_{\text{ret}} d\ell$$



Test Case

<u>Incident Turbulence Noise</u>

Experiment – Paterson and Amiet

United Technologies, 1976

NACA 0012 airfoil in homogeneous,

isotropic turbulence

Incident Turbulence Noise

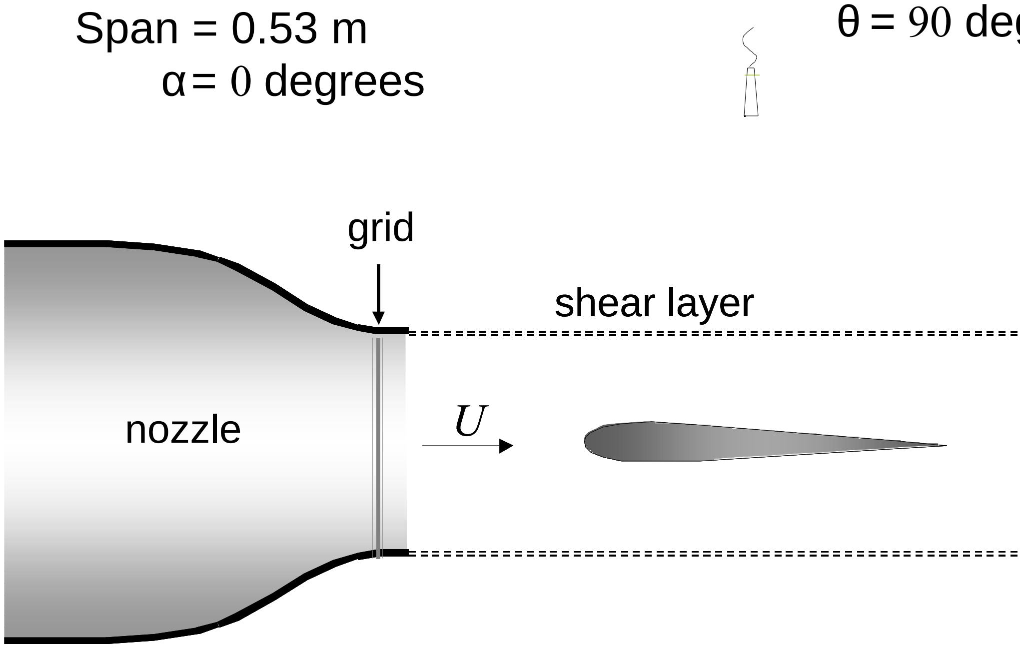
Experiment: Paterson and Amiet (1976)

NACA 0012 Airfoil

Chord = 0.23 m
Span = 0.53 m
$\alpha = 0$ degrees

Microphone:

$r = 2.25$ m,
$\theta = 90$ degrees

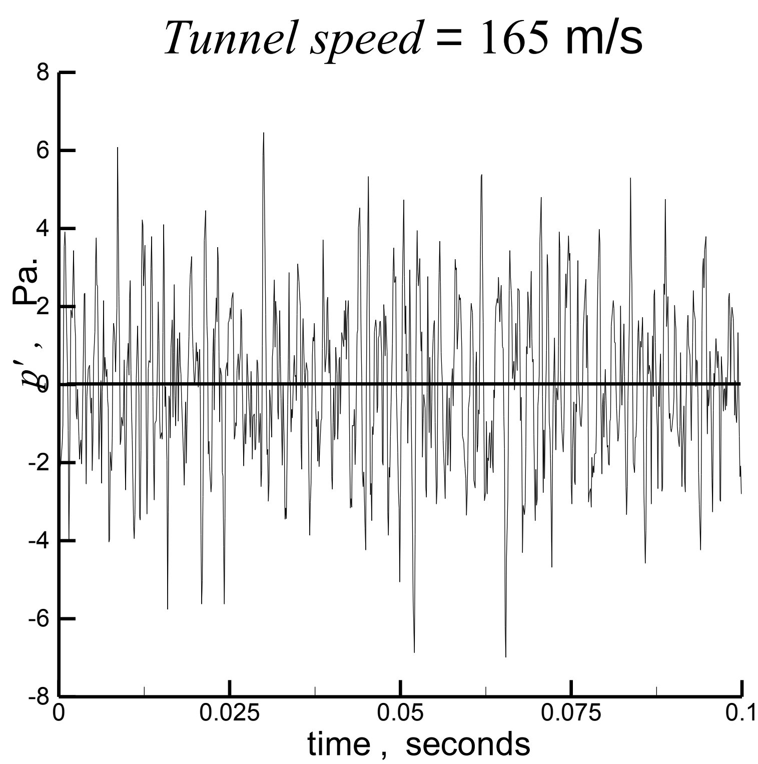


Broadband Prediction in Time Domain

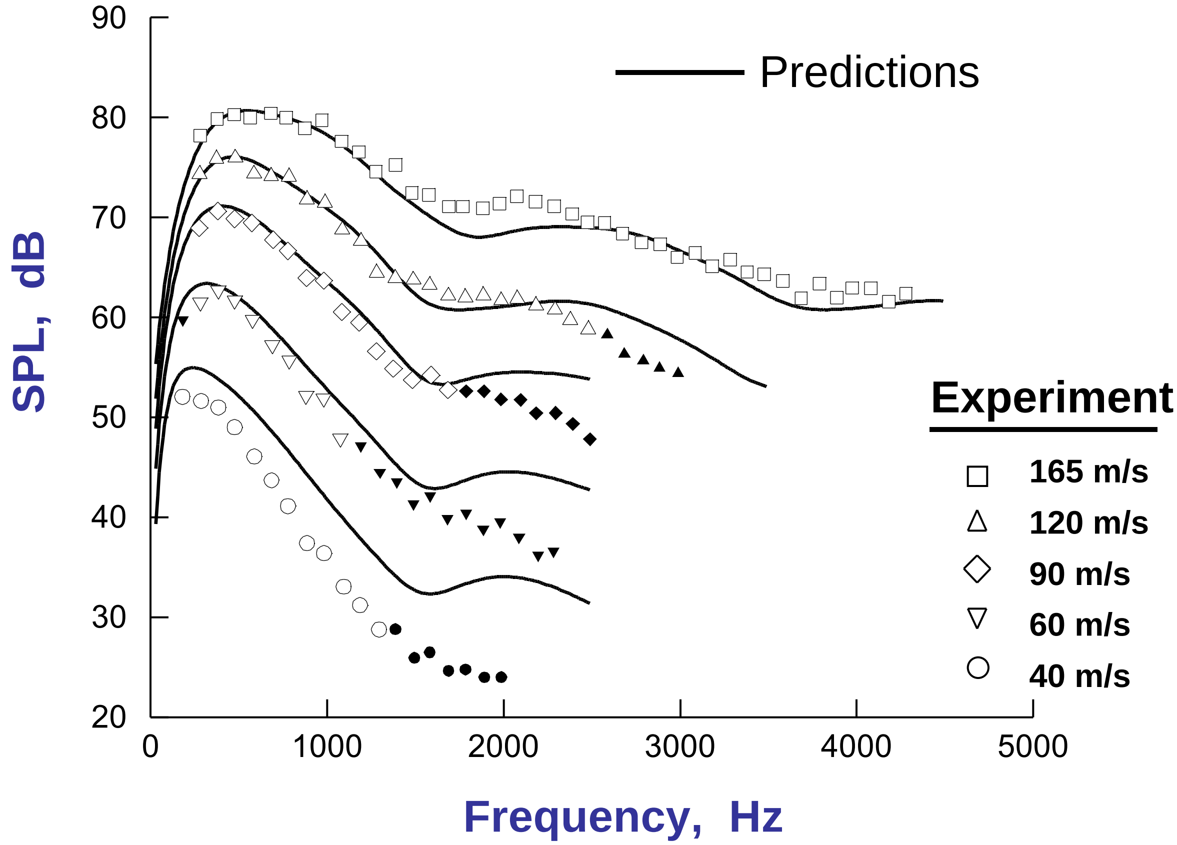
- Surface pressure for Formulation 1B from Amiet unsteady airfoil theory using measured inflow turbulence

- Directivity and amplitude corrected for refraction through shear layer

Predicted Signal



Far Field Noise Spectrum



Broadband Summary

- New solution of Ffowcs Williams-Hawkings eqn.
  - Simple, computer-friendly

- First time domain prediction of airfoil BB noise
  - Duplicates Amiet freq. domain prediction
  - Excellent agreement w/ experiment

Second Example:

The Development of the Ducted Fan Noise Propagation and Radiation Code CDUCT-LaRC

