Preliminary Investigation of Acoustic Radiation from Large-Scale Turbulent Structures within a Two-Dimensional Shear Layer

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Outline

- Preliminary
- Introduction
- Mathematical Methods
- Preliminary Results
  - Computational Fluid Dynamics
  - Acoustic Radiation
- Future Research Direction
Preliminary
Brief Biography

University of Florida
• Asst. Prof. of Mech. & Aero. Eng.

Previously at NASA
• NASA Civil Servant from 2009 - 2016
• Research Aerospace Engineer

Education
• Ph.D. (NASA Grant)
  Aerospace Engineering, Penn State
• M.S. (NREL Grant)
  Aerospace Engineering, Penn State
• B.S., Mechanical Engineering, Michigan State University
Research Overview

Steven A. E. Miller, Ph.D.
Assistant Professor of Mech. and Aero. Eng.
Ph.D., Penn State University, 2009

- Theoretical fluid dynamics, aeroacoustics, and turbulence
- Compressible turbulent jets, shock waves, shear layers, boundary layers, fluid structure interaction
- Nonlinear propagation of waves
- Applications – rocket and jet engines, external aerodynamics, wave propagation, sources of sound, and more…
UF Student Research

- Carr, Alex – Jet structure interaction
- Endurthi, Vijay – Rotorcraft aeroacoustics
- Pager, Elisha - University Scholars, turbulent boundary layers, CFD class development
- Patel, Trushant – Aeroacoustic modeling
- Roberts, Kyle – Sonic boom and counter-flowing jets
- Shen, Weiqi – LES and decomposition of jets
- Wang, Wei - Multiphase flow of off-design supersonic jets (with Dr. Bala)
Introduction
Radiation of Waves from Turbulence

Van Dyke 1982
Jet Noise Spectra

\[ M_d = 1.00, \ M_j = 1.50, \ TTR = 1.00, \ D = 0.0254 \text{ m}, \ R/D = 100 \]

Predictions

\[ \psi = 150^\circ \]

\[ \psi = 90^\circ \]

\[ \psi = 50^\circ \]
Large-Scale Coherent Anisotropic Structures and Instability Waves

Dimotakis and Brown JFM 1976

Liu JFM 1974

Figure 4. Large structure 120 cm (picture centre) downstream of the splitter plate; $U_1 = 100 \text{cm/s}$, flow from right to left, high-speed side at the bottom. (a) Injection from high-speed side. (b) Injection from low-speed side.
Large-Scale Coherent Anisotropic Structures and Instability Waves

Experiments of Mollo-Christiansen 1967

Crighton and Huerre JFM 1990
Large-Scale Coherent Anisotropic Structures and Instability Waves

Unforced jet - top radial velocity trace, dye line, vortex element
Acton 1976
Large-Scale Coherent Anisotropic Structures and Instability Waves

Jordon and Colonius
Annual Review Fluids 2013

Figure 4
Wave packets: (a) instantaneous slice of the $M_f = 0.9$, Re = 3,600 DNS of Freund (2001); (b) the most energetic axisymmetric ($m = 0$) and helical ($m = 1$) pressure wave packets from the DNS; (c) the streamwise structure as a function of St and $m$ based on the cross-spectral density (CSD) of the pressure from a near-field caged microphone array (Suzuki & Colonius 2006) at $M_f = 0.5$, Re = 700,000; and (d) radial decay at $x/D = 3.5$ from the same experiments. The lines represent the exponential radial decay associated with $J_m(i \beta r)$, where $\beta = \sqrt{a^2 - \left( \frac{\alpha}{a_{\infty}} \right)^2}$, with $\alpha$ the measured local wave number.
A Note on the Universality: Wavenumber Spectra of Structure Functions

Velocity

\[ E_u \propto c_u \epsilon^{\alpha_u} \kappa^{-5/3} \]


Pressure

\[ E_p \propto c_p \epsilon^{\alpha_p} \kappa^{-7/3} \]


Temperature

\[ E_T \propto c_T \epsilon^{\alpha_T} \kappa^{-5/3} \]


Density

\[ E_\rho \propto c_\rho \epsilon^{\alpha_\rho} \kappa^{-5/3} \]

