Prediction of Fine-Scale and Shock-Associated Noise from Turbulence

Steven A. E. Miller

University of Florida
Department of Mechanical and Aerospace Engineering
Theoretical Fluid Dynamics and Turbulence Group

Office: MAE-A 220; Students: MAE-A 331
saem@ufl.edu; 352-392-0886
https://faculty.eng.ufl.edu/fluids; https://saemiller.com

Outline

- Introduction
  - Research group
  - Noise from jet turbulence
- Prediction theory overview and CFD
- Development and validation
- Example prediction and reduction study
- Other research efforts
- Future research
- Acknowledgements

Boeing / Atlas

Theoretical Fluid Dynamics and Turbulence Group

- Interested in understanding turbulence physically and mathematically
- Interested in understanding how sound is produced by and propagated through turbulent fields
- Central questions within the field of fluid dynamics
- My research focuses on *analytical* and computational (combined) methods

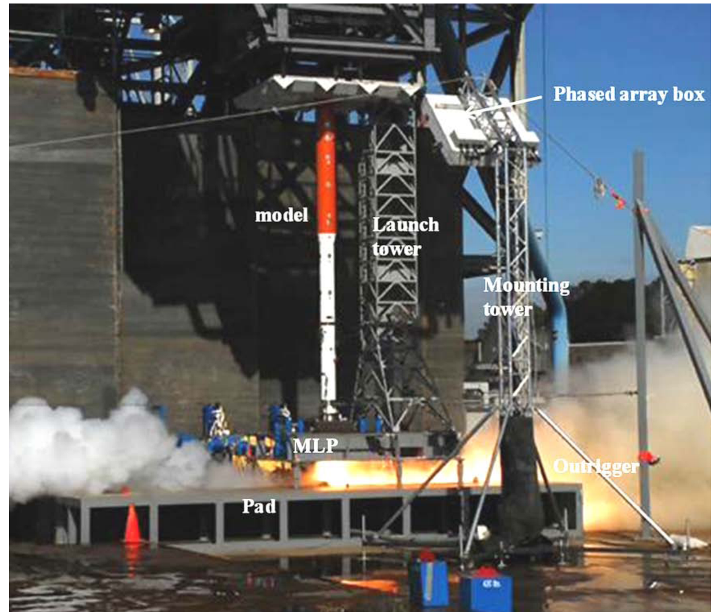
Leonardo da Vinci – notebook c. 1485.

Aerospace Flight Vehicles

Need for first principles mathematical theory to predict pressure radiated noise from turbulence

Illustration of the X-59 QueSST landing on a runway. LM illustration via NASA.gov

Image Credit: NASA/Boeing Co.
Website: NASA.gov



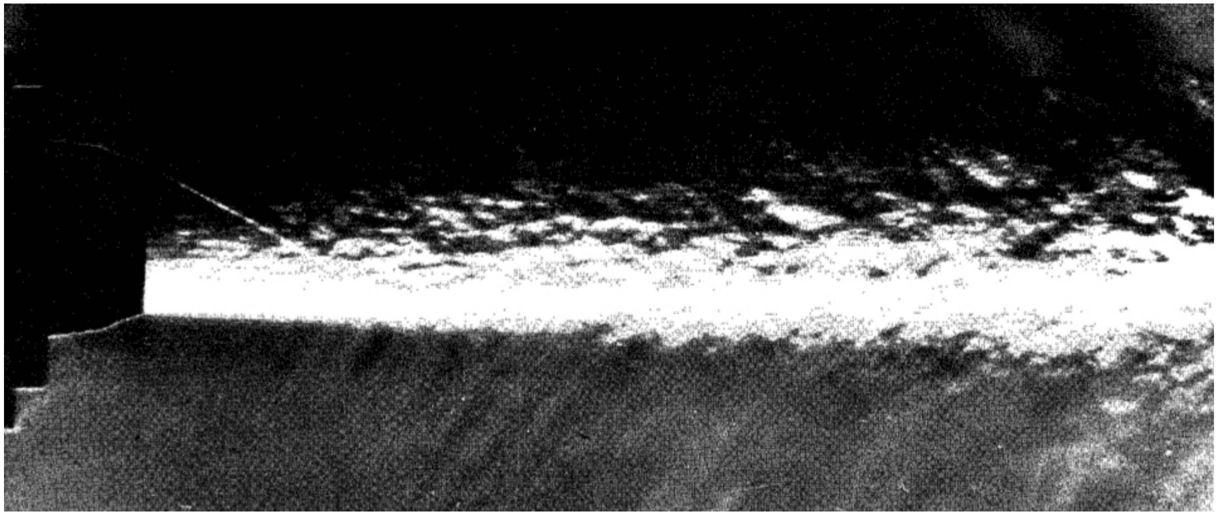
Panda, J. and Mosher, R., “Microphone Phased Array to Identify Liftoff Noise Sources in Model Scale Tests,” Journal of Spacecraft and Rockets, (2013)

JSF take-off courtesy of U.S. ONR (Martens 2018).

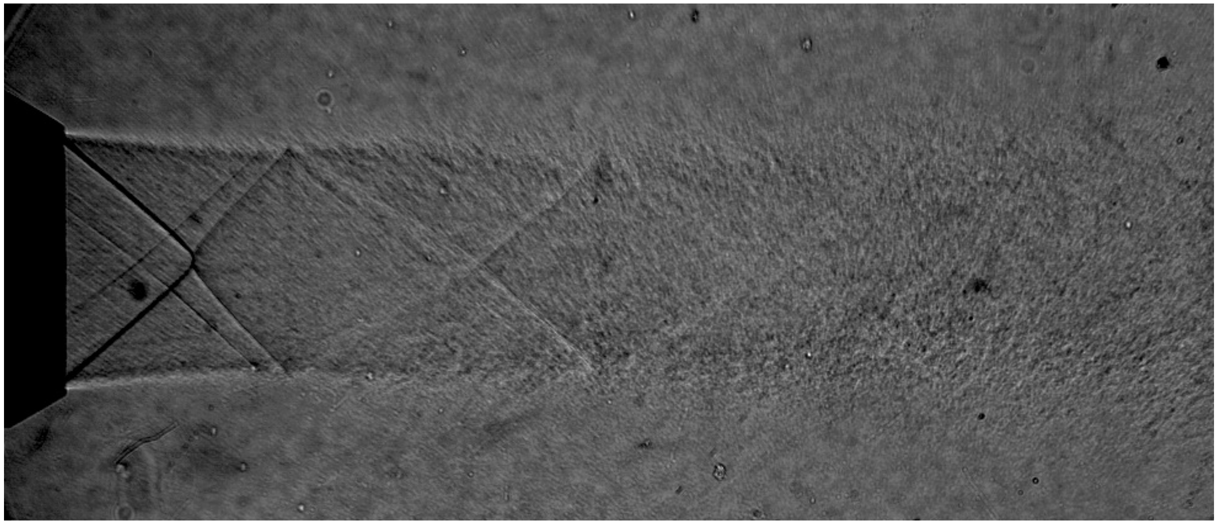
Jet Aerodynamics

Subsonic, Transonic, Supersonic, Shock Waves, Shear Layers, Boundary Layer, Inviscid, Transitional, Fully Turbulent, Incompressible, Compressible, etc.

Eggers, J. M., "Velocity Profiles and Eddy Viscosity Distributions Downstream of a Mach 2.22 Nozzle Exhausting to a Quiescent Air," NASA Technical Note D-3601, 1966.

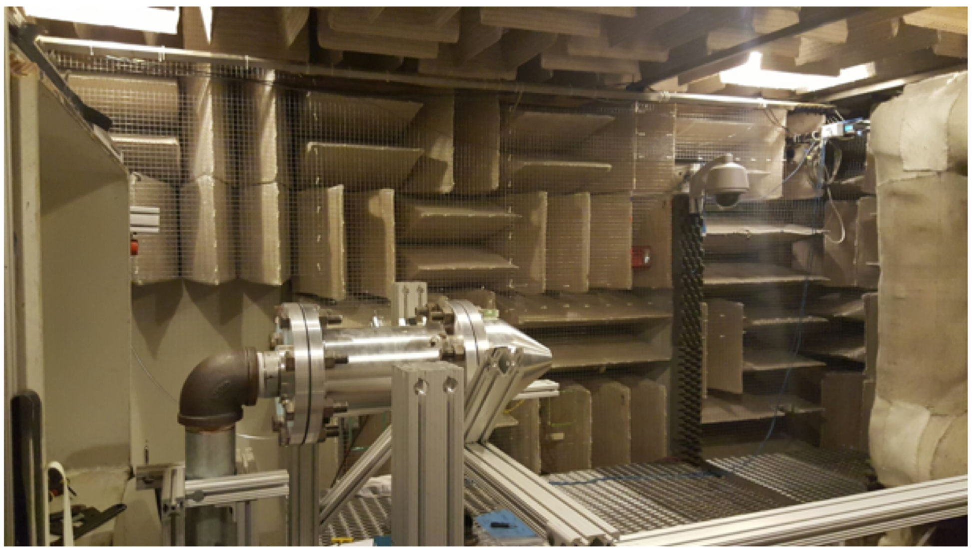


Zaman, K. B. M. Q., Bencic, T., Clem, M., and Fagan, A., "Shock-Induced Boundary Layer Separation in C-D Nozzles and Its Impact on Jet Noise," 49th AIAA Aerospace Sciences Meeting, Orlando, Florida, AIAA Paper 2011-1031, 2011.

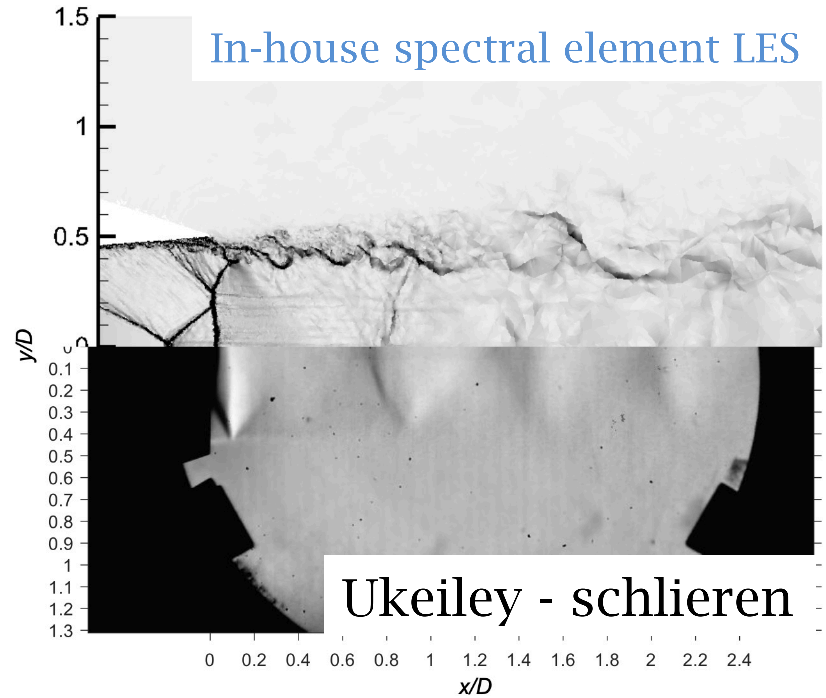


Experiments and Predictions

- Careful experiments and computations yield insight into high speed turbulent jets and acoustic radiation.
- Numerical simulation takes 30 days of computer time on 2,000 CPUs (Miller, 2020).

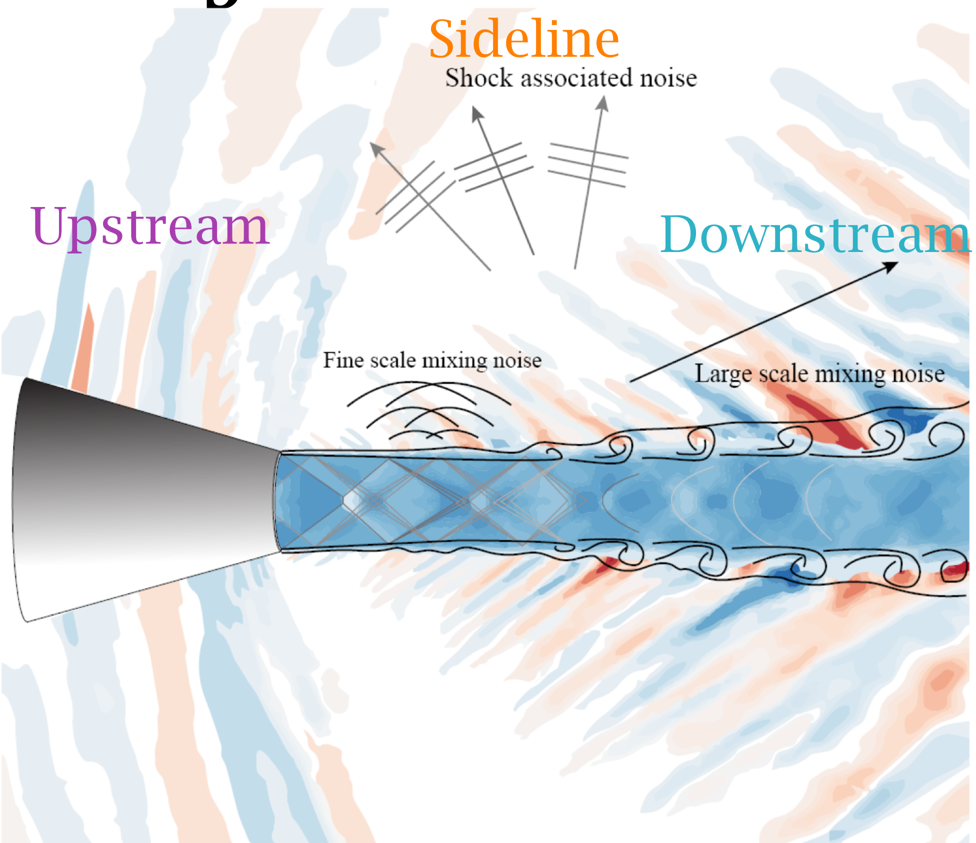


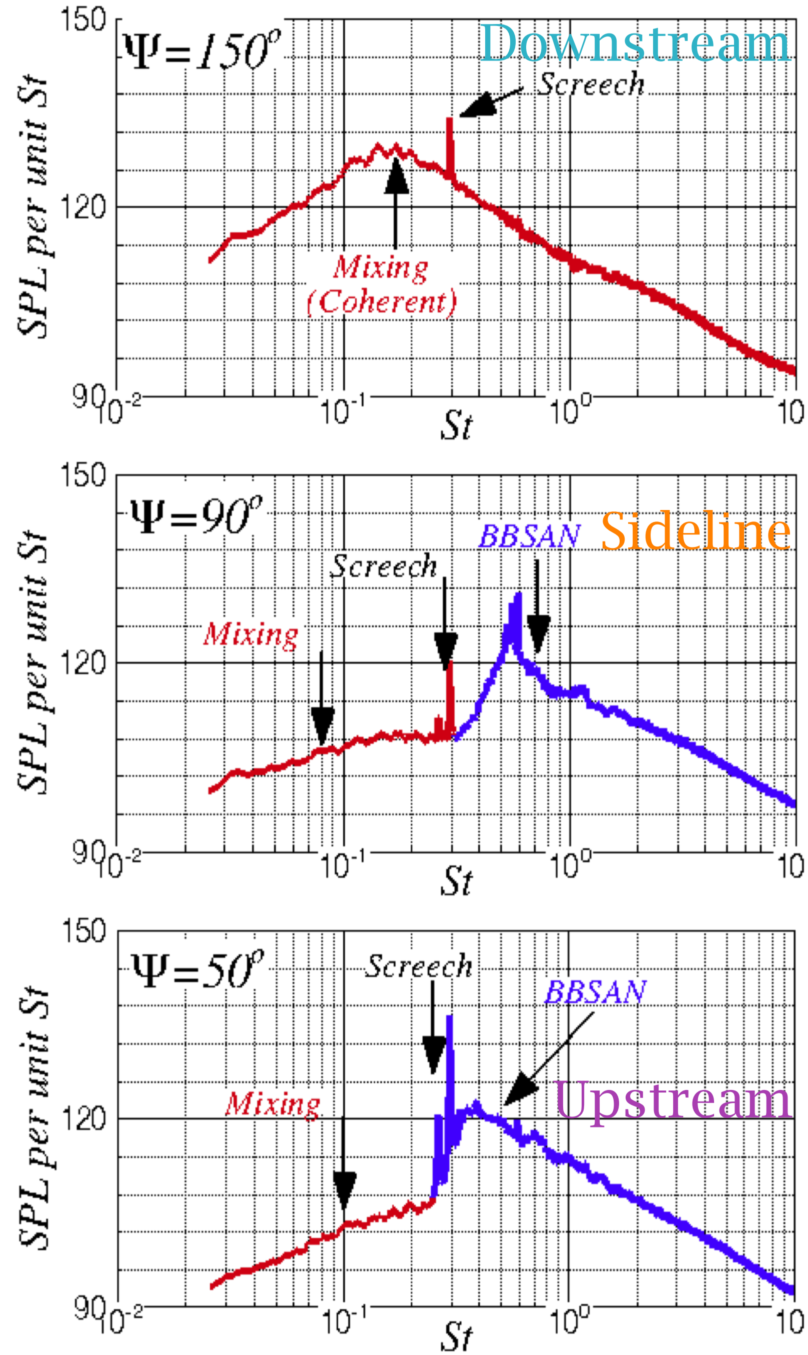
Prof. Ukeiley's - Unsteady Fluid Dynamics Group Anechoic Chamber with installed nozzle for studying jet turbulence and acoustics located in MAE-A.



