Analysis of Noise Reduction Method for Supersonic Jets in the Sideline and Upstream Directions

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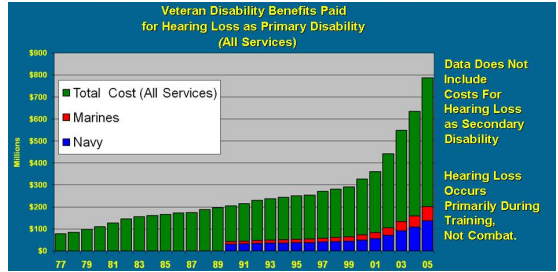
Outline

Motivation

- More than 107,000 sailors are living and working aboard US Navy ships
- Over a billion dollars were spent each year by US Department of Veterans Affairs for hearing loss disability benefits in the last decade[1]

US Navy Public Release Photo: 180123-N-GP724-1102

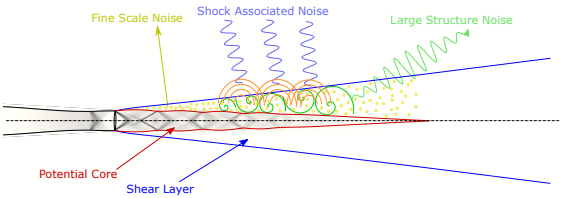


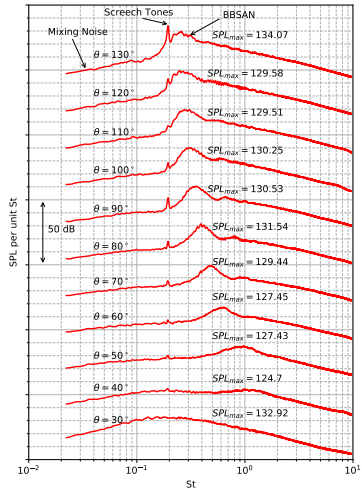
Source: https://www.public.navy.mil/navsafecen/Pages/acquisition/noise_control.aspx

[1] Doychak J., "Department of Navy Jet Noise Reduction Project Overview," *15th Annual Partners in Environmental Technical Symposium and Workshop*, Washington D.C., 2010.

Components of Jet Noise

- Two main components of jet noise - turbulent mixing noise and shock-associated noise
- Broadband shock-associated noise is generated due to *coherent interaction* of large-scale structures with the shock-cell structure
- Fine-scale mixing noise is relatively spatially incoherent
- Mainly dominant in the sideline and upstream direction



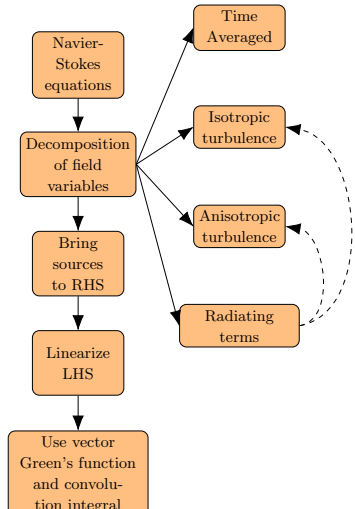


Noise spectra at different observer locations[2]

[2] Brown, C., and Bridges, J. E., "Small Hot Jet Acoustic Rig Validation," *NASA/TM-2006-214234*, 2006.

Prediction Model[3]

- We start with the Navier-Stokes equations as the governing equations
- The *field-variables* such as density, velocity, pressure, and temperature are decomposed into base flow ($\overline{q}$), aerodynamic fluctuations ($\breve{q}$ and $\hat{q}$), and acoustic fluctuations (q' and q'')
- The aerodynamic turbulent fluctuations (sources) are brought to the right-hand side
- The radiating acoustic components (propagators) are brought on the left-hand side
- The spectral density of the radiating components is obtained by *convolving* the vector Green's function with the source terms present on the right-hand side



[3] Miller, S. A. E., "Noise from Isotropic Turbulence," *AIAA Journal*, Vol. 55, No. 3, 2017.