Modeling Goals

• Create an acoustic analogy to predict noise from turbulent flows that is closed-form

• Arguments of the model
  • Large-scale anisotropic turbulence
  • Wavenumber `energy’ spectra

• Validate the model through comparison with measurements

• Gain insight into the physical mechanism of sound generation
Mathematical Methods
Mathematical Outline

- Governing equations
- Decomposition
- Sources
- A statistical solution through acoustic analogy
- Modeling sources
- Final model equation
Governing Equations

Navier-Stokes equations

\[
\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_j}{\partial x_j} = 0
\]

\[
\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_i u_j}{\partial x_j} = -\frac{\partial p}{\partial x_j} \delta_{ij} + \frac{\partial \tau_{ij}}{\partial x_j}
\]

\[
\frac{\partial \rho e_o}{\partial t} + \frac{\partial \rho u_j e_o}{\partial x_j} = -\frac{\partial u_j p}{\partial x_j} - \frac{\partial q_j}{\partial x_j} + \frac{\partial u_j \tau_{ij}}{\partial x_j}
\]
Decomposition of Governing Equations

Decompose Navier-Stokes equations where \( q \) is a field-variable

\[
q = \bar{q} + \tilde{q} + \tilde{\tilde{q}} + q' + q''
\]

and,

\[
\begin{align*}
\bar{q} & = \text{Time-evolving or steady non-radiating base flow} \\
\tilde{q} & = \text{Anisotropic turbulent fluctuations} \\
\tilde{\tilde{q}} & = \text{Isotropic turbulent fluctuations} \\
q' & = \text{Radiating waves associated with anisotropic turbulence} \\
q'' & = \text{Radiating waves associated with isotropic turbulence}
\end{align*}
\]

Source terms are exactly Navier-Stokes equations operators on \( q \).
Source Terms

\[ \Theta_0 = -\frac{\bar{\rho} + \tilde{\rho}}{\tau} - \frac{(\bar{\rho} + \tilde{\rho})(\bar{u} + \tilde{u})}{l_x} - \frac{(\bar{\rho} + \tilde{\rho})(\bar{v} + \tilde{v})}{l_y} \]

\[ \Theta_1 = -\frac{(\bar{\rho} + \tilde{\rho})(\bar{u} + \tilde{u})}{\tau} - \frac{(\bar{\rho} + \tilde{\rho})(\bar{u} + \tilde{u})^2}{l_x} - \frac{(\bar{\rho} + \tilde{\rho})(\bar{v} + \tilde{v})}{l_y} - \frac{\bar{p} + \tilde{p}}{l_x} + \frac{4\mu (\bar{u} + \tilde{u})^2}{3 l_x^2} + \mu \frac{(\bar{u} + \tilde{u})^2}{l_y^2} + \frac{\mu (\bar{v} + \tilde{v})^2}{3 l_x l_y} \]

\[ \Theta_2 = -\frac{(\bar{\rho} + \tilde{\rho})(\bar{v} + \tilde{v})}{\tau} - \frac{(\bar{\rho} + \tilde{\rho})(\bar{u} + \tilde{u})(\bar{v} + \tilde{v})}{l_x} - \frac{(\bar{\rho} + \tilde{\rho})(\bar{v} + \tilde{v})^2}{l_y} - \frac{\bar{p} + \tilde{p}}{l_y} + \frac{4\mu (\bar{v} + \tilde{v})^2}{3 l_y^2} + \mu \frac{(\bar{v} + \tilde{v})^2}{l_y^2} + \frac{\mu (\bar{u} + \tilde{u})^2}{3 l_x l_y} \]