Miller – CFD comparison with experiment
Ukeiley - schlieren, bottom.

Jet Noise





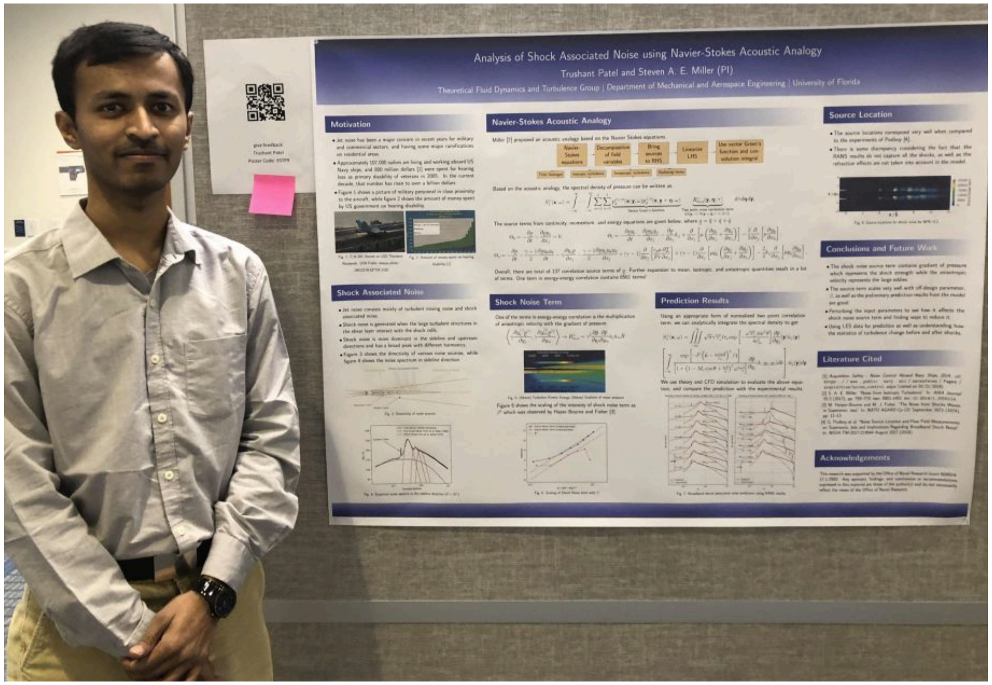
Turbulent Mixing

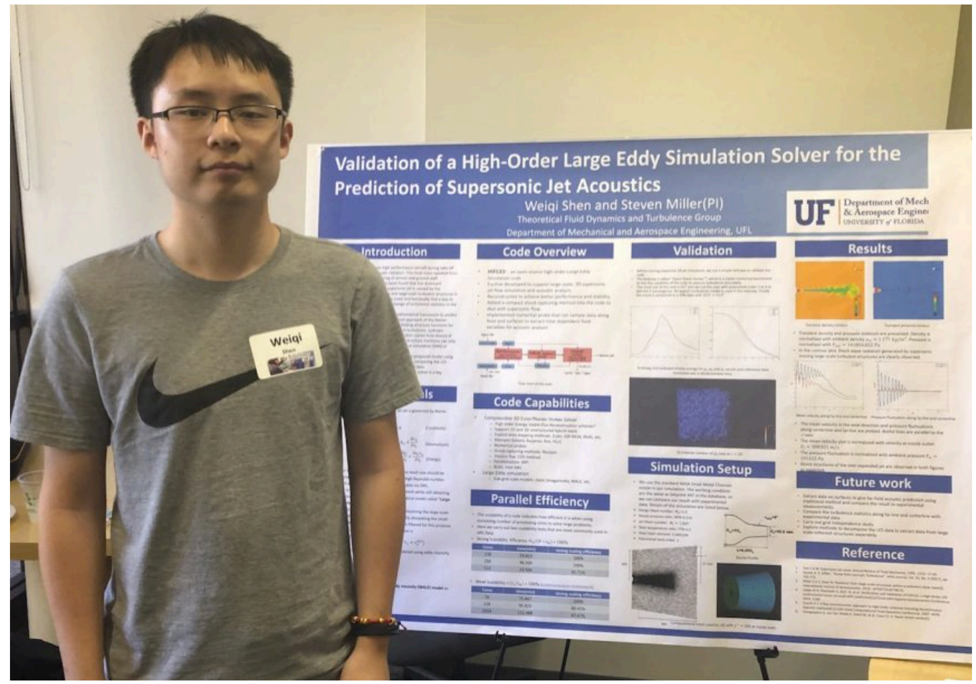
- Fine-Scale (incoherent)
- Large-Scale (coherent)

Shock-Associated

- Broadband
- Screech (tonal)

Special Acknowledgement for this part of my Research Program





Theoretics (math modeling)
Dr. Trushant Patel
Ph.D. Dec. 2020
Now at Naval Research Lab

Numerics (CFD - spectral LES)
Dr. Weiqi Shen
Ph.D. Dec. 2020
Now at Zhejiang University

ONR Jet Program - Objectives

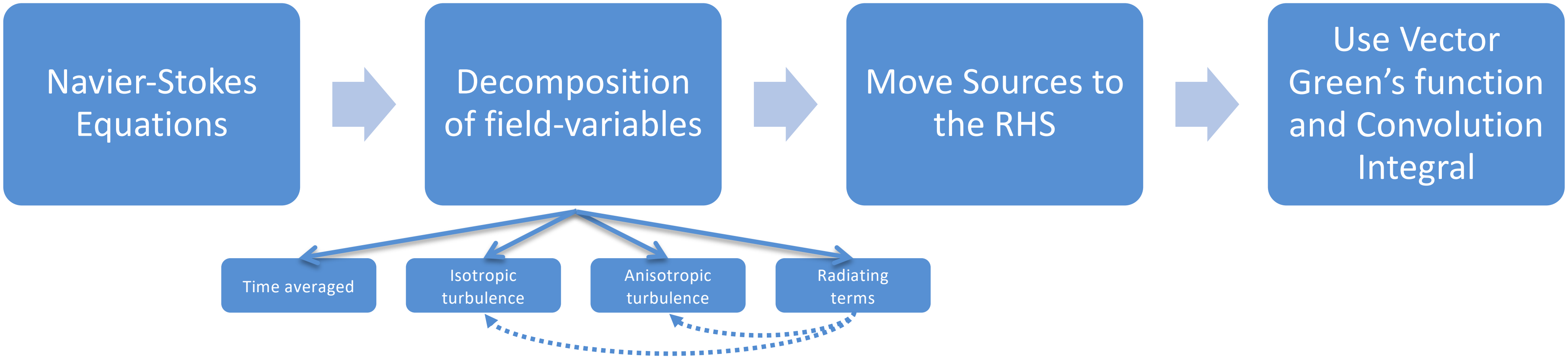
Program Objectives

1. Provide guidance and physical understanding to reduce near-field noise from high speed jet exhaust
2. Understand how turbulence statistics, wavenumber energy spectra, and the acoustic sources are changed as shear layer turbulence is altered by the shock cell structure
3. Perform and validate LES on off-design jets at operating conditions specified by the Navy to provide arguments for the mathematical models and capture turbulent statistics
4. Vary the nozzle geometry / operating conditions to ascertain the effect on the statistics of turbulence and radiated noise
5. Complete the semi-analytical model for the anisotropic portion of the turbulent field and connect the entire aeroacoustic model to LES

Bonus Additional Outcomes

Exact source models in time-domain and spectral domain for fine-scale mixing noise and broadband shock-associated noise.

Mathematical Model Overview, Solution, Sources



- We can write the spectral density of pressure as

$$S_4^{\perp}(\boldsymbol{x},\omega) = \int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty} \sum_{m=0}^{4} \sum_{n=0}^{4} p_g^{\perp,m}(\boldsymbol{x};\boldsymbol{y},\omega)\, p_g^{*\perp,n}(\boldsymbol{x};\boldsymbol{y}+\boldsymbol{\eta},\omega)\, R_{m,n}^{\perp}(\boldsymbol{y},\boldsymbol{\eta},\tau)\, d\tau\, d\boldsymbol{\eta}\, d\boldsymbol{y}$$

Vector Green's function

Two point cross-correlation

$$\langle \Theta_m(\boldsymbol{y},\tau), \Theta_n(\boldsymbol{y}+\boldsymbol{\eta},\tau+\Delta\tau) \rangle$$

- Source terms are shown below, where $q = \bar{q} + \breve{q} + \hat{q}$

$$\Theta_0 = -\frac{\partial \rho}{\partial t} - \frac{\partial \rho}{\partial x_j} \qquad \Theta_i = -\frac{\partial \rho\, u_i}{\partial t} - \frac{\partial \rho\, u_i\, u_j}{\partial x_j} + \frac{\partial}{\partial x_j}\left(\mu\left[\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right]\right) - \frac{2}{3}\frac{\partial}{\partial x_j}\left(\mu\frac{\partial u_k}{\partial x_k}\right) - \frac{\partial p}{\partial x_j}\delta_{ij}$$

$$\Theta_4 = -\frac{\partial p}{\partial t} - \frac{\gamma-1}{2}\frac{\partial \rho\, u_k\, u_k}{\partial t} - \gamma\frac{\partial u_j\, p}{\partial x_j} - \frac{\gamma-1}{2}\frac{\partial \rho\, u_j\, u_k\, u_k}{\partial x_j} + (\gamma-1)\frac{\partial}{\partial x_j}\left(\frac{c_p \mu}{Pr}\frac{\partial}{\partial x_j}T\right)$$
$$+(\gamma-1)\frac{\partial}{\partial x_j}\left[\mu u_i\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] - \frac{2}{3}\delta_{ij}\frac{\partial}{\partial x_j}\left[\mu u_i \frac{\partial u_k}{\partial x_k}\right]$$

Overview of Program – Theory

Navier-Stokes equations govern the dynamics of fluid turbulence

We decompose the field variables as

$$q = \bar{q} + \tilde{q} + \tilde{\tilde{q}} + q' + q''$$

Overbar - time-averaged base flow
Tilde – highly coherent anisotropic turbulent fluctuations
Double Tilde – "incoherent" isotropic turbulent fluctuations
Single Prime - radiating component due to anisotropic turbulence
Double prime – radiating component due to isotropic turbulence

Overview of Program – Theory

Resultant equations take the form (cont. equation example)

$$\frac{\partial \overline{\rho} + \tilde{\rho} + \tilde{\tilde{\rho}} + \rho' + \rho''}{\partial t} + \frac{\partial}{\partial x_j}\left[\left(\overline{\rho} + \tilde{\rho} + \tilde{\tilde{\rho}} + \rho' + \rho''\right)\left(\overline{u}_j + \tilde{u}_j + \tilde{\tilde{u}}_j + u_j' + u_j''\right)\right] = 0$$

Rearranging NSE results in sources that are NSE oper. w/o acoustics

$$\Theta_0 = -\frac{\partial \underline{\rho}}{\partial t} - \frac{\partial \underline{\rho} \underline{u}_j}{\partial x_j}$$

$$\Theta_i = -\frac{\partial}{\partial t}\left[\underline{\rho}\underline{u}_i\right] - \frac{\partial}{\partial x_j}\left[\underline{\rho}\underline{u}_i\underline{u}_j\right] + \frac{\partial}{\partial x_j}\left\{\mu\left[\frac{\partial \underline{u}_i}{\partial x_j} + \frac{\partial \underline{u}_j}{\partial x_i}\right]\right\} - \frac{2}{3}\frac{\partial}{\partial x_j}\left\{\mu\frac{\partial}{\partial x_k}\underline{u}_k\right\} - \frac{\partial \underline{p}}{\partial x_j}\delta_{ij}$$

$$\Theta_4 = -\frac{\partial \underline{p}}{\partial t} - \frac{\gamma - 1}{2}\frac{\partial \underline{\rho}\underline{u}_k\underline{u}_k}{\partial t} - \gamma\frac{\partial \underline{u}_j\underline{p}}{\partial x_j} - \frac{\gamma - 1}{2}\frac{\partial \underline{\rho}\underline{u}_j\underline{u}_k\underline{u}_k}{\partial x_j} + (\gamma - 1)\frac{\partial}{\partial x_j}\left(\frac{c_p\mu}{\mathcal{P}r}\frac{\partial}{\partial x_j}\underline{T}\right)$$
$$+ (\gamma - 1)\frac{\partial}{\partial x_j}\left[\mu\underline{u}_i\left(\frac{\partial \underline{u}_i}{\partial x_j} + \frac{\partial \underline{u}_j}{\partial x_i}\right)\right] - \frac{2}{3}\delta_{ij}\frac{\partial}{\partial x_j}\left[\mu\underline{u}_i\frac{\partial \underline{u}_k}{\partial x_k}\right]$$

where $\underline{q} = \overline{q} + \tilde{q} + \tilde{\tilde{q}}$ We now seek a statistical solution

Overview of Program – Theory

Solution takes the form

$$q_k^{\perp}(\boldsymbol{x},t)=\int_{-\infty}^{\infty}\dots\int_{-\infty}^{\infty}\sum_{n=0}^{4}\boldsymbol{q}_{g,k}^{\perp n}(\boldsymbol{x},t;\boldsymbol{y},\tau)\,\Theta_n(\boldsymbol{y},\tau)\,d\tau d\boldsymbol{y}$$

Spectral density of $k=(\rho,u_i,p)$ is

$$S_k^{\perp}(\boldsymbol{x},\omega)=\int_{-\infty}^{\infty}\dots\int_{-\infty}^{\infty}\sum_{m=0}^{4}\sum_{n=0}^{4}\hat{q}_{g,k}^{*\perp m}(\boldsymbol{x};\boldsymbol{y},\omega)\,\hat{q}_{g,k}^{\perp n}(\boldsymbol{x};\boldsymbol{y}+\boldsymbol{\eta},\omega)\,R_{m,n}^{\perp}(\boldsymbol{y},\boldsymbol{\eta},\tau)\,d\tau d\boldsymbol{\eta} d\boldsymbol{y}$$

With linear acoustics we can divide sources and sound

$S_k^{\perp}(\boldsymbol{x},\omega)=S_k'(\boldsymbol{x},\omega)+S_k''(\boldsymbol{x},\omega)$ and $R_{m,n}^{\perp}=R_{m,n}'(\boldsymbol{y},\boldsymbol{\eta},\tau)+R_{m,n}''(\boldsymbol{y},\boldsymbol{\eta},\tau)$