Spectral Density of Pressure

After some simplifications[4], we obtain the spectral density of the field variable as

$$S_k^{\perp}(\mathbf{x},\omega) = \int_{-\infty}^{\infty}\cdots\int_{-\infty}^{\infty}\sum_{m=0}^{4}\sum_{n=0}^{4} q_{g,k}^{*\perp,m}(\mathbf{x};\mathbf{y},\omega)\, q_{g,k}^{\perp,n}(\mathbf{x};\mathbf{y}+\boldsymbol{\eta},\omega)\, R_{m,n}^{\perp}(\mathbf{y},\boldsymbol{\eta},\tau)\, e^{i\omega\tau}\, d\tau\, d\boldsymbol{\eta}\, d\mathbf{y},$$

where

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

Substituting $k = 4$ to find the spectral density of pressure, we obtain

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

[4] Patel T. K., and Miller, S. A. E., "Statistical sources for broadband shock-associated noise using the Navier-Stokes equations," *The Journal of the Acoustical Society of America*, Vol. 146, No. 6, 2019.

Source Terms

- The source terms on the RHS are

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

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

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

- Different researchers[5,6] have found that viscous terms are not important for sound generation

[5] Lighthill, M. J., "On Sound Generated Aerodynamically I. General Theory," *Proceedings of the Royal Society of London. Series A. Mathematical, Physical, and Engineering Sciences*, Vol. 211, No. 1107, 1952.

[6] Mollö-Christensen, E., "Jet Noise and Shear Flow Instability Seen From an Experimenter's Viewpoint," *Journal of Applied Mechanics*, Vol. 34, No. 1, 1967.

FSMN and BBSAN Source Term

- The same FSMN source term proposed by Tam and Auriault[7] is also obtained from the Navier-Stokes equations as

$$R_{FSMN} = (\gamma - 1)^2 \left\langle \frac{D\overline{\rho}^{(1)} K_s^{(1)}}{D\tau}, \frac{D\overline{\rho}^{(2)} K_s^{(2)}}{D\tau} \right\rangle \approx (\gamma - 1)^2 \frac{\overline{\rho}^2 K_s^2}{\tau_s^2} \breve{R}$$

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

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

[7] Tam, C. K. W., and Auriault, L., "Jet Mixing Noise from Fine-Scale Turbulence," AIAA Journal, Vol. 37, No. 2, 1999.

Statistical FSMN Model

For fine-scale noise, we use the same normalized two-point cross-correlation as Tam and Auriault as

$$\breve{R} = \exp\left(-\frac{|\xi|}{\overline{u}\tau_s} - \frac{\ln 2}{l_s^2}\left[(\xi - \overline{u}\tau)^2 + \eta^2 + \zeta^2\right]\right)$$

We obtain the spectral density as

$$S_4^{\perp}(\mathbf{x},\omega) = \left(\frac{\pi}{4\ln 2}\right)^{3/2}(\gamma-1)^2 \int_{-\infty}^{\infty}\iiint \frac{\overline{\rho}^2 K_s^2 l_s^3}{\tau_s} |p_g^{\perp 4}(\mathbf{x},\mathbf{y},\omega)|^2 \frac{\exp\left[-\frac{\omega^2 l_s^2}{\overline{u}^2(4\ln 2)}\right]}{\left[1 + \left(1 - \frac{\overline{u}}{c_\infty}\cos\theta\right)^2 \omega^2 \tau_s^2\right]} d\mathbf{y}$$

The resulting model is equivalent to the Tam and Auriault model

Statistical BBSAN Model

We now consider different length scales in the cross-stream directions and model the normalized two-point cross-correlation as

$$\hat{R} = \exp\left[-\frac{|\tau|}{\tau_s}\right]\exp\left[-\frac{(\xi - u_c\tau)^2}{l_1^2}\right]\exp\left[-\frac{\eta^2}{l_2^2} - \frac{\zeta^2}{l_3^2}\right]$$

After integrating and simplifying, we obtain a closed-form prediction model as

$$S_4^{\perp}(\mathbf{x},\omega) = \frac{\gamma^2\omega^2}{16\pi\sqrt{\pi}c_\infty^4 r^2}\iiint_{-\infty}^{\infty} l_1 l_2 l_3 \tau_s \exp\left[-\frac{\omega^2}{4a_\infty^2}\sin^2\theta\left(l_2^2\cos^2\phi + l_3^2\sin^2\phi\right)\right]\frac{\partial\overline{p}}{\partial y_j}(\mathbf{y})\hat{u}_j(\mathbf{y})$$