\[ \Theta_3 = -\frac{\bar{p} + \tilde{p}}{\tau} - \frac{\gamma - 1}{2} \left( \frac{(\bar{\rho} + \tilde{\rho})(\bar{u} + \tilde{u})}{\tau} + \frac{(\bar{\rho} + \tilde{\rho})(\bar{v} + \tilde{v})}{\tau} \right) - \gamma \left( \frac{(\bar{u} + \tilde{u})(\bar{p} + \tilde{p})}{l_x} + \frac{(\bar{v} + \tilde{v})(\bar{p} + \tilde{p})}{l_y} \right) - \frac{\gamma - 1}{2} \left( \frac{(\bar{\rho} + \tilde{\rho})(\bar{u} + \tilde{u})^3}{l_x} + \frac{(\bar{\rho} + \tilde{\rho})(\bar{u} + \tilde{u})(\bar{v} + \tilde{v})}{l_x} + \frac{(\bar{\rho} + \tilde{\rho})(\bar{u} + \tilde{u})^2(\bar{v} + \tilde{v})}{l_y} + \frac{(\bar{\rho} + \tilde{\rho})(\bar{v} + \tilde{v})^3}{l_y} \right) \]

\[ + (\gamma - 1) \frac{c_p \mu}{Pr} \left( \frac{T + \tilde{T}}{l_x^2} + \frac{T + \tilde{T}}{l_y^2} \right) + (\gamma - 1) \mu \left( \frac{2(\bar{u} + \tilde{u})^2}{l_x^2} + \frac{(\bar{u} + \tilde{u})^2}{l_x l_y} + \frac{(\bar{u} + \tilde{u})(\bar{v} + \tilde{v})}{l_x^2} \right) \]

\[ + (\gamma - 1) \mu \left( \frac{2(\bar{v} + \tilde{v})^2}{l_y^2} + \frac{(\bar{v} + \tilde{v})^2}{l_x l_y} + \frac{(\bar{u} + \tilde{u})(\bar{v} + \tilde{v})}{l_y^2} \right) \]

\[ - \frac{2\mu}{3} \left( \frac{(\bar{u} + \tilde{u})^2}{l_x^2} + \frac{(\bar{u} + \tilde{u})(\bar{v} + \tilde{v})}{l_x l_y} \right) - \frac{2\mu}{3} \left( \frac{(\bar{v} + \tilde{v})^2}{l_y^2} + \frac{(\bar{u} + \tilde{u})(\bar{v} + \tilde{v})}{l_x l_y} \right) \]
Seek a Solution

Takes the form

\[ q_{k}^\perp (\mathbf{x}, t) = \int_{-\infty}^{\infty} \ldots \int_{-\infty}^{\infty} \sum_{n=0}^{3} q_{g,k}^\perp (\mathbf{x}, t; \mathbf{y}, \tau) \Theta_{n} (\mathbf{y}, \tau) \, d\tau \, d\mathbf{y}. \]

Satisfies the vector Green’s function

\[
\frac{\partial \rho_{g}^\perp}{\partial t} + \frac{\partial}{\partial x_{j}} \left[ \rho_{g}^\perp \mathbf{u}_{j} + \mathbf{u}_{j,g}^\perp \rho \right] = \delta (\mathbf{x} - \mathbf{y}) \delta (t - \tau) \delta_{0n} \]

\[
\frac{\partial}{\partial t} \left[ \rho_{g}^\perp \mathbf{u}_{i} + \mathbf{u}_{i,g}^\perp \rho \right] + \frac{\partial}{\partial x_{j}} \left[ \rho_{g}^\perp \mathbf{u}_{i,j} + \mathbf{u}_{i,j,g}^\perp \rho \right] - \frac{1}{\mu} \frac{\partial}{\partial x_{j}} \left[ \frac{\partial \mathbf{u}_{i}^\perp}{\partial x_{j}} + \frac{\partial \mathbf{u}_{j}^\perp}{\partial x_{i}} \right] \]

\[
\frac{\partial p_{k}^\perp}{\partial t} + \frac{\partial}{\partial t} \left[ \rho_{k}^\perp u_{k}^2 + 2u_{k}^\perp \rho u_{k} \right] + \frac{\partial}{\partial x_{j}} \left[ p_{k}^\perp \mathbf{u}_{j} + u_{j,k}^\perp p \right] \]

\[
+ \frac{\gamma - 1}{2} \frac{\partial}{\partial x_{j}} \left[ \rho^\perp \mathbf{u}_{j} \mathbf{u}_{k}^2 + u_{j,k}^\perp \rho u_{k}^2 + 2u_{k}^\perp \rho u_{k} \right] - \frac{\partial}{\partial x_{j}} \frac{c_{p} \mu}{\rho R} \frac{\partial}{\partial x_{j}} \left[ \frac{\bar{p}^n}{\bar{\rho}^n} + \frac{\bar{\rho}^n}{\bar{\rho}^n} \right] \]