Must model or ascertain sources… $\boldsymbol{\Theta_i}$

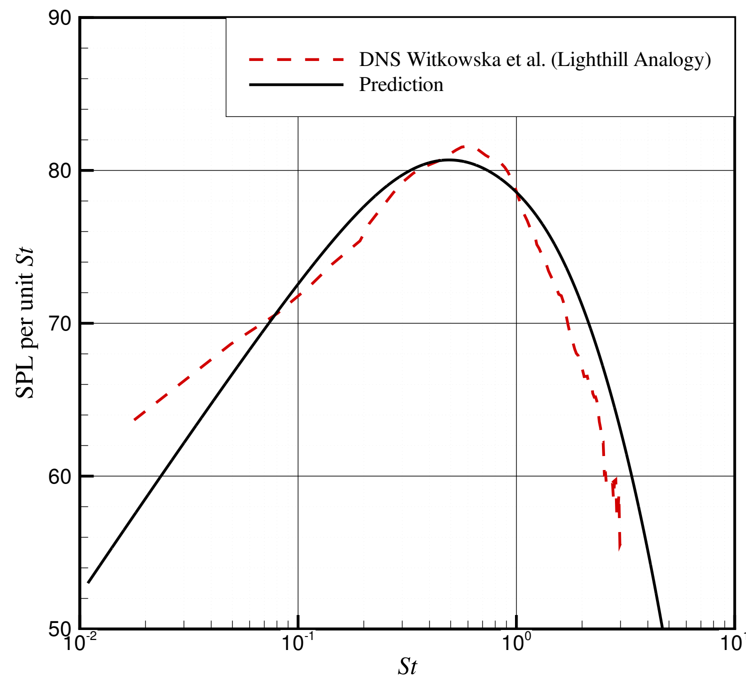
Statistical (Analytical) Prediction of Fine-Scale Noise Compared to DNS

No CFD used in prediction

Locally homogeneous isotropic source modeling

Find two-point cross-correlations from ‘Russian school’ (Kolmogorov and followers)

Modeled source term for continuity – energy two-point cross-correlation magnitude



Comparison of analytical theory with experiment.

$$R^{\perp}_{0,4}\left(\boldsymbol{y},\boldsymbol{\eta},\tau\right) \approx \left\{ \left(-\frac{3\left(\overline{\rho}+\widehat{\langle\tilde{\rho}\rangle}\right)\widehat{\langle\tilde{u}\rangle}}{l} - \frac{\left(\overline{\rho}+\widehat{\langle\tilde{\rho}\rangle}\right)}{\tau} \right) \left(-\frac{3\gamma\widehat{\langle\tilde{u}\rangle}\left(\overline{p}+\widehat{\langle\tilde{p}\rangle}\right)}{l} - \frac{6\overline{\mu}\widehat{\langle\tilde{u}\rangle}^{2}}{l^{2}} + \frac{3c_{p}\widehat{\langle\tilde{T}\rangle}\left(\gamma-1\right)\overline{\mu}}{Prl^{2}} \right.\right.$$
$$\left.\left. + \frac{9\overline{\mu}\left(\gamma-1\right)\widehat{\langle\tilde{u}\rangle}^{2}}{l^{2}} - \frac{9\left(\gamma-1\right)\left(\overline{\rho}+\widehat{\langle\tilde{\rho}\rangle}\right)\widehat{\langle\tilde{u}\rangle}^{3}}{2l} - \frac{\widehat{\langle\tilde{p}\rangle}}{\tau} - \frac{3\left(\gamma-1\right)\left(\overline{\rho}+\widehat{\langle\tilde{\rho}\rangle}\right)\widehat{\langle\tilde{u}\rangle}^{2}}{2\tau} \right) \right\} \boldsymbol{R}$$

Identification of Shock Noise Term(s)

Expansion of all two-point cross-correlation results in many terms → 6561 terms

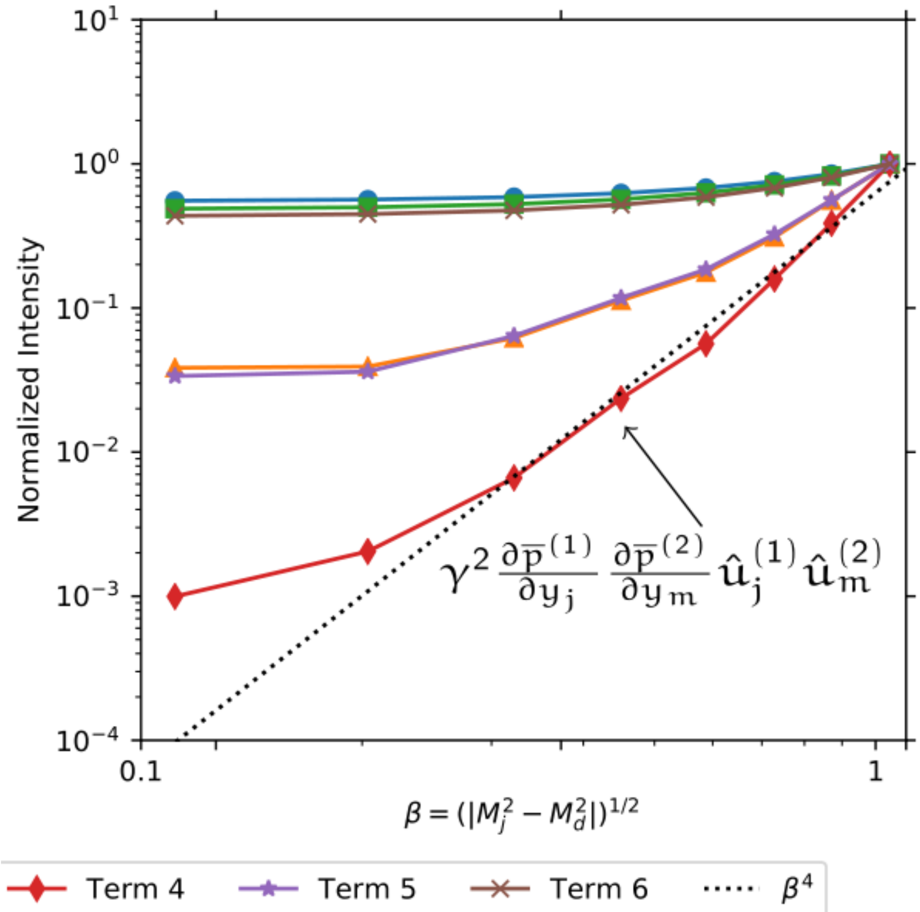
$$\Theta_4 = -\frac{\partial \underline{p}}{\partial t} - \frac{\gamma-1}{2}\frac{\partial \underline{\rho}\,\underline{u_k}\,\underline{u_k}}{\partial t} - \gamma\frac{\partial \underline{u_j}\,\underline{p}}{\partial x_j} - \frac{\gamma-1}{2}\frac{\partial \underline{\rho}\,\underline{u_j}\,\underline{u_k}\,\underline{u_k}}{\partial x_j} + (\gamma-1)\frac{\partial}{\partial x_j}\left(\frac{c_p\mu}{Pr}\frac{\partial}{\partial x_j}\underline{T}\right)$$
$$+(\gamma-1)\frac{\partial}{\partial x_j}\left[\mu\underline{u_i}\left(\frac{\partial \underline{u_i}}{\partial x_j}+\frac{\partial \underline{u_j}}{\partial x_i}\right)\right] - \frac{2}{3}\delta_{ij}\frac{\partial}{\partial x_j}\left[\mu\underline{u_i}\frac{\partial \underline{u_k}}{\partial x_k}\right]$$

Shock-associated noise is generated when the large-scale turbulence interacts with the shock-cell structure.

BBSAN Source

$$\left\langle \gamma\frac{\partial \underline{u_j}^{(1)}\,\underline{p}^{(1)}}{\partial y_j}, \gamma\frac{\partial \underline{u_m}^{(2)}\,\underline{p}^{(2)}}{\partial y_m} \right\rangle$$

Multiplication of 'anisotropic' velocity with the gradient of pressure.



Summary of Source Terms

Broadband shock-associated noise (BBSAN) source

Time-domain

$$R_{BBSAN} = \gamma^2 \left\langle \frac{\partial \underline{u}_j^{(1)} \underline{p}^{(1)}}{\partial y_j}, \frac{\partial \underline{u}_m^{(2)} \underline{p}^{(2)}}{\partial y_m} \right\rangle \rightarrow \gamma^2 \frac{\partial \bar{p}^{(1)}}{\partial y_j} \frac{\partial \bar{p}^{(2)}}{\partial y_m} \hat{u}_j^{(1)} \hat{u}_m^{(2)} \hat{R}$$

Fine-scale mixing noise source

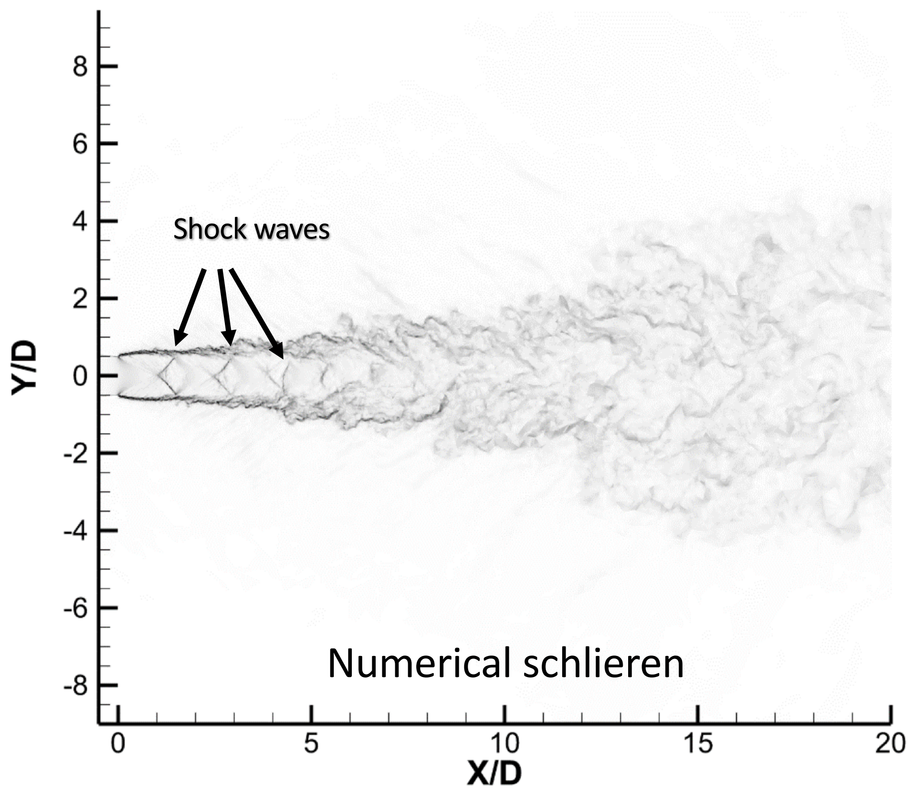
$$\mathrm{R_{FSMN}} = (\gamma - 1)^2 \left\langle \frac{\mathrm{D}\bar{\rho}^{(1)} \mathrm{K}_s^{(1)}}{\mathrm{D}\tau}, \frac{\mathrm{D}\bar{\rho}^{(2)} \mathrm{K}_s^{(2)}}{\mathrm{D}\tau} \right\rangle \rightarrow (\gamma - 1)^2 \frac{\bar{\rho}^2 \mathrm{K}_s^2}{\tau_s^2} \breve{\mathrm{R}}$$

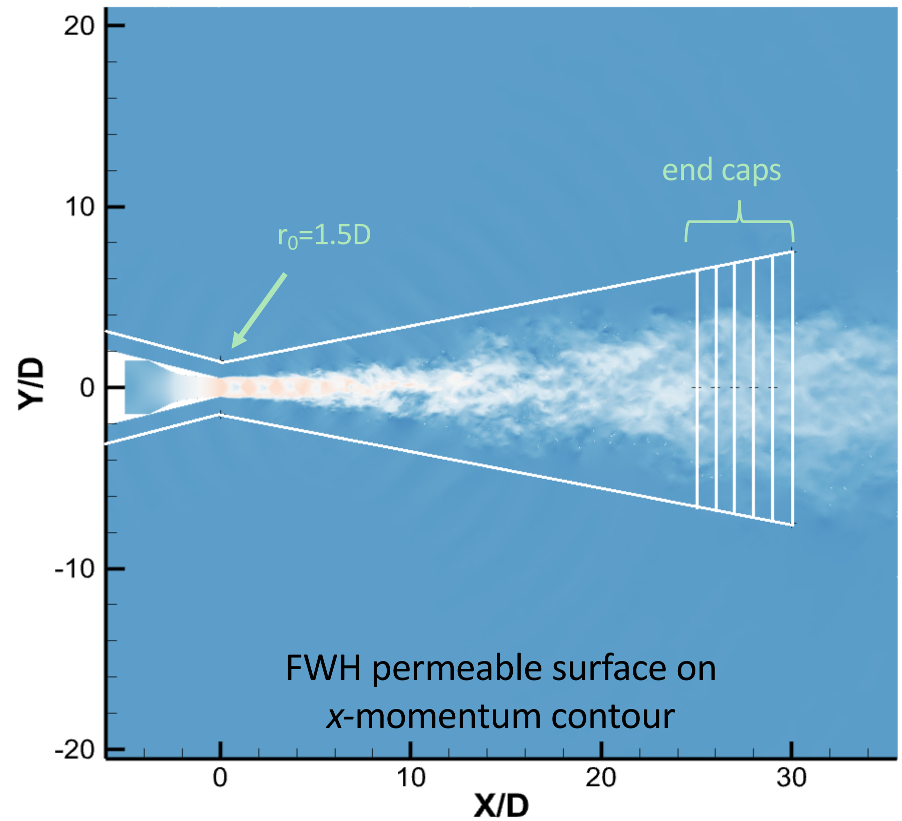
Time-domain

But how to evaluate these terms? If we knew them exactly we would already have solved the Navier-Stokes equations for turbulent flows …

- We can find them analytically (statistically) for specific problems
- We can connect them to Reynolds-averaged Navier-Stokes (RANS)
- We can connect them to large-eddy simulation (LES)

LES Simulations of Turbulent Jets





2/3D Euler/ Navier-Stokes solver

High-order Energy-Stable Flux Reconstruction (ESFR) schemes

Support 2D and 3D unstructured hybrid mesh: Quad, Tri, Tetra, Prism, Hexa

Riemann solvers: Rusanov, Roe

Time scheme: Runge-Kutta 4-5th order

LES subgrid-scale models: Smagorinsky, WALE, etc.

