A Prediction Method for Jet Noise Scattering due to Airframe Bodies and its Validation with Measurement

Steven A. E. Miller
The National Aeronautics and Space Administration

Matthew J. Smith*
The National Institute of Aerospace / Virginia Tech.

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*Former NIA/VT Graduate Student – Presently with The Boeing Company
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High Speed Project

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Outline

• Introduction
• Theoretical Approach
  – Acoustic Analogy
  – Tailored Vector Green’s Function – Ray Theory
• Results
  – Fluid Dynamic Predictions - Jet Flows Near Surfaces
  – A Non-Dimensional Approach
  – Aeroacoustic Predictions - Scattering of Jet Mixing Noise
• Summary and Conclusion
INTRODUCTION
Jet Flow

The Most Beautiful Phenomenon in Fluid Dynamics
Subsonic, Transonic, Supersonic, Shock waves, Shear Layers, Boundary Layer, Inviscid, Transitional, Fully turbulent, Incompressible, Compressible, etc.


Jet-Structure Interaction

Three Classifications:

Jet noise diffraction: Jet flow is unaltered and sound propagation is altered by airframe

Jet scrubbing: Jet flow interacts with airframe or adjacent surface

Jet impingement: Jet flow stagnates on airframe or external surface
Example Jet-Structure Interaction

Brown and Bridges, `Jet Structure Interaction Test,' NASA GRC.

Boeing 787

NASA Supersonic Iconic Vehicle
**Objective:** Create and validate a prediction method for scattered jet mixing noise.
THEORETICAL APPROACH
Overview of the Approach

- Governing equations – Euler
- Form an acoustic analogy
- Solve for pressure in terms of vector Green’s function (GF) of linearized Euler equations (LEE) and equivalent sources
- Model the equivalent sources
- Connect source model to steady RANS
- Write vector GF of LEE with arguments of Lilley’s equation and periodic GF of convective wave equation – retain jet shear layer refraction effects
- Numerically evaluate GF for appropriate jet flow and airframe geometry
A `Partially’ Comprehensive Model

\[ S(x, \omega) = 2\pi^{3/2} \rho^2 c^4 \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{c^2 l_x l_y l_z \tau_s x^2}{\rho^2 c^4 x^2 + (u x_1 + v x_2 + w x_3 - c_x x)^2 \tau_s^2 \omega^2} \]

\[ \pi^0_g \left( x, y, \omega \right) \pi^0_g \left( x, y, \omega \right) A^2 \frac{\left( u_s / c_\infty \right)^4}{\tau_s^2} \]

\[ + \sum_{n=1}^{3} \sum_{m=1}^{3} \pi^{n*}_g \left( x, y, \omega \right) \pi^{m}_g \left( x, y, \omega \right) B^2 \frac{\left( u_s / c_\infty \right)^2 u_s^4}{l_x^2} \]

\[ + \sum_{n=1}^{3} \sum_{m=1}^{3} \pi^{n*}_g \left( x, y, \omega \right) \pi^{m}_g \left( x, y, \omega \right) \frac{a_{mn} p_s(y) k}{\rho^2 u^2 l_x^2} \int_{-\infty}^{\infty} \tilde{p}_s(k_1, y_2, y_3) \exp[-ik_1 y_1] \, dk_1 \]

\[ + \text{ a term for the discrete tones...} \]


We need to find the vector Green’s function

Integral scales of turbulence
Terms informed by base-flow
Vector Green’s Function
A Simplified Approach via a Bridging Function

Relate vector Green’s function to Green’s function of Lilley’s equation,

\[
\pi^0_g(x, y, \omega) = \omega^2 g_l(x, y, \omega) - 2i\omega \frac{\partial g_l(x, y, \omega)}{\partial y_x} - u^2 \frac{\partial^2 g_l(x, y, \omega)}{\partial y_x^2}
\]

\[
\pi^1_g(x, y, \omega) = -\left(i\omega + u \frac{\partial}{\partial y_x}\right) \frac{\partial}{\partial y_x} g_l(x, y, \omega)
\]

\[
\pi^2_g(x, y, \omega) = -\left\{3 \frac{\partial u}{\partial y_r} \frac{\partial}{\partial y_x} - \left(i\omega + u \frac{\partial}{\partial y_x}\right) \frac{\partial}{\partial y_r}\right\} g_l(x, y, \omega)
\]

\[
\pi^3_g(x, y, \omega) = -\left(i\omega + u \frac{\partial}{\partial y_x}\right) \frac{1}{y_r y_\theta} \frac{\partial}{\partial y_\theta} g_l(x, y, \omega)
\]

Based on asymptotic solutions (Goldstein & Balsa) of Lilley’s equation,

\[
g_l(x, y, \omega) = \frac{i}{c^2 c_0^\alpha \omega} \frac{c_\infty}{c} \exp\left[-c_\beta \omega / c_\infty\right] \times \exp\left[-i\omega \left(x \cos \theta + r \sin \theta \cos \phi_0 - \phi\right)\right] g
\]

and \(g\) is the Green’s function of the periodic convective wave equation.

Implication: A tailored form of \(g\) connects a modern acoustic analogy with sound scattering about arbitrary bodies

Potential Methods to Find GF, $g$

Direct Method
- Directly solve LEE with appropriate source
- Adjoint approach of LEE
- Parallel flow assumption
- Very high comp. cost

Boundary Problem
- Boundary element methods
- Equivalent source (eg: FSC)
- New Prof. Hu method
- Best at lower freq.