\[- (\gamma - 1) \mu \frac{\partial}{\partial x_{j}} \left[ \mathbf{u}_{i} \left( \frac{\partial \mathbf{u}_{i}^\perp}{\partial x_{j}} + \frac{\partial \mathbf{u}_{j}^\perp}{\partial x_{i}} \right) + \frac{\partial \mathbf{u}_{j}^\perp}{\partial x_{i}} \frac{\partial \mathbf{u}_{i}^\perp}{\partial x_{j}} \right] \]

\[+ \frac{\partial}{\partial x_{j}} \left[ \frac{\partial \mathbf{u}_{k}^\perp}{\partial x_{k}} + \frac{\partial \mathbf{u}_{j}^\perp}{\partial x_{i}} \right] \]

\[= \delta (\mathbf{x} - \mathbf{y}) \delta (t - \tau) \delta_{3n}. \]
Seek a Predictable Statistical Solution

Fourier transform of the solution

\[ \hat{q}_k^\perp (x, \omega) = \int_{-\infty}^{\infty} \ldots \int_{-\infty}^{\infty} \sum_{j=0}^{4} q_{g,k}^\perp j (x, t; y, \tau) \Theta_j (y, \tau) \exp [-i\omega t] dtd\tau dy. \]

Represents the Fourier transform of \( q \) and is complicated by the fact that it contains both the retarded time, \( \tau \), and frequency, \( \omega \)

\[ S_k^\perp (x, \omega) = \int_{-\infty}^{\infty} \langle q_k^\perp (x, t) q_k^\perp (x, t + \tau^\dagger) \rangle \exp [i\omega \tau^\dagger] d\tau^\dagger, \]
A General Model for Spectral Density

We define $R_{m,n} (y, \eta, \tau)$ as the two-point space-time cross-correlation of the equivalent source

$$S_k^\perp (x, \omega) = \int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty} \sum_{m=0}^{3} \sum_{n=0}^{3} \hat{q}_{g,k}^\perp m (x; y, \omega) \hat{q}_{g,k}^\perp n (x; y + \eta, \omega) R_{m,n}^\perp (y, \eta, \tau) d\tau d\eta dy.$$

where

$$R_{m,n}^\perp (y, \eta, \tau) = \langle \Theta_m (y, \tau) \Theta_n (y + \eta, \tau + \Delta \tau) \rangle = \int_{-\infty}^{\infty} \Theta_m (y, \tau) \Theta_n (y + \eta, \tau + \Delta \tau) d\Delta \tau.$$

Model the source terms and assume separable

$$R_{m,n}^\perp (y, \eta, \tau) \approx \{ R_{m,n}^\perp \} R$$
Modeling Two-Point Cross-Correlation

Normalized two-point cross-correlation

\[ R = \int_{-\infty}^{\infty} P_1(y_1, \Delta_1, \Delta_2, t) P_2(y, \delta_1, \delta_2, \eta_1, t, \tau) dt \]

is a function of two large-scale instability waves of the form

\[ P_1(y_1, \Delta_1, \Delta_2, t) = \exp \left[ - \frac{\Delta_2^2}{l^2_y, (1)} \right] \exp \left[ - \frac{t^2}{\tau_c, (1)} \right] \]

\[ \times \exp \left[ - \frac{(\Delta_2(1) + y_2(1))^2}{l^2_x, 1} \right] \exp \left[ i (\kappa_1(1)(\Delta_2(1) + y_2(1)) - \kappa_1(1)t u_{c, (1)}) \right] \]
Models of Source Terms