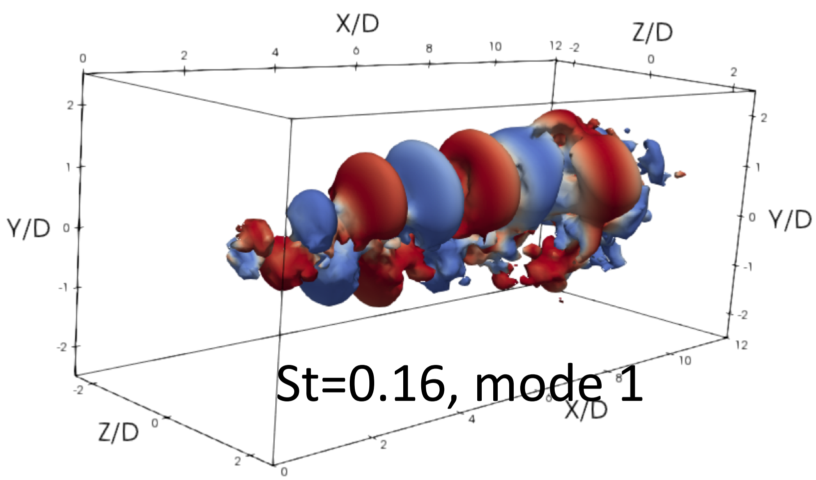
HLLC Riemann solver

Shock capturing: Persson's shock detector and exponential filter

Decomposition of LES Results

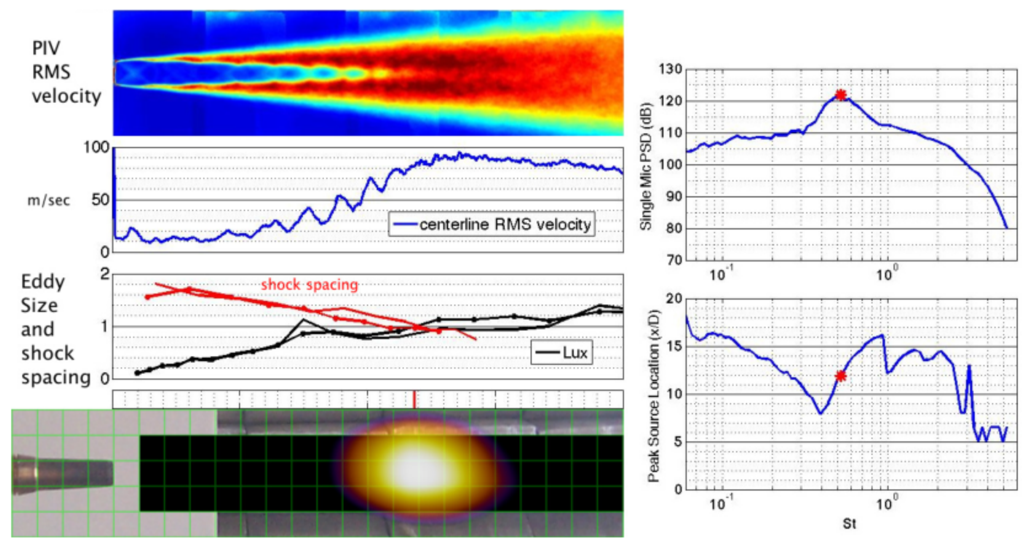
Spectral POD is used to extract structures that are coherent

Volume: $12D \times 5D \times 5D$, Spacing: 0.1D,
Variable: pressure

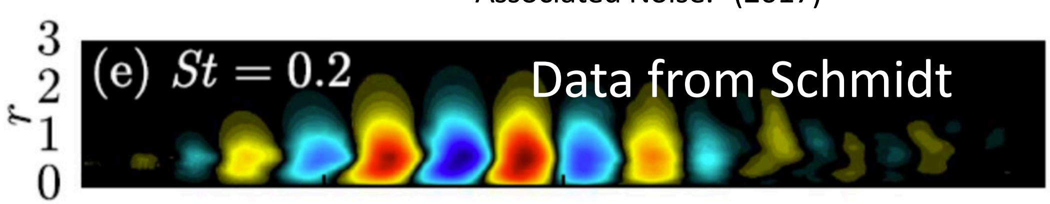


Normalized pressure magnitude iso-surface (0.003) colored with real part to indicate phase.

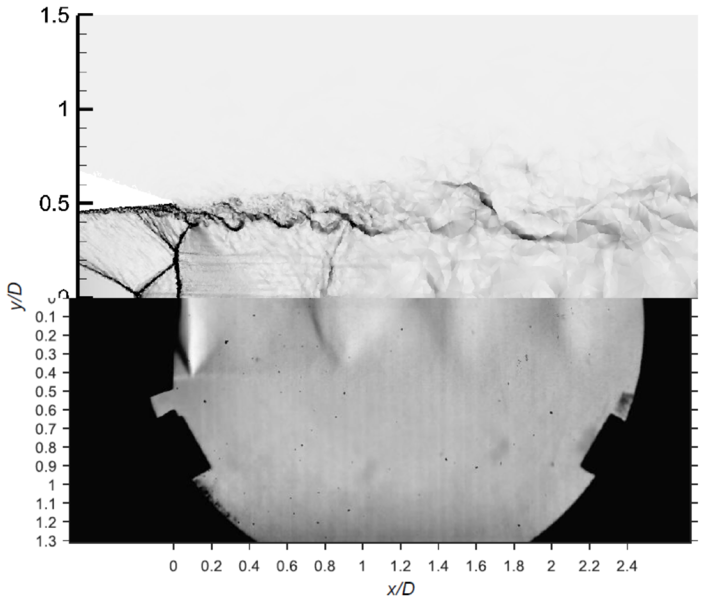
Experimental results of NASA GRC from Podboy are used to guide our source modeling and decomposition validation



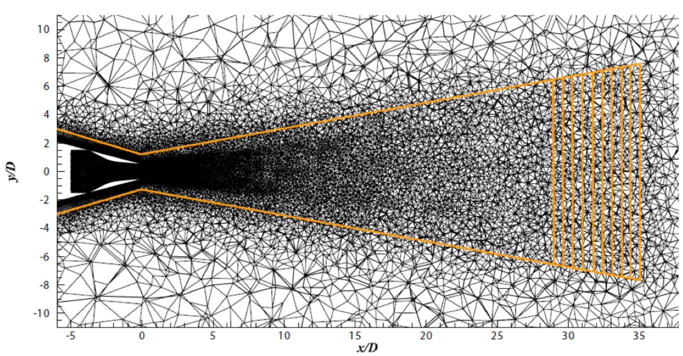
Podboy, G., et al., "Noise Source Location and Flow Field Measurements on Supersonic Jets and Implications Regarding Broadband Shock Associated Noise." (2017)

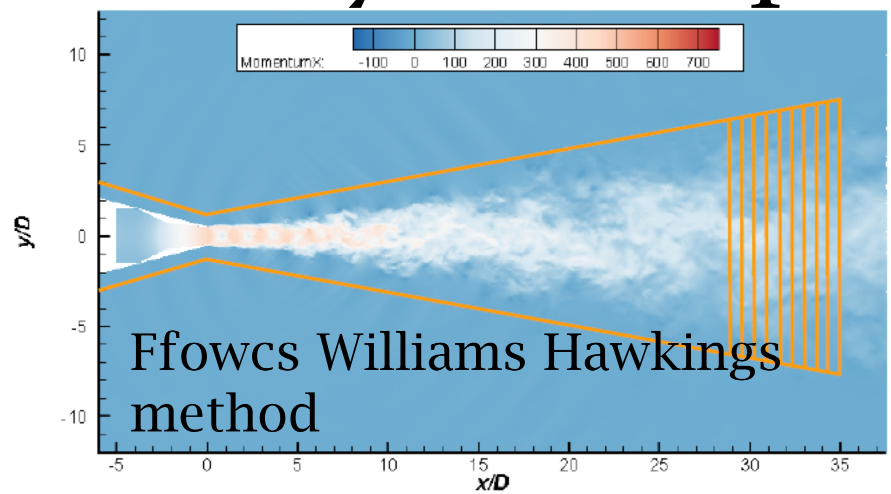


Examples of LES and Collaboration with Prof. Ukeiley's Group

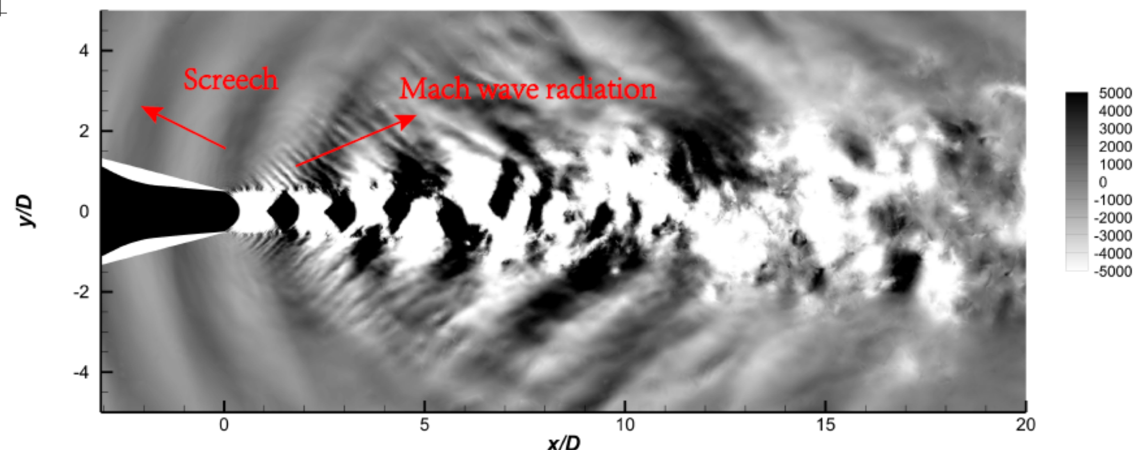


Recent schlieren of UF SERDP nozzle captured by Prof. Ukeiley's lab





Ffowcs Williams Hawkings method



Direct comparisons of experiments with LES for further validation

Prediction Validation
Shock-Associated Noise (BBSAN)

The term that scales as β^4, the product of gradient of mean pressure and the large-scale velocity fluctuations

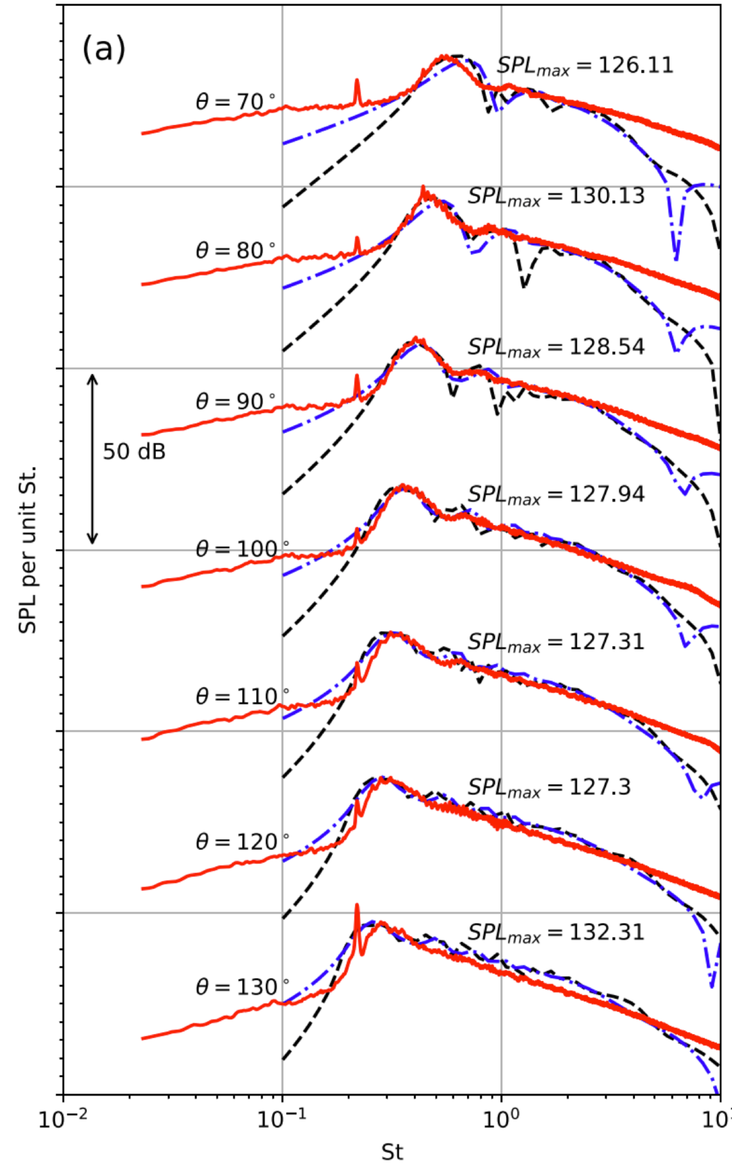
Time-domain source

$$\Theta_s = -\gamma \hat{u}_j \frac{\partial \bar{p}}{\partial y_j}$$

Spectral source

$$R_{BBSAN} = \gamma^2 \left\langle \frac{\partial \underline{u}_j^{(1)} \underline{p}^{(1)}}{\partial y_j}, \frac{\partial \underline{u}_m^{(2)} \underline{p}^{(2)}}{\partial y_m} \right\rangle$$

- Shen, W., Patel, T. K., and Miller, S. A. E., "A Time Domain Approach for Shock Noise Prediction with Decomposition Analyses of Large-Scale Coherent Turbulent Structures in Jets," Journal of Sound and Vibration, Vol., 499, 2021. DOI: 10.1016/j.jsv.2021.115996
- Patel, T. and Miller S. A. E., "Statistical Sources for Broadband Shock-Associated Noise using the Navier-Stokes Equations," Journal of the Acoustical Society of America, Vol. 146, No. 4339, 2020, pp. 4339-4351. DOI: 10.1121/1.5139216



Prediction Validation
Fine-Scale Mixing Noise

Fine-scale mixing noise sources
Spectral terms derived from time-domain term

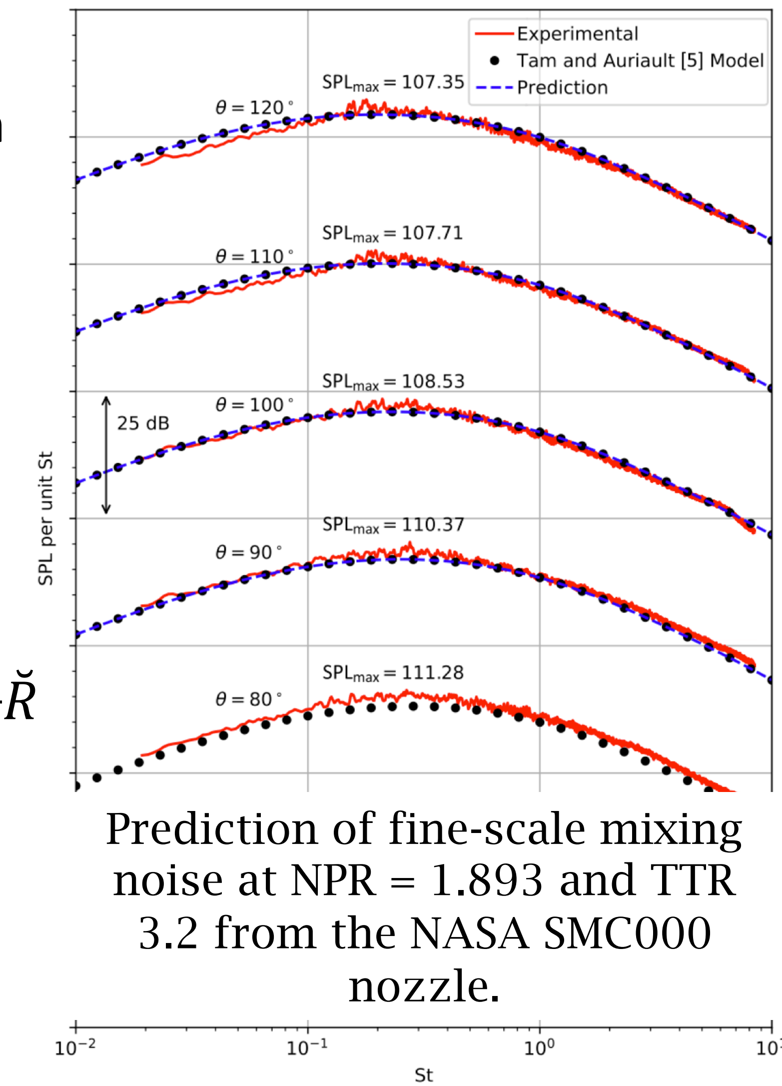
$$R^{(8)} = \left\langle \frac{D\breve{p}^{(1)}}{Dt}, \frac{D\breve{p}^{(2)}}{Dt} \right\rangle \approx \frac{\bar{\rho}^2 K_s^2}{\tau_s^2} \breve{R}$$

$$R^{(9)} = \left\langle \frac{D\breve{p}^{(1)}}{Dt}, \frac{D\bar{\rho}^{(2)}\breve{u}_k^{(2)}\breve{u}_k^{(2)}}{Dt} \right\rangle \approx \frac{\bar{\rho}^2 K_s^2}{\tau_s^2} \breve{R}$$

$$R^{(10)} = \left\langle \frac{D\bar{\rho}^{(1)}\breve{u}_k^{(1)}\breve{u}_k^{(1)}}{Dt}, \frac{D\bar{\rho}^{(2)}\breve{u}_k^{(2)}\breve{u}_k^{(2)}}{Dt} \right\rangle \approx \frac{\bar{\rho}^2 K_s^2}{\tau_s^2} \breve{R}$$