Douglas M. Nark, F. Farassat

D. Stuart Pope, Veer Vatsa

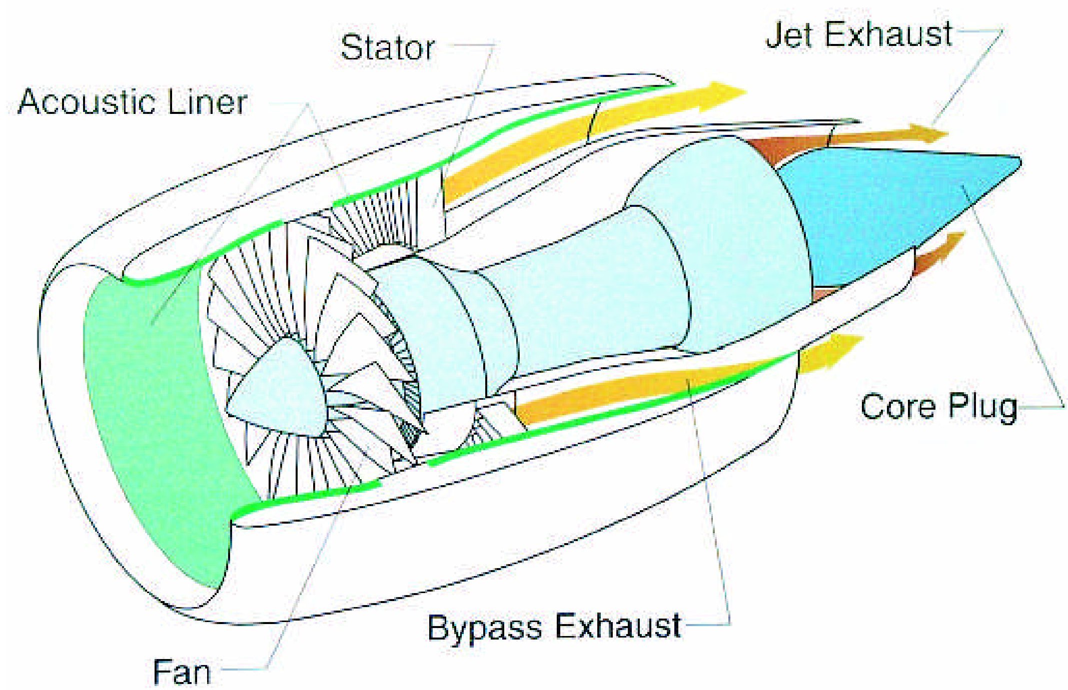
AIAA-2003-3242

9th AIAA/CEAS Aeroacoustics Conference

May 12-14, 2003

Hilton Head, South Carolina

Introduction



Create a flexible and efficient environment in which to study propagation within and radiation from complex duct geometries

Background Flow Module

Approach :

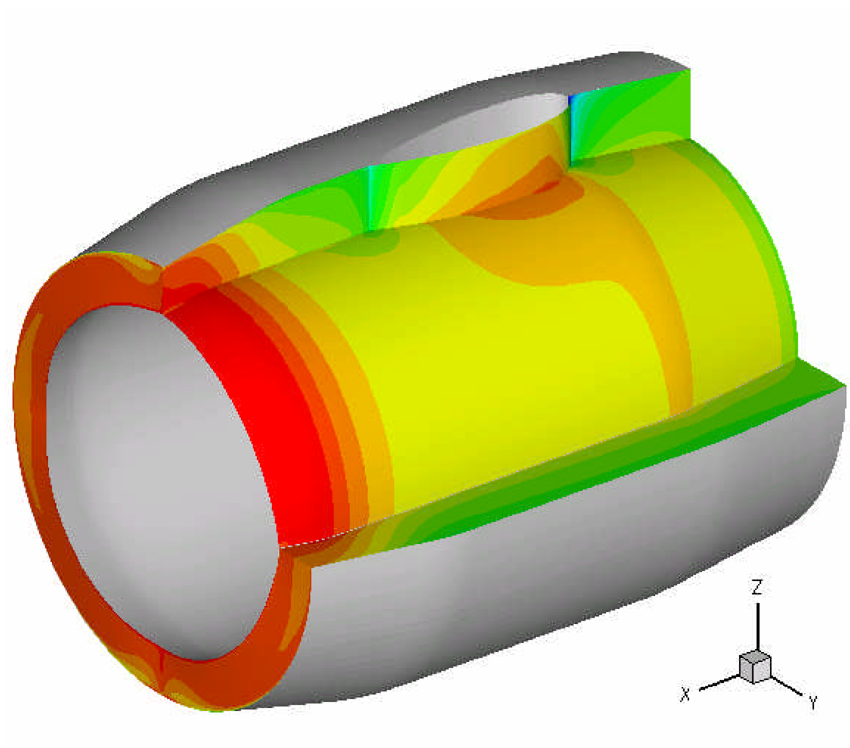
• Steady compressible inviscid CFD computation

Input :

• Structured multi-block grid in PLOT3D format
• Flow Conditions

Output :