One of 16 source terms

\[ \Theta_1 \Theta_3 = \left( \frac{4 \mu (\ddot{u}(1) + \ddot{u}(1))^2}{3l_x(1)} + \frac{\mu (\ddot{v}(1) + \ddot{v}(1))^2}{3l_y(1)} - \frac{\ddot{P}(1) + \ddot{P}(1)}{l_x(1)} - \frac{(\ddot{P}(1) + \ddot{P}(1))(\ddot{u}(1) + \ddot{u}(1))^2}{l_y(1)} \right) 
\]

\[ + \frac{\mu (\ddot{u}(1) + \ddot{u}(1))^2}{l_x(1)} - \frac{(\ddot{P}(1) + \ddot{P}(1))(\ddot{u}(1) + \ddot{u}(1))(\ddot{v}(1) + \ddot{v}(1))}{l_x(1)} - \frac{(\ddot{P}(1) + \ddot{P}(1))(\ddot{u}(1) + \ddot{u}(1))}{l_y(1)} \right) 
\]

\[ \times \left( \frac{(\gamma - 1) c_p \mu \left( \frac{\ddot{u}_x(2) + \ddot{u}_y(2)}{l_x(2)} + \frac{\ddot{u}_y(2) + \ddot{u}_x(2)}{l_y(2)} \right)}{\mathcal{P}_r} + (\gamma - 1) \mu \left( \frac{(\ddot{u}_x(2) + \ddot{u}_y(2))(\ddot{v}_x(2) + \ddot{v}_y(2))}{l_x(2)} \right) \right) 
\]

\[ + \frac{2(\ddot{u}_y(2) + \ddot{u}_y(2))^2}{l_x(2)} + \frac{(\ddot{u}_x(2) + \ddot{u}_x(2))^2}{l_y(2)} \right) - \frac{2}{3} \mu \left( \frac{(\ddot{u}_x(2) + \ddot{u}_y(2))^2}{l_x(2)} + \frac{(\ddot{u}_x(2) + \ddot{u}_y(2))(\ddot{v}_x(2) + \ddot{v}_y(2))}{l_y(2)} \right) \right) 
\]

\[ +(\gamma - 1) \mu \left( \frac{(\ddot{v}_x(2) + \ddot{v}_y(2))^2}{l_x(2)} + \frac{(\ddot{u}_x(2) + \ddot{u}_y(2))(\ddot{v}_x(2) + \ddot{v}_y(2))}{l_y(2)} \right) \right) 
\]

\[ - \frac{2}{3} \mu \left( \frac{(\ddot{u}_x(2) + \ddot{u}_y(2))(\ddot{v}_x(2) + \ddot{v}_y(2))}{l_x(2)} + \frac{(\ddot{v}_x(2) + \ddot{v}_y(2))^2}{l_y(2)} \right) \right) 
\]

\[ - \frac{1}{2} (\gamma - 1) \left( \frac{(\ddot{P}_x(2) + \ddot{P}_y(2))(\ddot{u}_x(2) + \ddot{u}_y(2))^3}{l_x(2)} + \frac{(\ddot{P}_x(2) + \ddot{P}_y(2))(\ddot{u}_x(2) + \ddot{u}_y(2))(\ddot{v}_x(2) + \ddot{v}_y(2))^2}{l_x(2)} \right) \right) 
\]

\[ + \frac{(\ddot{P}_x(2) + \ddot{P}_y(2))(\ddot{u}_x(2) + \ddot{u}_y(2))^2(\ddot{v}_x(2) + \ddot{v}_y(2))}{l_x(2)} + \frac{(\ddot{P}_x(2) + \ddot{P}_y(2))(\ddot{v}_x(2) + \ddot{v}_y(2))^3}{l_y(2)} \right) \right) \right) 
\]

\[ - \frac{1}{2} (\gamma - 1) \left( \frac{(\ddot{P}_x(2) + \ddot{P}_y(2))(\ddot{u}_x(2) + \ddot{u}_y(2))^2}{l_y(2)} + \frac{(\ddot{P}_x(2) + \ddot{P}_y(2))(\ddot{v}_x(2) + \ddot{v}_y(2))^2}{l_y(2)} \right) \right) \right) \right) 
\]

\[ \cdot \left( \Theta_2 \Theta_3 \right) \]

\[ \ddot{u}_i(y, \tau) = \sqrt{\frac{2}{3}} \left( \int_{\kappa_1}^{\kappa_2} E_u(y, \kappa, \tau) d\kappa \right)^{1/2} \]

\[ \ddot{p}(y, \tau) = \left( \int_{\kappa_1}^{\kappa_2} E_p(y, \kappa, \tau) d\kappa \right)^{1/2} \]

\[ \ddot{\rho}(y, \tau) = \left( \int_{\kappa_1}^{\kappa_2} E_{\rho}(y, \kappa, \tau) d\kappa \right)^{1/2} \]

\[ \ddot{T}(y, \tau) = \left( \int_{\kappa_1}^{\kappa_2} E_T(y, \kappa, \tau) d\kappa \right)^{1/2} \]
Final Aeroacoustic Equation