Ten terms contribute, but these are dominant

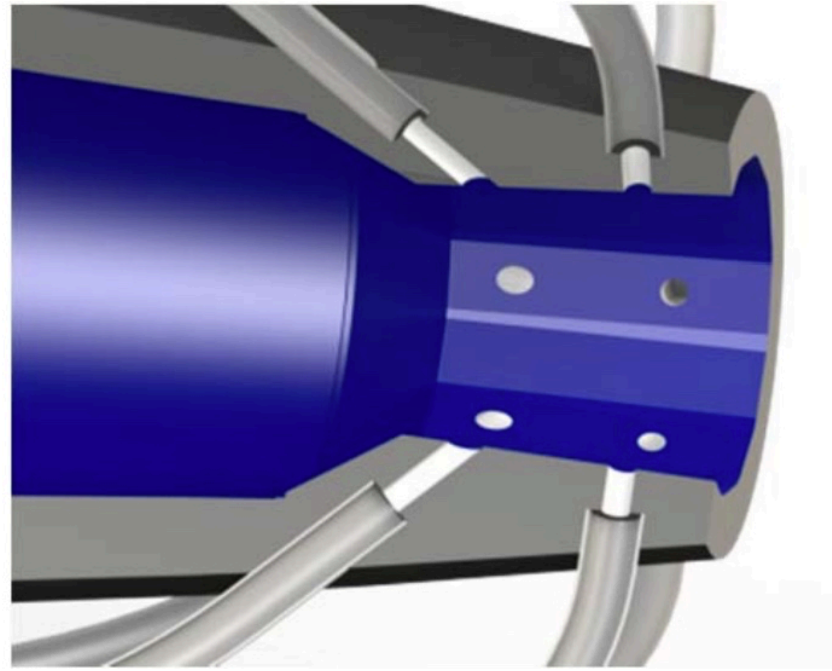
Patel, T. K. and Miller, S. A. E., “Source of Fine-Scale Turbulent Mixing Noise Using the Navier–Stokes Equations,” AIAA Journal, 2021. DOI: 10.2514/1.J059647



Prediction of fine-scale mixing noise at NPR = 1.893 and TTR 3.2 from the NASA SMC000 nozzle.

Example - Noise Prediction and Reduction Study - Fluidic Injection

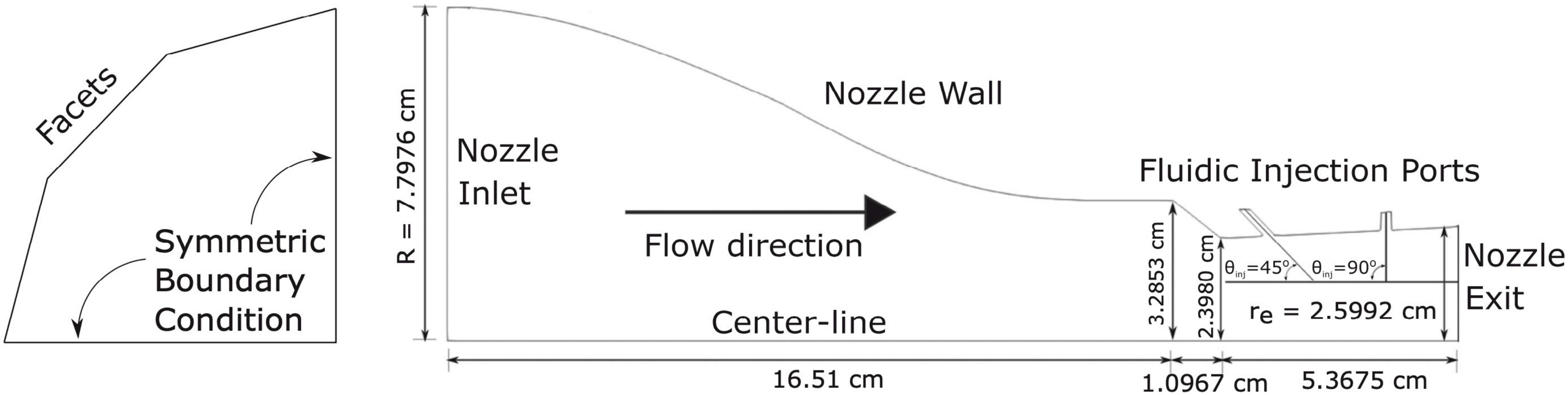
- Example - apply our equations to make noise predictions and analyze source distribution
- Example is fluidic injection into nozzles of Penn State Aerospace, led by Prof. P. Morris
- Core idea is to alter flow-field via injection of bypass into divergent nozzle section

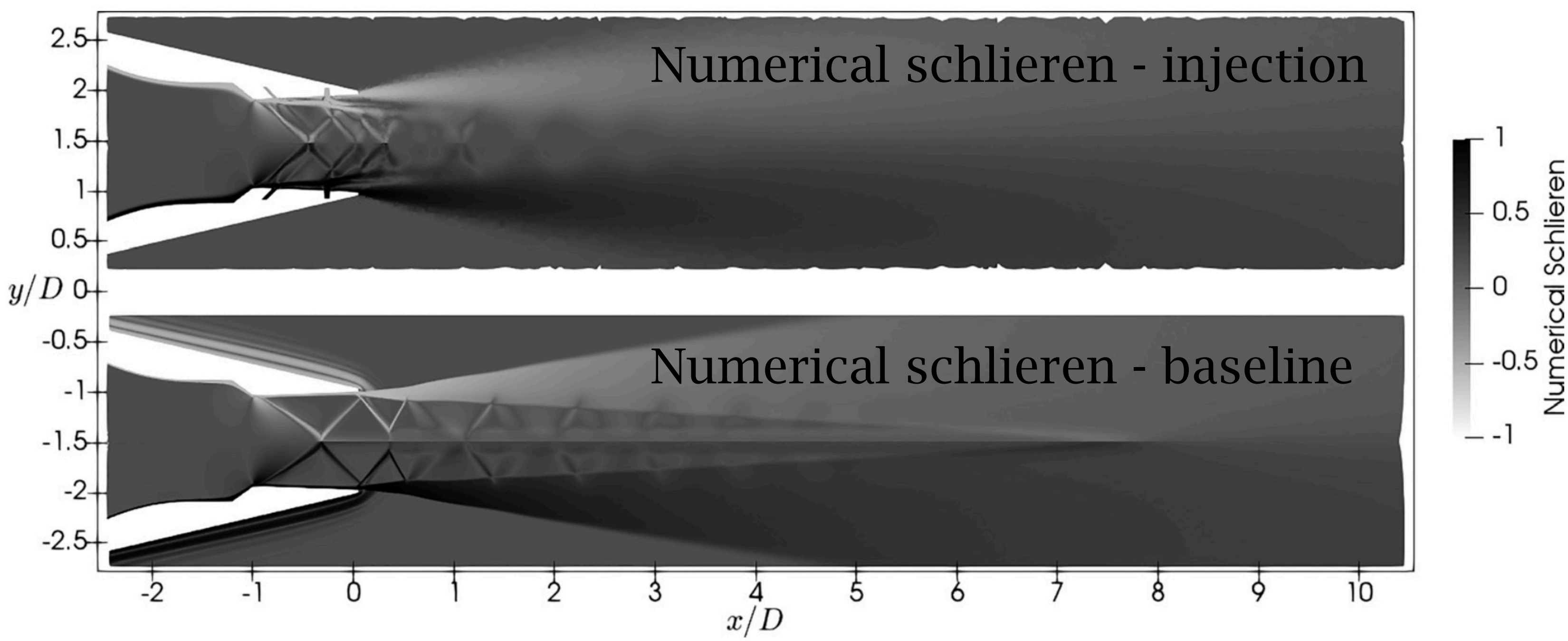


Morris et al., Penn State, 2014.

Based on fluidic injection experiments of P. J. Morris, D. K. McLaughlin, R. W. Powers, and, and M. J. Kapusta, “Prediction, experiments and optimization of high-speed jet noise reduction using fluidic inserts,” in Proceedings of the 50th AIAA/ASME/SAE/ ASEE Joint Propulsion Conference, Cleveland, OH (July 28–30, 2014), AIAA Paper No. 2014-3737.

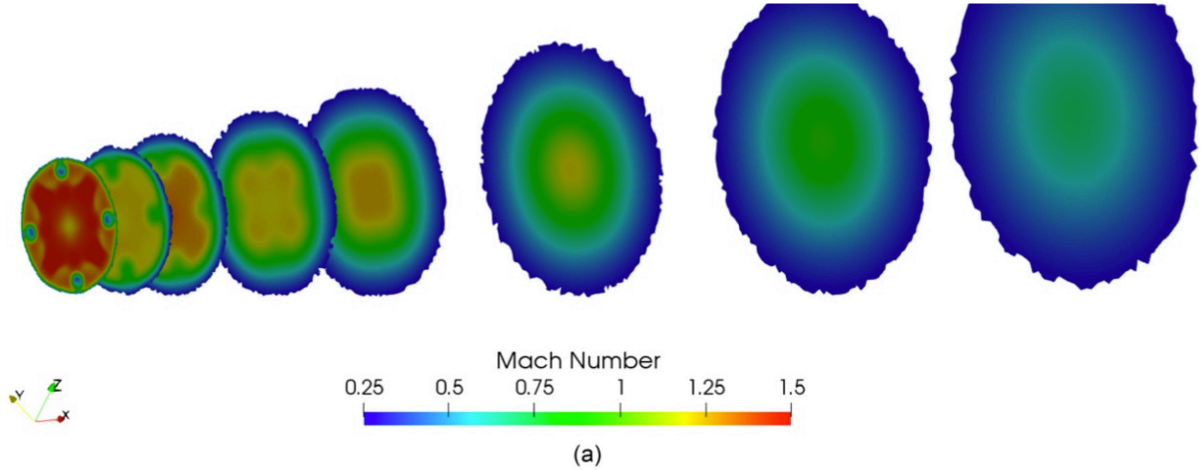
Example - Noise Prediction and Reduction Study - Fluidic Injection





Example - Noise Prediction and Reduction Study - Fluidic Injection

CFD - Mach number contours – cross-stream planes



CFD - Turbulent kinetic energy contours – cross-stream planes

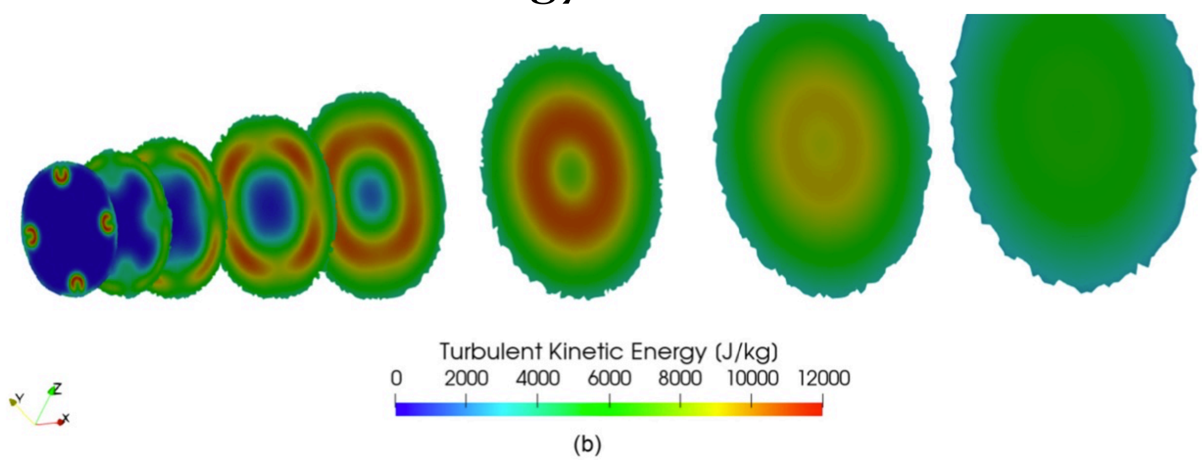
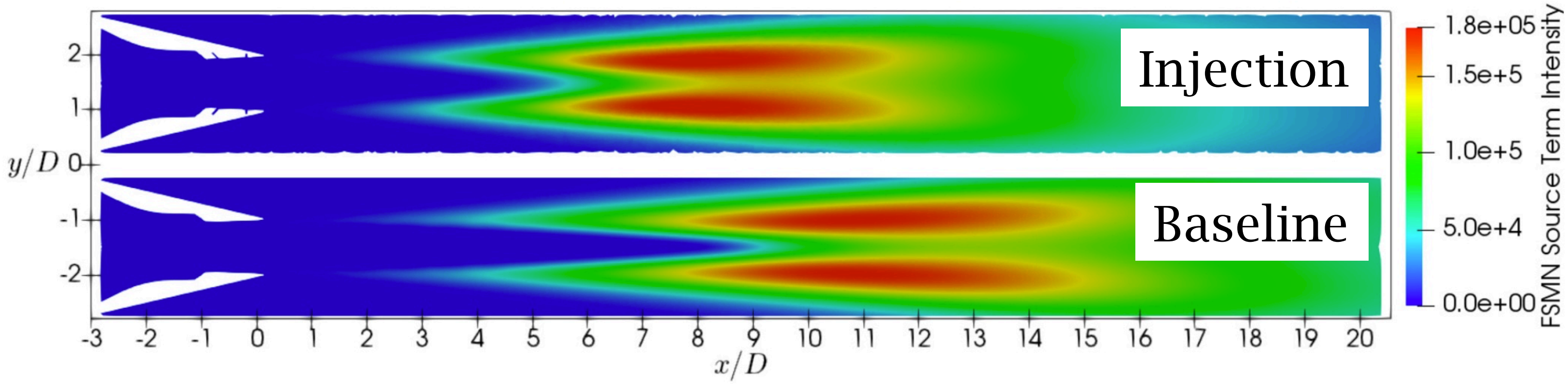
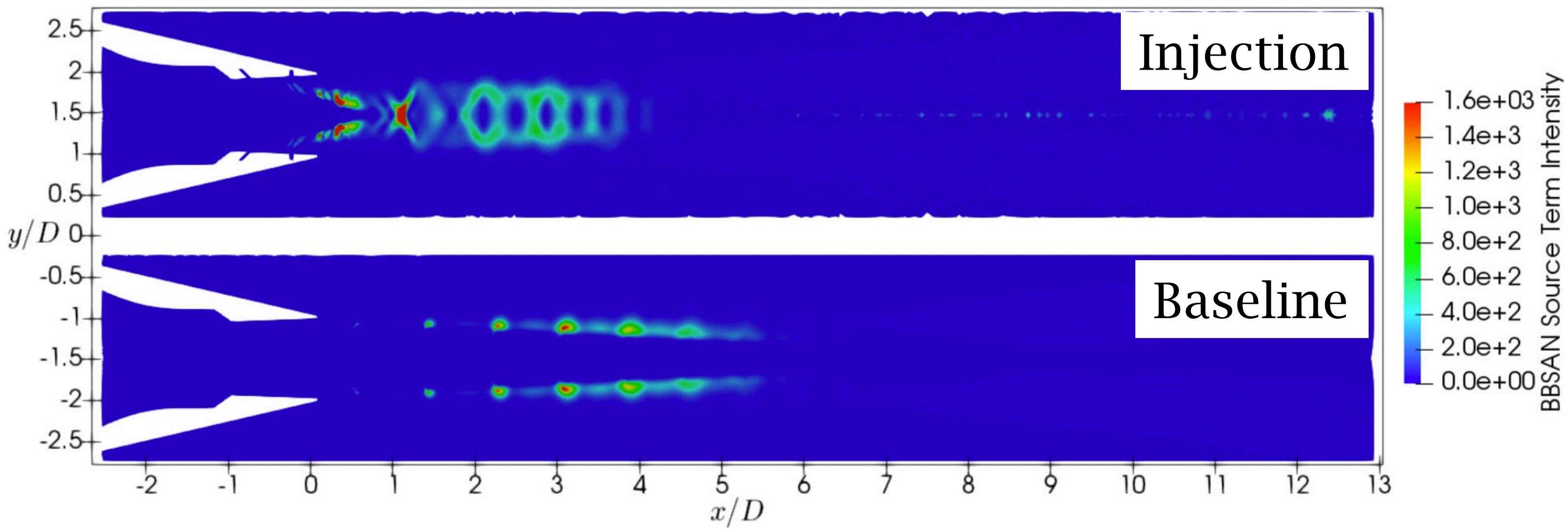


FIG. 14. (Color online) Cross-stream contours of at different axial locations, $x/D = 0$, 0.5, 1.0, 2.0, 3.0, 5.0, 7.5, and 10.0 for the fluidic insert nozzle operating at NPR = 2.750 and TTR = 3.0. (a) Contours of Mach number. (b) Contours of turbulent kinetic energy.