Ray Tracing
- Geometric acoustics
- Best at high freq.
- Low comp. cost
Application of Diffraction Theory

\[ g = g_I + \sum g_D \]

\[ g_I = \frac{e^{ikr}}{4\pi r} \]

\[ g_D = Dg_I(V) \left[ \frac{\rho}{r(r + \rho)} \right]^{1/2} e^{ikr} \]

\[ D = \frac{e^{\frac{i\pi}{4}} \nu \sin(\nu \pi)}{\sqrt{2\pi k \sin(\theta)}} \left[ \frac{1}{\cos(\nu \pi) - \cos(\nu(\phi_s - \phi_o))} + \frac{1}{\cos(\nu \pi) - \cos(\nu(\phi_s + \phi_o + \pi))} \right] \]

Must solve for geometric solution
Implementation of Ray Theory

1. Read Geometry
2. Find 3D Projection
3. Find Edge
4. Shadow Zone Test
5. Find Diffracted Rays
6. Sum Rays at Observers
Results: Jet Flows Near Surfaces

Free Jet Aerodynamic Validation

- Free jet
- FUN3D and PIV data
- $M_j = 0.50$
- TTR = 1.00
Semi-Infinite Flat Plate (Jet Structure Interaction Test)

\[ M_j = 0.513, \ TTR = 1.00, \ x_p / D = 10 \text{ and } y_p / D = 1 \]
Aerodynamic Validation

\[ M_j = 0.985, \ TTR = 1.00, \ y_p / D = 1, \text{ and } x_p / D = 10 \]
RESULTS: VARIATION OF THE AERODYNAMIC SOURCE RELATIVE TO AIRFRAME POSITION

A Non-Dimensional Approach
Noise Prediction Results

Aerodynamic Noise Source Contours

\[ M_j = 0.513, \quad TTR = 1.00, \quad x_p / D = 10, \quad \text{and} \quad f = 1000 \text{ Hz} \quad (St \approx 0.3) \]
Analysis Results: $\Delta OASPL$ vs. $\Gamma$

\[
\Gamma = \frac{D_j x_p \tan(\delta_p)}{y_p (y_p - D/2)} = \frac{\text{Product of Jet/Airframe Length Scales}}{\text{Cross-Stream Length Scales}}
\]
RESULTS: PREDICTIONS
JET STRUCTURE INTERACTION TEST

Flow-Structure Interaction
Prediction and Measurement (JSIT) Overview

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<thead>
<tr>
<th>Nozzle</th>
<th>$M_j$</th>
<th>NPR</th>
<th>TTR</th>
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<tr>
<td>SMC000</td>
<td>0.678</td>
<td>1.36</td>
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<tr>
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<td>SMC016</td>
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<td>3.67</td>
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Axial Distance to Trailing Edge ($x_p/D$) | Radial Distance to Jet Centerline ($y_p/D$)

<table>
<thead>
<tr>
<th>Axial Distance to Trailing Edge ($x_p/D$)</th>
<th>Radial Distance to Jet Centerline ($y_p/D$)</th>
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<td>20</td>
<td>2, 4, 6, 8, 10</td>
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</tbody>
</table>

Measurements of Brown, NASA GRC

04/16/2014

Steve Miller, Ph.D., s.miller@nasa.gov
Scattered Jet Mixing Noise Predictions

SMC000 Nozzle
$M_j = 0.678$, $TTR = 1.926$
$D = 0.0508 \text{ m}$, $R/D = 100$
$x_p/D = 20$, $y_p/D = 2$
Scattered Jet Mixing Noise Predictions

SMC000 Nozzle

$M_j = 0.985$, $TTR = 1.00$

$D = 0.0508$ m, $R/D = 100$

$x_p/D = 10$, $y_p/D = 6$
Scattered Jet Mixing Noise Predictions

SMC000 Nozzle

$M_j = 0.985$, $TTR = 1.00$

$D = 0.0508$ m, $R/D = 100$

$x_p/D = 20$, $y_p/D = 2$
Scattered Jet Mixing Noise Predictions

SMC016 Nozzle

\( M_j = 1.50, \ TTR = 1.00 \)

\( D = 0.0508 \text{ m}, \ R/D = 100 \)

\( x_p/D = 4, \ y_p/D = 2 \)
Scattered Jet Mixing Noise Predictions

SMC000 Nozzle

\( M_j = 1.290, \ TTR = 1.00 \)
\( D = 0.0508 \text{ m}, \ R/D = 100 \)
\( x_p/D = 10, \ y_p/D = 8 \)
RESULTS: PREDICTION
HYBRID WING BODY

Application to flight vehicles
Delta dB relative to isolated twin jet
Max $\Delta$SPL = -19.6
At $\Psi=90^\circ$ $\Delta$SPL $\approx$ -3.5 dB, $St = 0.3$

Example Hybrid Wing Body Prediction

Current method compared with point source at $St = 1.10$

Newly Developed Approach

Equivalent Point Source

Benefits of a physics based and distributed source apparent
Summary and Conclusions

• New prediction method for scattered jet mixing noise
• Validated for a wide range of jet Mach numbers, temperatures, and airframe configurations (360 validations total)
• Demonstrated on the HWB Aircraft
• Uses integrated ray-tracing method and compatible with other approaches for GF
• Predictions capture most trends – aerodynamic and acoustic
• Non-dimensional view is useful, $\Gamma \sim 1$ result in jet structure interaction noise
QUESTIONS

Contact
s.miller@nasa.gov