We set $k = 4$ for pressure and find

$$S_k^\perp (x, \omega) = \int_{-\infty}^{\infty} \ldots \int_{-\infty}^{\infty} \sum_{m=0}^{3} \sum_{n=0}^{3} \hat{q}_{g,k}^* m (x; y, \omega) \hat{q}_{g,k} n (x; y + \eta, \omega)$$

$$\times \pi \tau(1) \tau(2) \exp \left[ -\frac{1}{4} \kappa^{(1)} \tau_{(1)}^2 u_{c,(1)}^2 + i \kappa^{(1)} (\Delta_1 + y_1) - \frac{1}{4} \kappa^{(2)} \tau_{(2)}^2 u_{c,(2)}^2 + i \kappa^{(1)} (\delta_2 + \eta_1 + y_1) - \frac{(\Delta_1 + y_1)^2}{l_{x,(1)}^2} - \frac{(\delta_1 + \eta_1 + y_1)^2}{l_{x,(2)}^2} - \frac{\Delta_2^2}{l_{y,(1)}^2} - \frac{\delta_2^2}{l_{y,(2)}^2} \right]$$

$$\times \left\{ R_{m,n}^\perp (y, \eta, \tau) \right\} d\eta dy$$

We are evaluating this equation with a Python program in conjunction with RANS and/or LES solutions

Working to further simplify for the 2D shear layer case
Preliminary Results
Overview

- Three shear layer Mach numbers 0.75, 1.25, and 1.75
- Select RANS and LES results
- Example instability wave model
- Acoustic Predictions
Steady RANS Contours of $u$

Contours of $u$

*Fluent Simulations*

$M = 0.75$

$M = 1.25$

$M = 1.75$
Steady RANS Model
Steady RANS Model
Large-Eddy Simulation

2D Shear layer at Mach 0.75
Schlieren at $M = 0.75$
Large-Eddy Simulation

$E_u$ Power Spectrum
Instability Wave Evolution
Instability Wave
Interaction of Instability Waves
Previous Predictions for Isotropic Turbulence

Published this year in AIAAJ by Miller (single author)
Acoustic Prediction at Mach 1.75
RANS Based Sources

![Graph showing acoustic prediction at Mach 1.75 with RANS based sources. The graph plots Far-Field SPL (in dB) against angle θ (in degrees) for different cases with Tam and Morris and Prediction RANS at different ω values.]
Acoustic Prediction
RANS Based Sources

![Graph showing the comparison between Tam and Morris and Prediction RANS for different Mach numbers (M).

- Tam and Morris $M = 0.75$
- Tam and Morris $M = 1.25$
- Tam and Morris $M = 1.75$
- Prediction RANS $M = 0.75$
- Prediction RANS $M = 1.25$
- Prediction RANS $M = 1.75$]
Summary and Future Research
Summary

• Previously made predictions for isotropic turbulence (analytical approach)
• Conducted predictions for large-scale turbulence associated noise for 2D shear layer
• Captures large-scale structure and large-scale structure interactions
• RANS and LES based source models
Future Research

- Extend model to anisotropic-isotropic sources
- Extend model to large-scale structures interacting with shock waves
- Perform simulations of 3D off-design jets and predict noise
- Examine radiated noise, turbulence statistics, as function of nozzle conditions and geometry
- Future Seminars
  - Weiqi Shen – LES and Decomposition
  - Trushant Patel – Aeroacoustic Modeling
“My dear, here we must run as fast as we can, just to stay in place. And if you wish to go anywhere you must run twice as fast as that.”

Through the Looking Glass (and what Alice found there), Lewis Carroll (Rev. Charles Dodgson)