• Mean flow quantities in PLOT3D solution file format

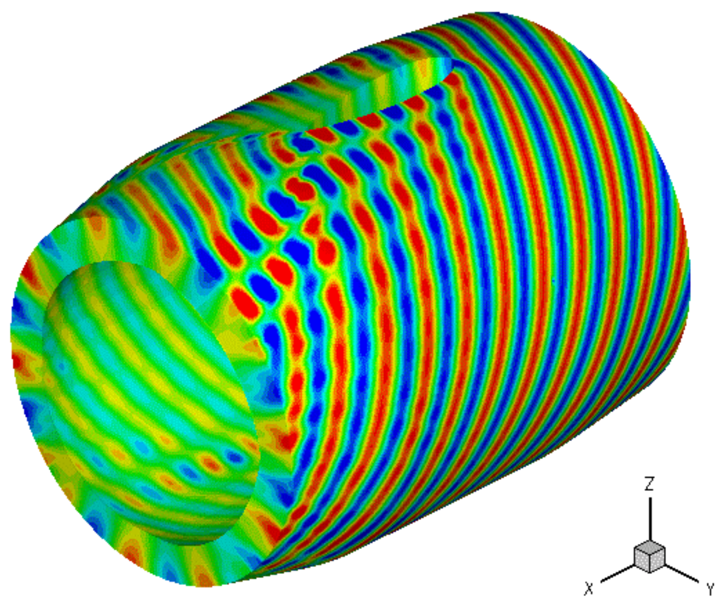


Duct Propagation Module

Approach :

•Boeing CDUCT code based on parabolic approximation with no reflections, Dougherty (1997) - Lan(2001)

• New calculation block for each major geometry change



Input :

• Mach no. distribution from the mean flow calculations

• Acoustic excitation = specification of modal amplitudes at inflow plane

Acoustic Radiation Module

***Approach** (aft hemisphere):*

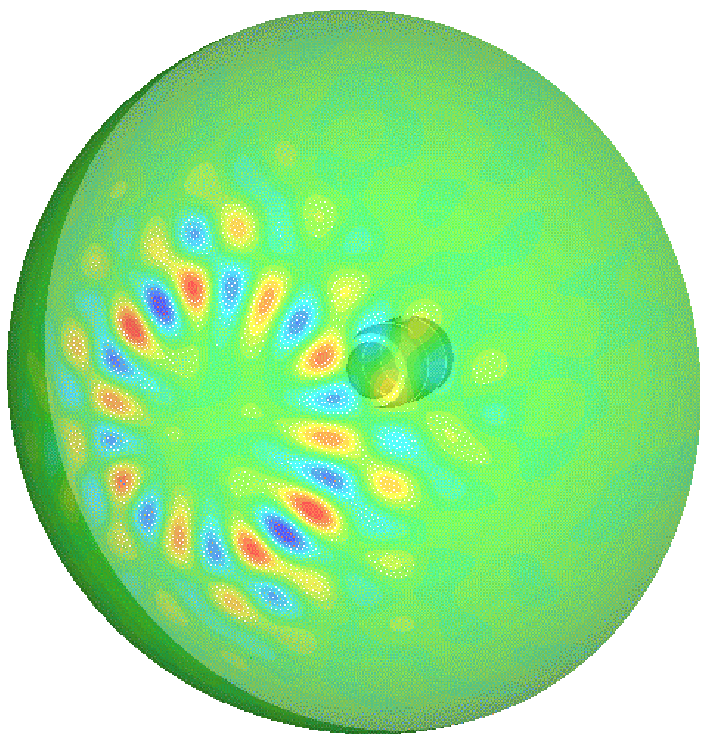
• Ffowcs Williams-Hawkings equation with a penetrable data surface

Data Input for FW-H:

• Specified on exhaust plane:

✓Mean flow quantities (ρ, **U)** from background flow calculations

✓Acoustic quantities (ρ’, p’, **u**’,   p’, **u**’) from CDUCT

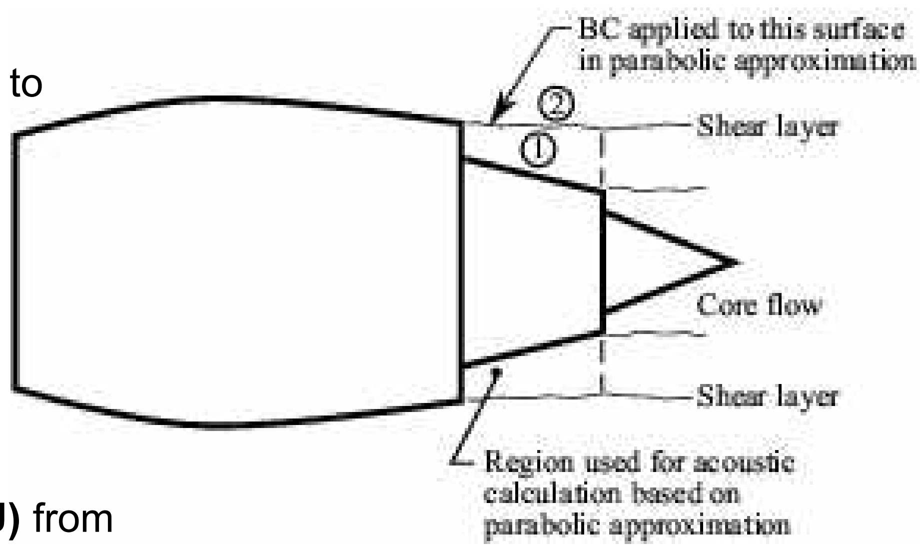


Acoustic Radiation Module

Approach

(forward hemisphere):