Example - Noise Prediction and Reduction Study - Fluidic Injection



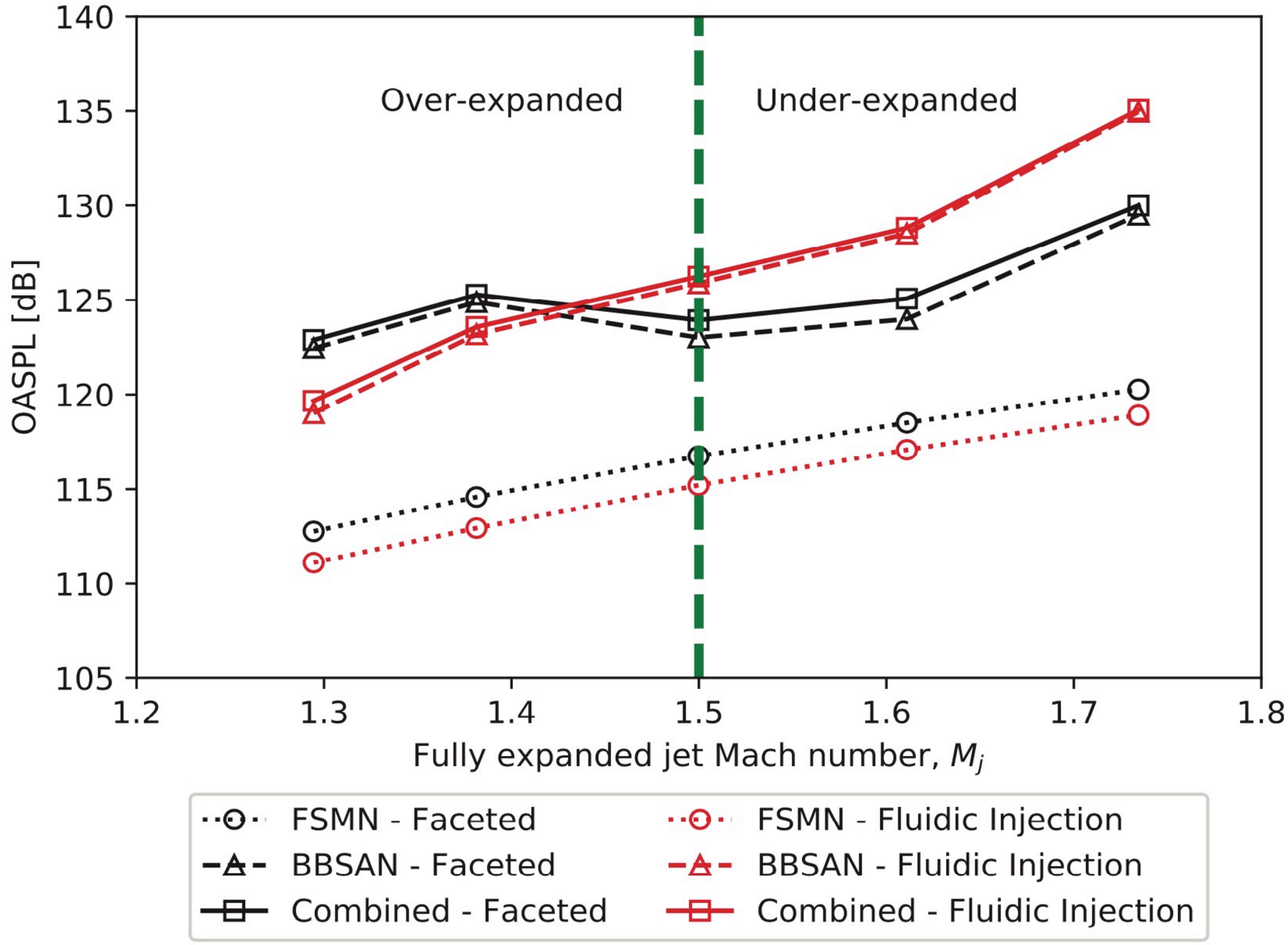
Source contours of fine-scale mixing noise



Source contours of BBSAN

FIG. 16. (Color online) Comparison of the contours of FSMN and BBSAN source locations between (top) the fluidic injection nozzle and (bottom) the faceted nozzle operating at NPR = 2.750 and TTR = 3.0. (a) FSMN source locations. (b) BBSAN source locations.

Example - Noise Prediction and Reduction Study - Fluidic Injection



OASPL between fluidic insert nozzle cases and faceted nozzle cases at varying operating conditions in the sideline direction.

Summary of 2017-2021 Office of Naval Research Jet Program

- Created time domain integration models compatible with unsteady flows and derived statistical models compatible with steady flows
- Fine-scale model is generalized and missing terms are derived relative to famous Tam method
- Large-scale noise model is elusive – but way forward is possible
- LES databases can analyze source and reduction without calculating acoustics, and terms are already known for shock-noise and fine-scale
- Demonstrate analysis of sensitivity and noise distribution for one noise reduction technology

Collaborations

Collaborators on Funded Research Programs

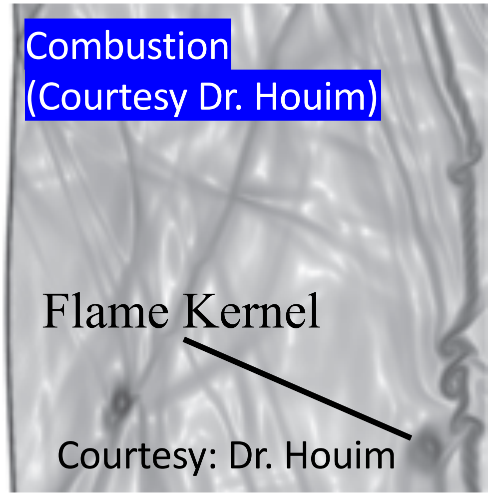
- S. Balachandar (UF MAE)
- K. Gurley (UF ESSIE)
- B. Hirth (Texas - Wind)
- P. Ifju (UF MAE)
- W. Lear (UF MAE)
- J. Lonzaga (NASA)
- P. Markowski (PSU Meteorology)
- S. Roy (UF MAE)
- J. Schroeder (Texas - Wind)
- L. Ukeiley (UF MAE)
- R. Waxler (U Miss. - NCPA)

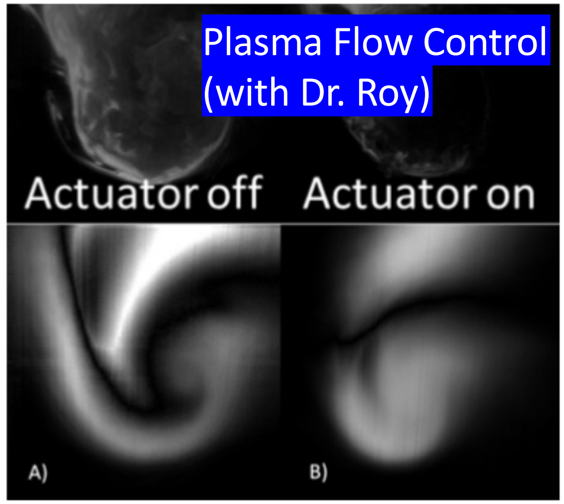
Collaborations for Proposal Writing, Unfunded, or Informal

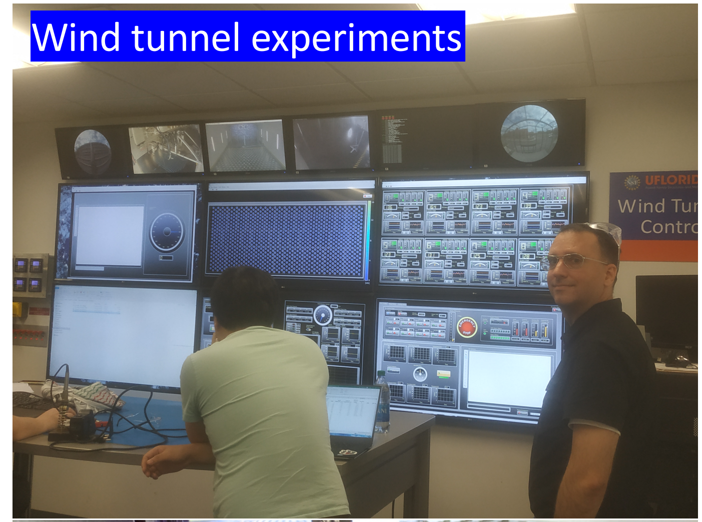
- R. Crabbs (NASA/UCF/Optics)
- A. Farrukh (FSU)
- D. Gaitonde (OSU MAE)
- R. Gosse (UF FLARE - Hypersonics)
- M. Hale (UF MAE)
- R. Houim (UF MAE)
- T. Jackson (UF MAE)
- M. Kinzel (UCF)
- R. Kumar (FSU)
- R. Lind (UF MAE)
- S. Moghaddam (UF MAE)
- R. Phillips (U. Arizona Optics)
- D. Prevatt (UF Civ. & Coastal)
- C. Segal (UF MAE)
- M. Sheplak (UF MAE/EE)
- Two UF Math professors

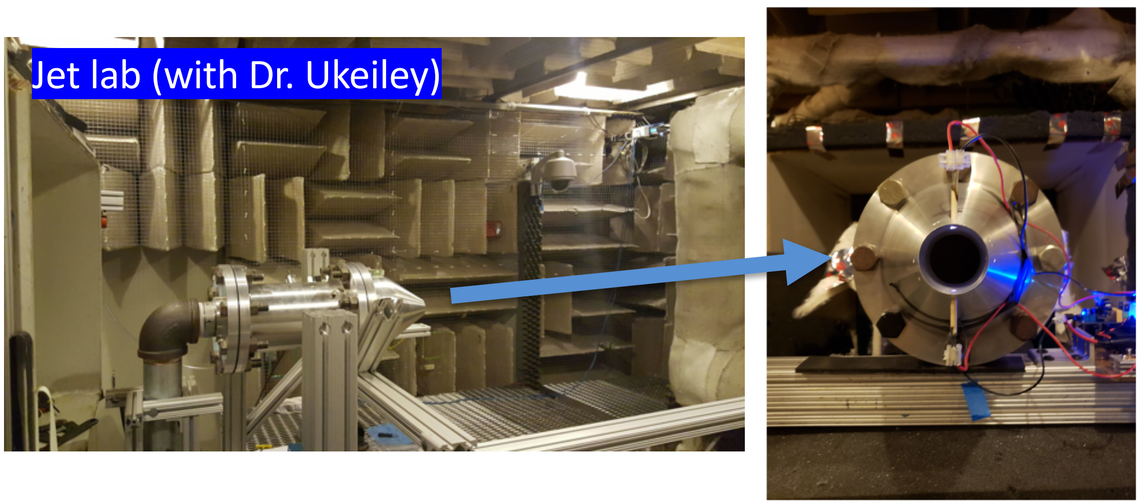
These are from memory – sorry if I forgot someone …

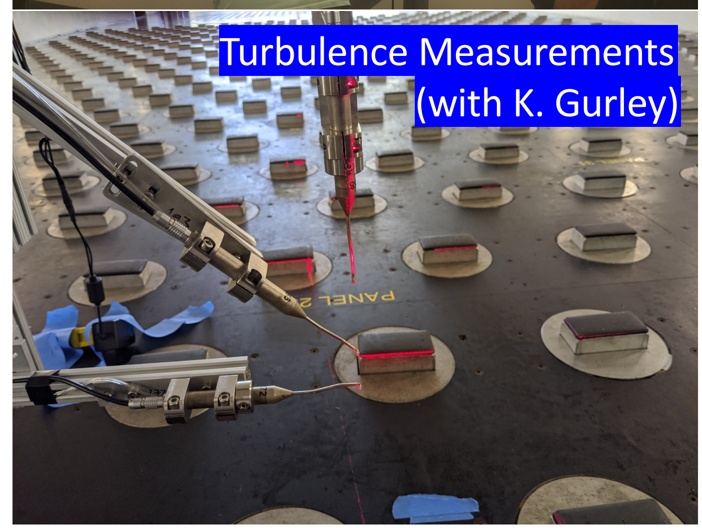
Other Research Efforts





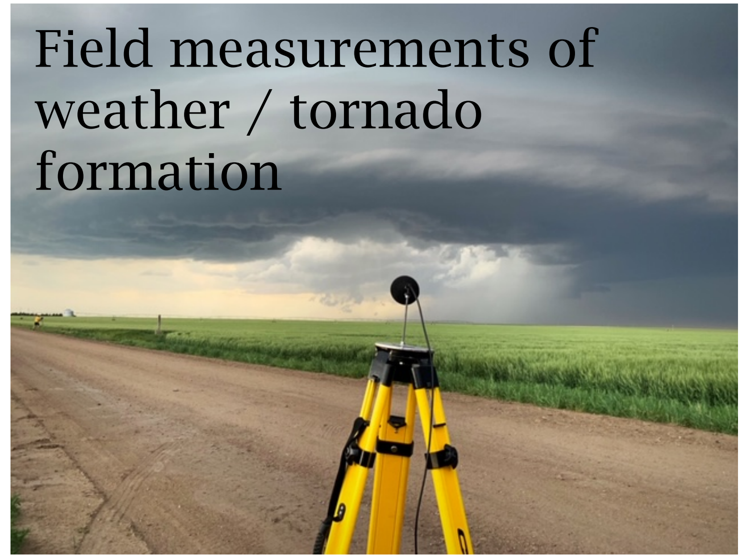




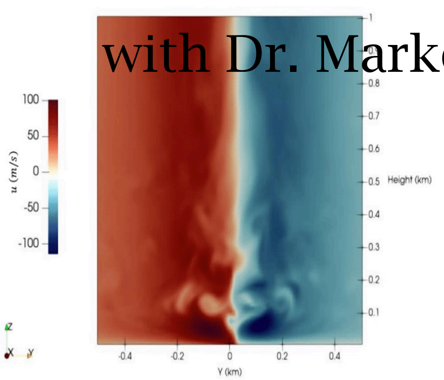


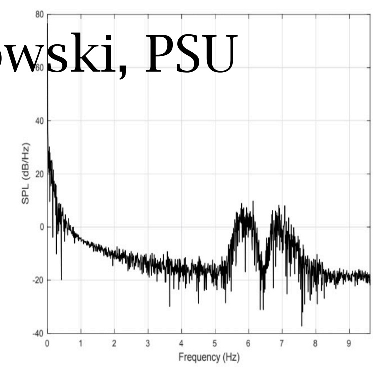
Other Research Efforts

Tornado studies with Texas Tech. Univ.