• Extend CDUCT calculation to shear layer external to duct.
• Apply FW-H equation with penetrable data surface



Data Input for FW-H:

• Specified at shear layer:
✓Mean flow quantities (ρ, **U)** from background flow calculations
✓Acoustic quantities (ρ', p', **u**', p', **u**') from CDUCT

Preliminary Calculations

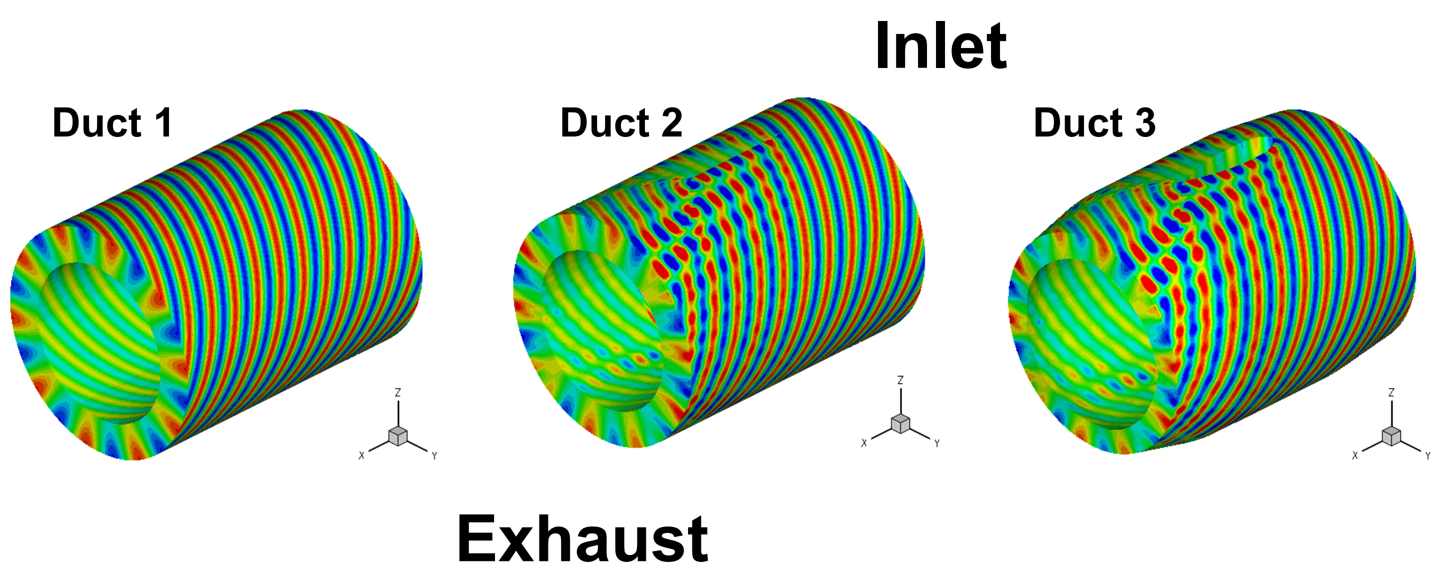
Three ducts have been initially tested:

- Duct 1: straight co-annular duct having inner and outer radii 0.285 m (11.23 in) and 0.412 m (16.22 in), respectively. The duct length is 1.07 m (42.88 in).
- Duct 2: similar to duct 1 except that infinitely thin pylons are placed in the top and bottom of the middle third of the duct.
- Duct 3: bypass duct of a small business jet with dimensions similar to duct 1. The pylon is modeled as a NACA 0015 airfoil.

Configurations similar to ducts 2 and 3 may include only a single pylon.

Preliminary Calculations

Real Part of Acoustic Potential – Mode (10, 1)
Inlet Mach No. 0.4, Frequency 5000 Hz
O.D. = 0.285m, I.D. = 0.421m, L = 1.07m

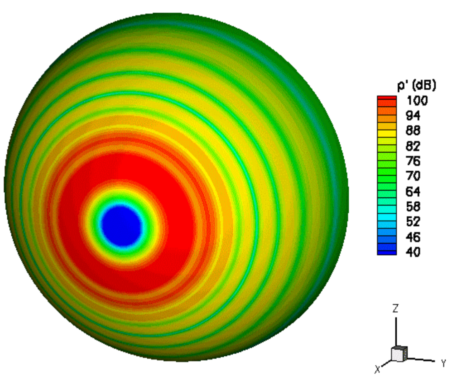


Preliminary Calculations

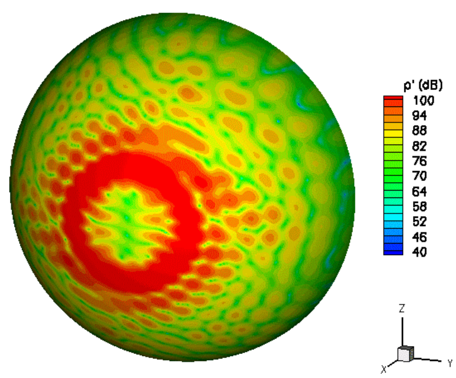
Radiated Sound Pressure Level – Mode (10, 1)
Inlet Mach Number 0.4, Frequency 5000 Hz

Sphere of radius 5 duct diameters centered on the duct axis in the exhaust plane

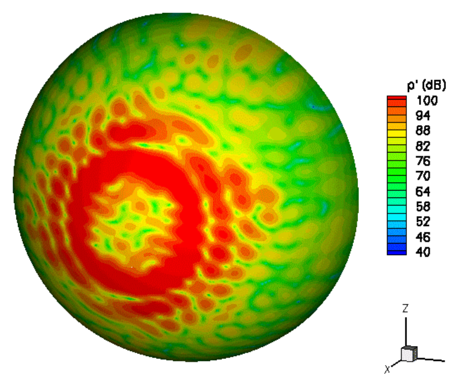
Duct 1



Duct 2



Duct 3



CDUCT-LaRC Summary

- Preliminary results:

  Duct propagation and radiation modules good for noise prediction

- Study of lined pylon geometry may identify new approach for engine noise control

Third Example:

Development of a Jet Noise Prediction Method for Installed Jet Configurations

Craig A. Hunter

Russell H. Thomas

AIAA 2003-3169

9th AIAA/CEAS Aeroacoustics Conference

May 12-14, 2003 / Hilton Head, SC

Motivation

- **Goal:** To develop a CFD-based noise prediction method for installed jets with complex 3D turbulent flows

- **Vision**: This tool will be used to discover & develop revolutionary noise reduction technologies

Approach

- RANS–CFD simulations (PAB3D flow solver)
- Lighthill's Acoustic Analogy (LAA)
  - LAA replaces complicated jet flow by fictitious distribution of quadrupoles radiating into uniform medium

Correlation Model for $\langle v_i(\vec{z},t)\, v'_m(\vec{z}+\vec{\zeta}, t+\tilde{\tau})\rangle$

$$\langle v_i v'_m \rangle = \langle v_i v_m \rangle \left[1 - \frac{1}{\mu^2}\left(\frac{\zeta_1^2}{\ell_1^2} + \frac{\zeta_2^2}{\ell_2^2} + \frac{\zeta_3^2}{\ell_3^2} \right) \right] \exp\left\{ -\pi \left(\frac{\zeta_1^2}{\ell_1^2} + \frac{\zeta_2^2}{\ell_2^2} + \frac{\zeta_3^2}{\ell_3^2} \right) - \frac{\tilde{\tau}^2}{\tau_o^2} \right\}$$

where: $\tau_o = \alpha_\tau \dfrac{k}{\varepsilon}$ $\qquad \ell_j = \alpha_L \dfrac{\langle v_j^2 \rangle^{3/2}}{\varepsilon}$

Fixed calibration constants: $\alpha_\tau = 0.15$, $\alpha_L = 0.34$, $\mu = 0.735$

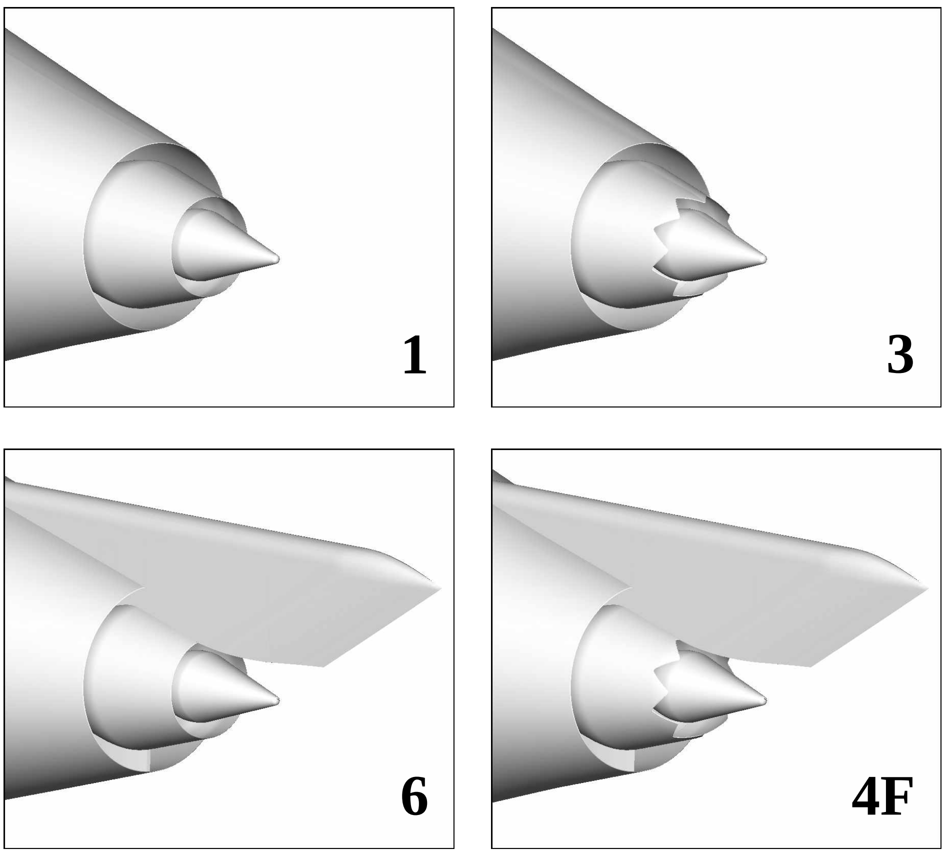
Important features:

1. One point limit at zero separation in space and time.
2. Loss of correlation for large separation.
3. Locally homogeneous in space, locally stationary in time.
4. Zero crossings in space to loosely satisfy continuity.
5. Amenable to ζ integration over unbounded space.
6. Scales with characteristic turbulence length and time scales.

Other Features of Jet3D

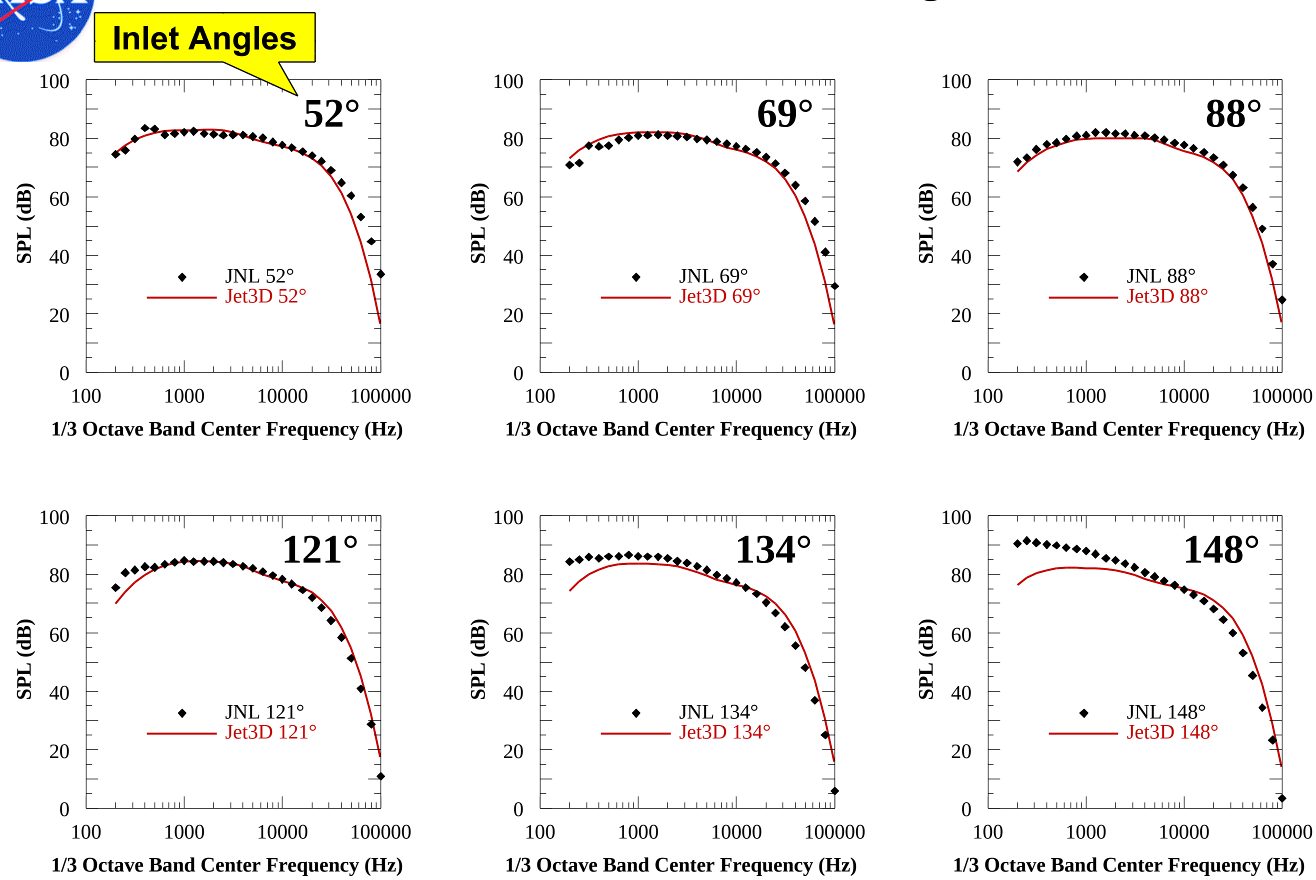
- Absorption effects computed using the Shields and Bass model.
- Anisotropic Reynolds stresses calculated using the nonlinear ASM of Shih, Zhu, and Lumley (SZL) or linear stress models.
- Empirical model used for the local convection Mach number based on the classic experiment of Davies et al.
- To improve predictions in the jet arc, a simple Snell's Law filter skips sources radiating into the zone of silence.
- Support for multiprocessing and vectorization on G4 / Mac OS X systems. Noise predictions run ~2-3 minutes per observer.
- Ability to output selected flow field and aeroacoustic data in Tecplot format, for noise source identification and analysis.