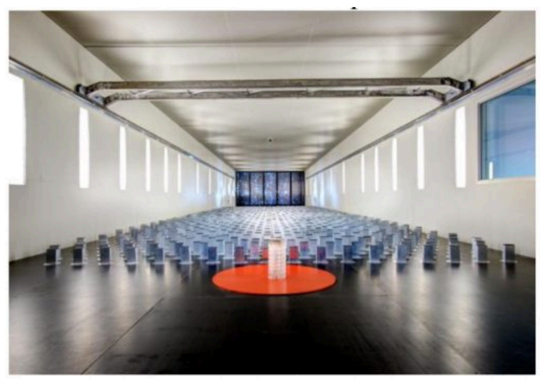
Field measurements of weather / tornado formation





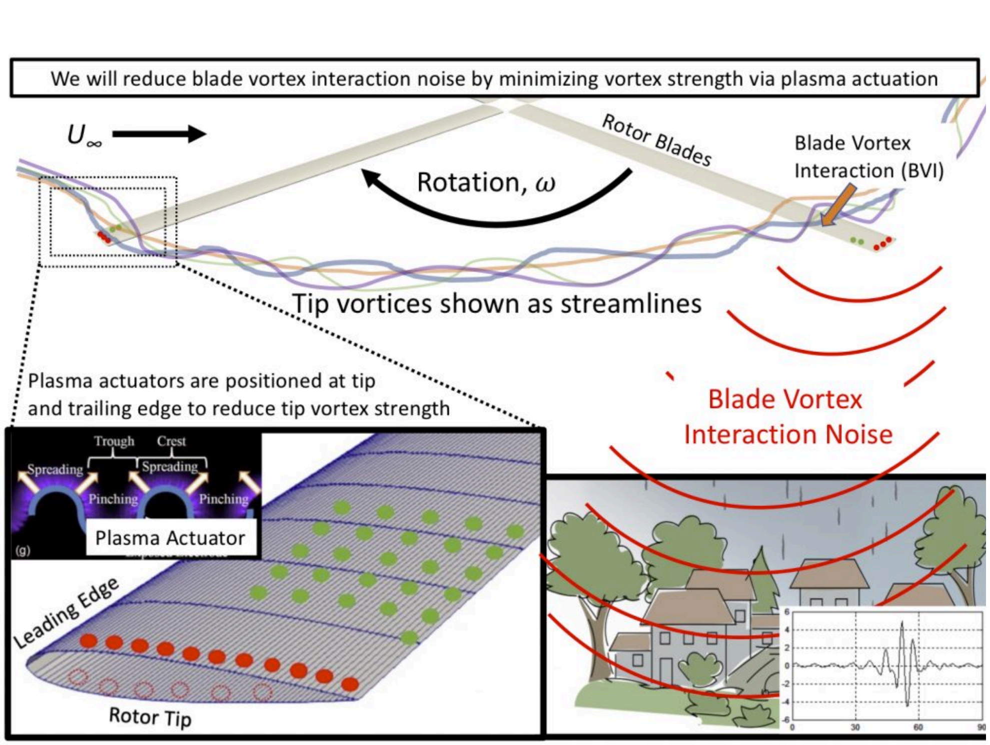
with Dr. Markowski, PSU

CFD of tornados with PSU

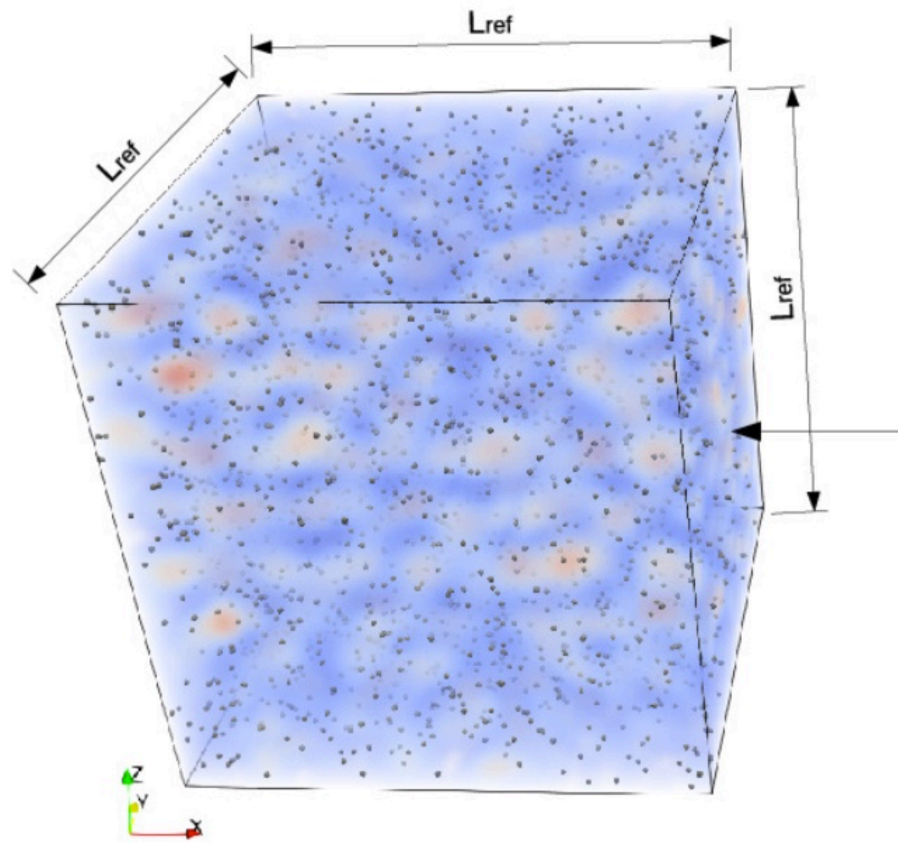


Boundary layer measurements for weather
At UF with ESSIE / NSF BLWT

Other Research Efforts



Rotorcraft aerodynamics / acoustics with plasma actuation / flow control with Profs. Lear and Roy

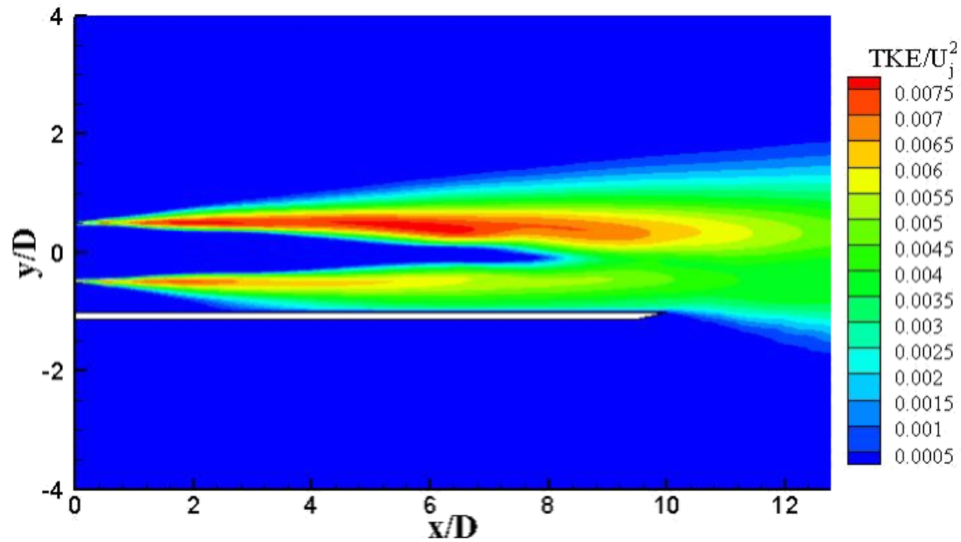


Direct numerical simulation (DNS) of particle laden flow within homogeneous isotropic decaying turbulence. Informal collaboration with Prof. Balachandar.

Other Research Efforts

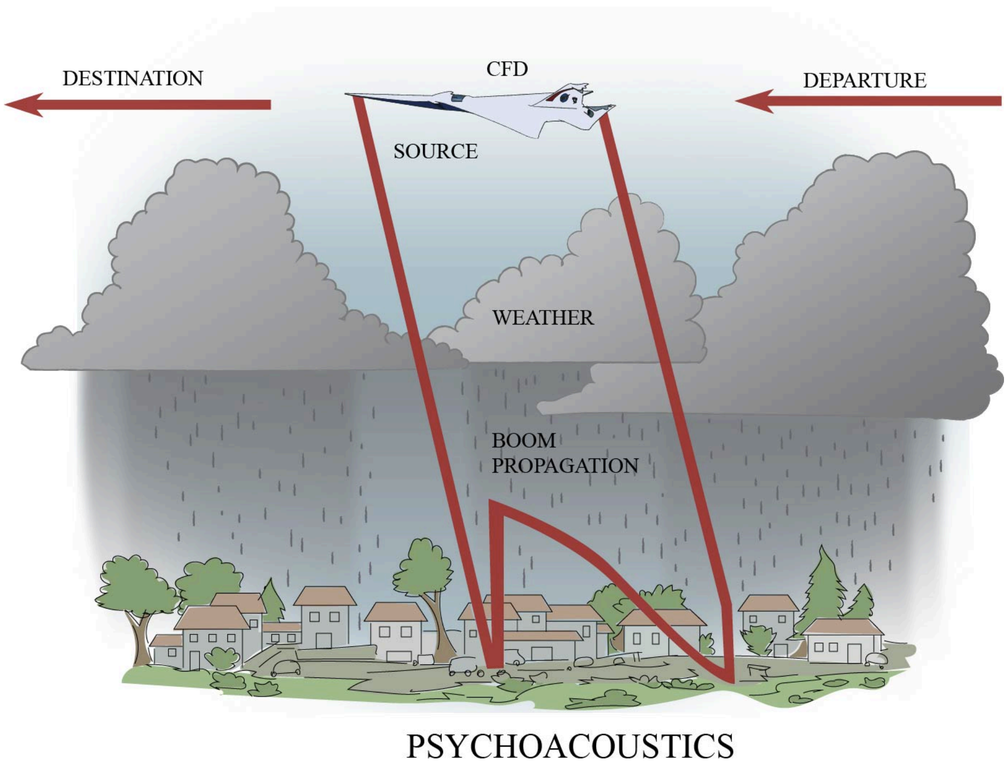
Aerodynamic / acoustic prediction with Archer Aviation. Collaboration with Profs. Ukeiley and Ifju.

Rapid distortion theory (turbulence), CFD, acoustic analogy, RANS

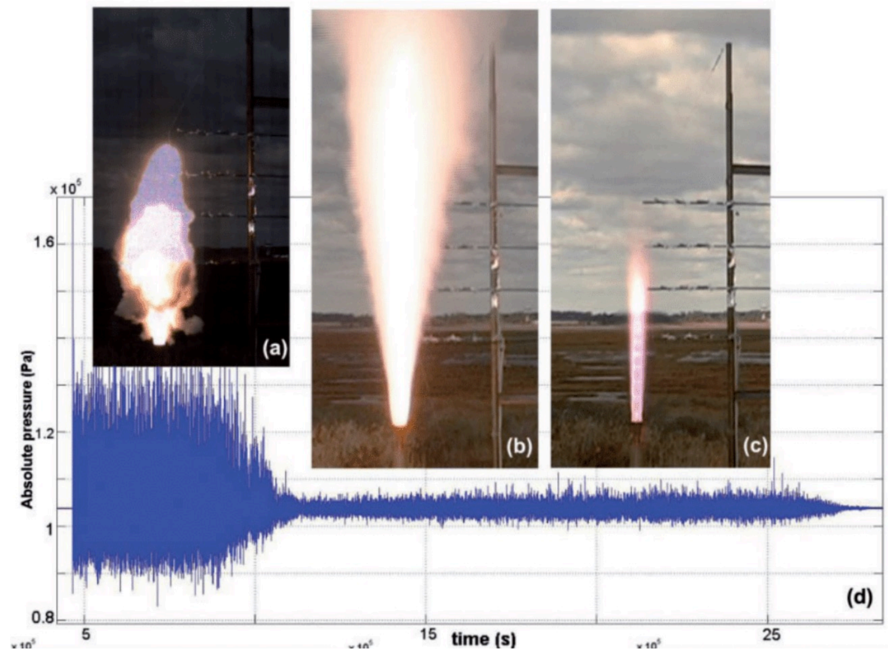


Fluid structure interaction CFD and semi-analytical prediction of pressure spectra and noise

Other Research Efforts

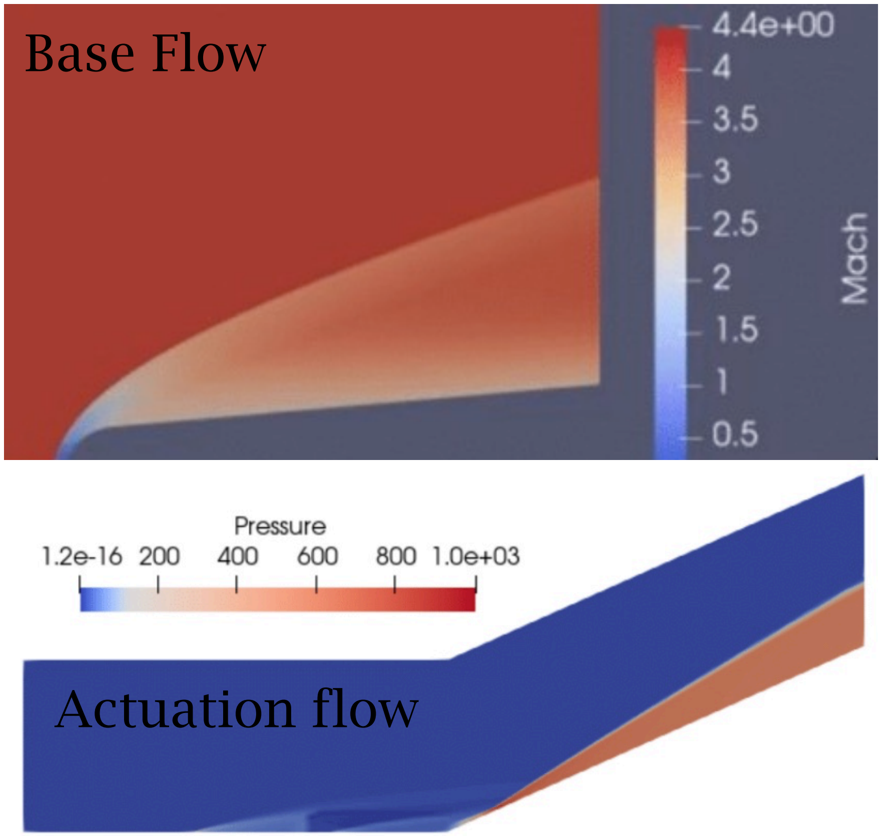


Sonic boom prediction and propagation through turbulent atmospheres for NASA.

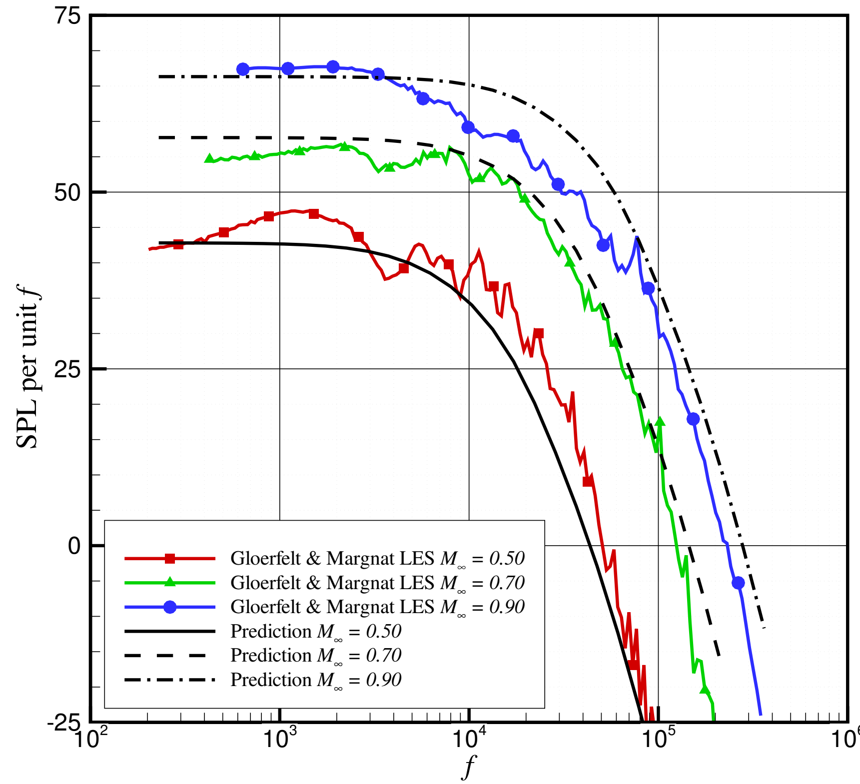


Multiphase jet flows – data and support from NASA Ames.
(with Dr. J. Panda, NASA Ames)

Other Research Efforts

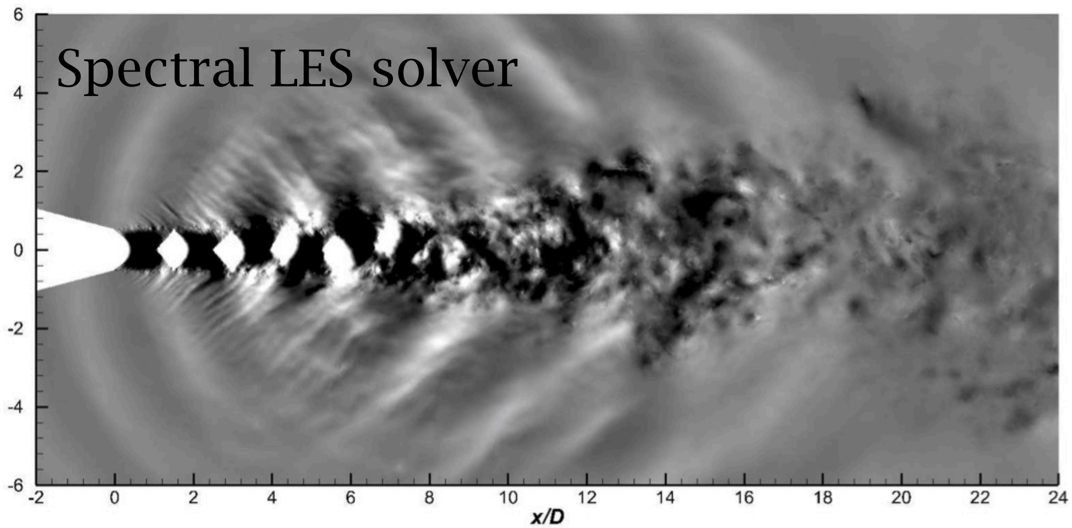


Supersonic / hypersonic transition/instability with plasma control / actuation.
(NASA/Florida SRI)

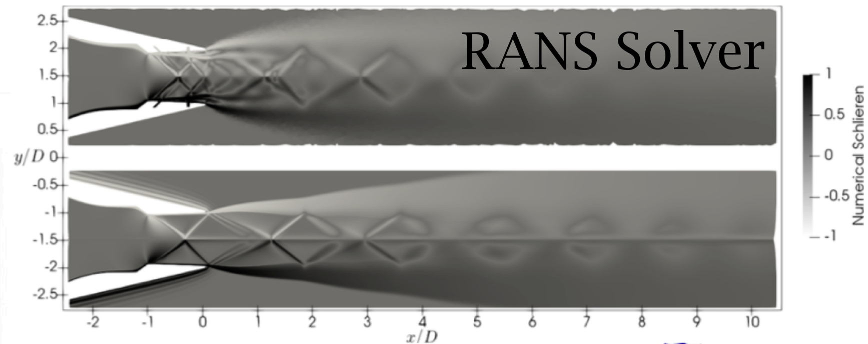


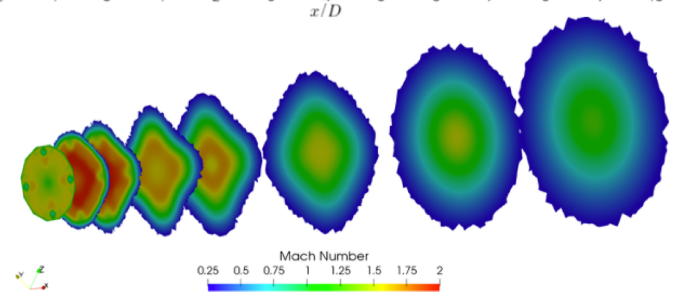
Prediction of turbulent boundary layer flow and noise.
(Informal with NASA GRC)

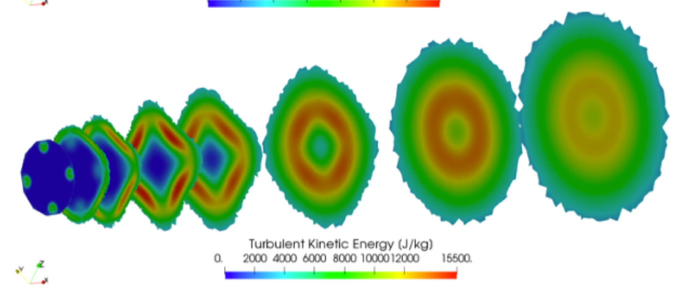
Other Research Efforts



In house spectral element large-eddy simulation applied to jets, wakes, and shear layers.





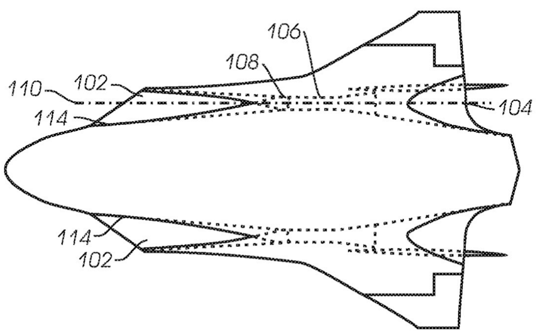


Traditional and advanced jet noise prediction.

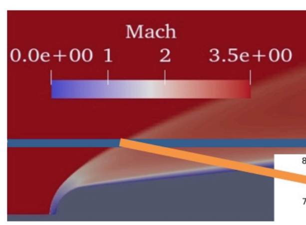
Future Research Plans
Hypersonic *Theoretics*

Defense Advanced Research Projects Agency (DARPA) Young Faculty Award, 2021

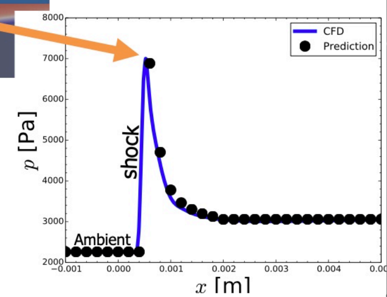
"Analytical Prediction of Near-Field Hypersonic Aerodynamics"



EP 1 818 257 A2



Proof of Concept: CFD over cone (left), M_∞ = 3.50, half-angle 7°, spherical leading edge, near-field p on blue line through shock and expansion.



Proof of Concept cont.: Preliminary prediction method (black dots) compared to CFD (blue line). Relatively excellent agreement observed. Prediction used no CFD or experiment.

Continue to seek new research areas and grow existing ones.

Students

Currently seeking two new additional Ph.D. students for fall / spring this year.

PH.D. ADVISOR AND COMMITTEE CHAIR

- *Ghannadian, Arman C. (Graduate Student, Ph.D.), Aug. 2021 - Present.*
- *Cheng, Jiahui, (Graduate Student, Ph.D.), Aug. 2018 - Present.*
- *Carr, Alex, (Graduate Student, Ph.D.), Aug. 2017 - Present.*
- *Lin, Albert, (Graduate Student, Ph.D.), Aug. 2021 – Present.*
- *Zhang, Tianshu, (Graduate Student, Ph.D.), Aug. 2018 - Present.*
- Shen, Weiqi, "Modeling of Broadband Shock-associated Noise in Supersonic Jets Using Large-eddy Simulation and Decomposition Methods," University of Florida, Ph.D. Dissertation, Dec. 2020.
- Patel, Trushant, "Analysis of Supersonic Jet Noise in The Sideline and Upstream Directions Using the Navier-stokes Equations," University of Florida, Ph.D. Dissertation, Dec. 2020.
- Wang, Wei, "A Numerical Study of Acoustics from Supersonic Particle-laden Jets via Multi-Phase Acoustic Analogy," University of Florida, Ph.D. Dissertation, Dec. 2020.

M.S. ADVISOR AND COMMITTEE CHAIR

- Rajendran, Achyuth, "Investigation of Acoustics from Turbulent Boundary Layers on Flat Plates with Suction," M.S. Thesis, Aerospace Engineering, Mar. 2021.
- Yalcin, Baran (Graduate Student, M.S.), "Investigation of shock-wave boundary layer separation prevention concepts," Aug. 2020.
- Smith, Matthew J., "The Analysis and Prediction of Jet Flow and Jet Noise about Airframe Surfaces," M.S. Thesis Aerospace Engineering, Dec. 2013.

Students (cont.)

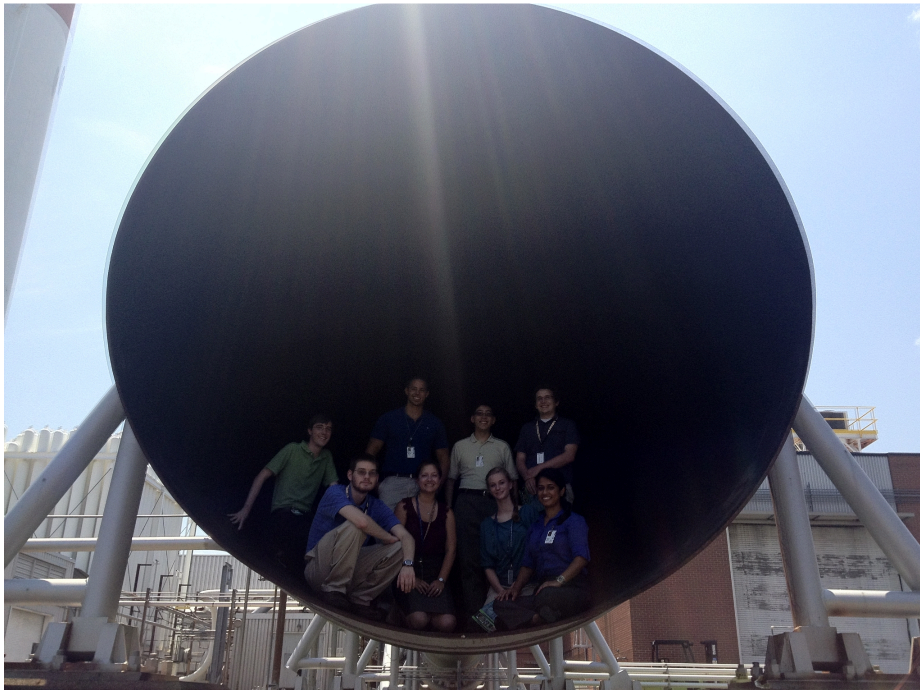
STUDENT AWARDS

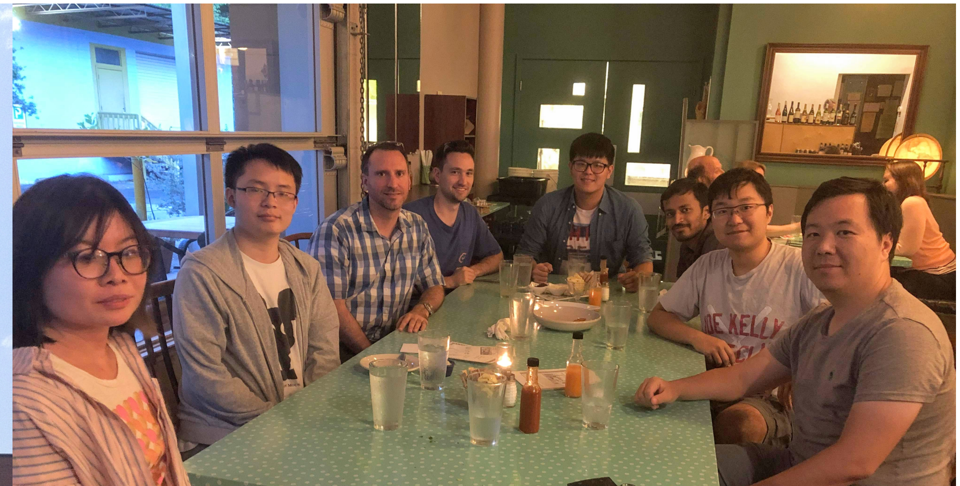
- Carr, Alexander, NASA Dissertation and Thesis Improvement Fellowship Program, 2021.Orr, Olivia, “UF MAE Student Leadership Award,” Sept. 2021.
- Pond, Ellie, “Aerospace Engineering Outstanding Senior Award,” Sept. 2021.
- Carr, Alexander, “UF MAE Graduate Student Research Award,” Sept. 2021.
- Rajendran, Achyuth, “AIAA Region II Student Conference Masters Category,” 2nd Place, April. 2021.
- Patel, Trushant K., “UF MAE Graduate Student Research Award,” April. 2020.
- Carr, Alexander, “Modeling Sonic Boom Propagation through Atmospheric Turbulence and Around the Lateral Extent of the Boom Carpet,” NASA Graduate Fellowship, 2019 - 2023.

STUDENT ADVISEES

- Munden, Katherine (Undergraduate, B.S.), “Tornado and Jet Flow-Field RANS Prediction Programs,” Jan. 2019 - Aug. 2019.
- Annunziata, Chris (Graduate Student, M.S.), Rocket Propulsion Design, Design of Heavy-lift, Liquid Chemical Propulsive Systems in Rockets, Jan. 2019 - May 2019.
- Pager, Elisha R., (Undergraduate, B.S.), Introduction to CFD Course Development and Undergraduate Research on Turbulent Boundary Layers, Jan. 2017 - June 2018.
- Vijay, Endurthi (Graduate Student, M.S.), Rotorcraft aerodynamics using CFD, Jan. 2017 - May 2018.
- Smith, Matthew (Graduate Student, M.S.), “The Analysis and Prediction of Jet Flow and Jet Noise about Airframe Surfaces,” June 2012 - Dec. 2013.
- Howton, Alexandra (NASA LARSS), “The Prediction of Noise Generated by Turbulent Jet Flow Past the Trailing Edge of a Flat Plate,” June 2013 - Aug. 2013.
- Hipp, Kyle (NASA LARSS), “The Sideline Refraction Effects of Twin Jet Flow.” June 2013 - Aug. 2013.
- Mazur, Emily (NASA LARSS), “Assessment of Nonlinear Propagation Methodology for Jet Noise,” June 2012 - Aug. 2012.
- Beisser, Megan (NASA Virginia Governor's School), “Prediction of Jet Impingement Locations for Fluid Structure Interaction,” June 2012 - July 2012.
- Massey, Benjamin C. (NASA LARSS), “Prediction of Jet Noise based on Empirical Flow-field Models and CFD Results,” June 2011 - Aug. 2011.

Students (cont.)





Students (cont.)

Sigma Gamma Tau

(UF MAE Aerospace Honor Society)

"The Sigma Gamma Tau Society is established to recognize and honor those individuals in the field of aeronautics and astronautics who have through scholarship, integrity, and outstanding achievement been a credit to their profession. The Society seeks to foster a high standard of ethics and professional practices and to create a spirit of loyalty and fellowship, particularly among students of Aerospace Engineering."

https://sgt.mae.ufl.edu

Thank you.

Questions?

Miller at NASA GRC 8 by 6 ft Supersonic Wind Tunnel, summer 2019.