Nozzle Configurations



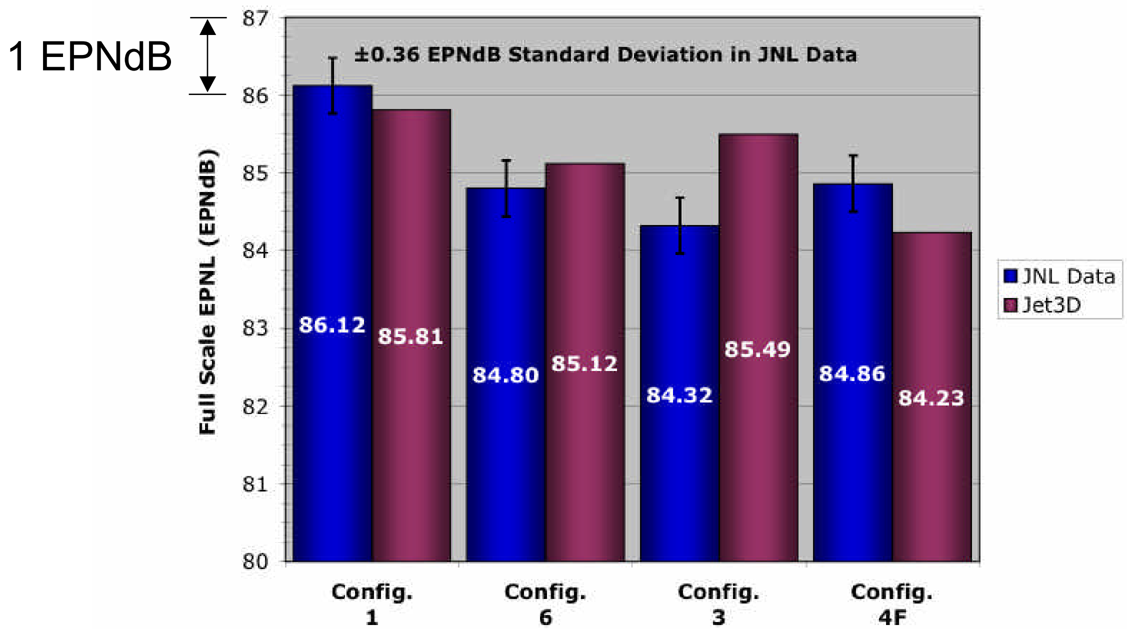
Model Core Diameter = 0.128m

Model Scale SPL - Configuration 4F*



*Chevron core nozzle, round fan nozzle, pylon, and lower fan bifurcator.

Full Scale EPNL Comparison



Jet3D Summary

- Predicted EPNL for round configurations in excellent agreement with JNL data

- Jet3D captured pylon effect

- CFD underpredicted mixing from chevrons, but EPNL still *within about 1 EPNdB* of experiment

Summary

- Model scale SPL predictions look good in the inlet arc, but progressively deteriorate in the jet arc. Low frequency underprediction due to the crude Snell's Law filter.
- Next major version of Jet3D will feature a revised Lighthill formulation which properly accounts for flow-acoustic interactions through spatial quadrupole phasing.
- Predicted full scale sideline EPNL for round configurations 1 and 6 are in excellent agreement with JNL data, and Jet3D captured the effect of the pylon.
- CFD under-mixing of chevron configurations 3 and 4F had a negative impact on noise prediction for those cases, but EPNL predictions are still within about 1 EPNdB of experiment.

Concluding Remarks

– Analytic methods successfully used in CAA for many important problems

– Many problems associated with CFD-based CAA do not appear in analytic-based CAA

–Hybrid codes often advantageous, with CFD-based CAA and analytic methods used in different field regions

Use of analytic methods in CAA will increase as other areas of mathematics are applied in acoustics, e.g., nonlinear generalized functions, nonstandard analysis, etc.