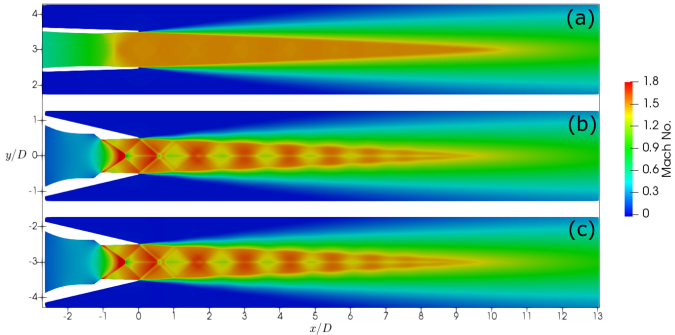
$$\left[\int_{-\infty}^{\infty}\frac{\exp\left[-l_1^2\left(\kappa - \frac{\omega\cos\theta}{c_\infty}\right)^2/4\right]}{\left[1+\left(1-M_c\cos\theta+\frac{u_c\kappa}{\omega}\right)^2\omega^2\tau_s^2\right]}\frac{\partial\overline{p}}{\partial y_m}(\kappa,y_2,y_3)d\kappa\right]\hat{u}_m(\mathbf{y})d\mathbf{y},$$

However, very good prediction results are obtained using LES data with the identified source term and free-space Green's function[8]

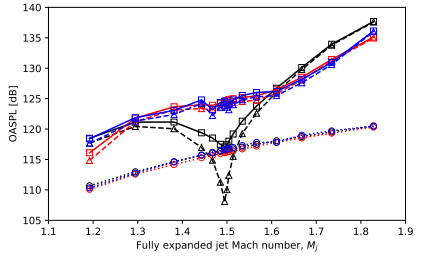
[8] Shen, W., Patel, T. K., and Miller, S. A. E., "Extraction of Large-Scale Coherent Structures from Large Eddy Simulation of Supersonic Jets for Shock-Associated Noise," *AIAA SciTech 2020 Forum*, AIAA Paper No. 2020-0742, 2020.

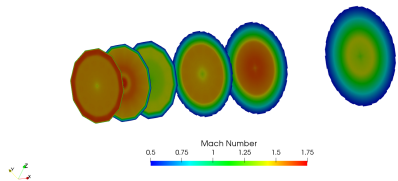
Comparison of Different Nozzle Geometries

- The biconic and faceted nozzle contains shocks even at design conditions
- Hence, shock-associated noise is present even at design condition



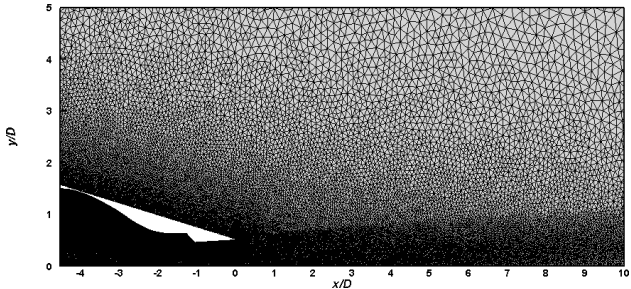
(a) SMC016 nozzle (b) biconic nozzle (c) faceted nozzle



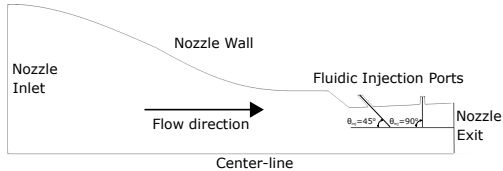


Nozzle Design and Computational Grid

- The design of the fluidic injection ports is performed following Morris et al.[9]
- $D_{inj} = 0.05D$; $m_{ratio} = 2.41\%$
- Fluidic injection ports are located at 20% and 70% of the divergent section with 45° and 90° injection angles

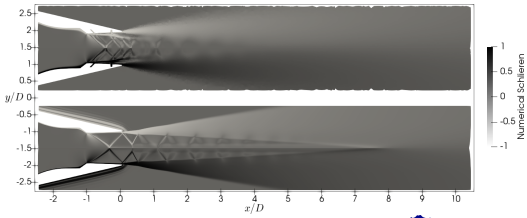


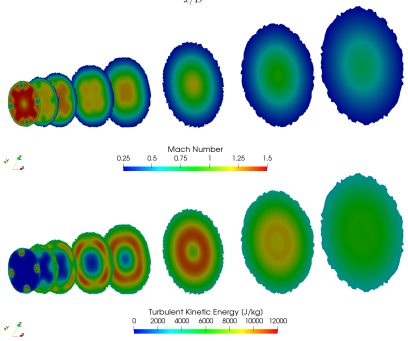
Nozzle		Injector	
NPR	TTR	IPR	ITR
2.750	3.000	2.750	1.000
3.100	3.000	3.100	1.000
3.670	3.000	3.670	1.000
4.320	3.000	4.320	1.000
5.200	3.000	5.200	1.000

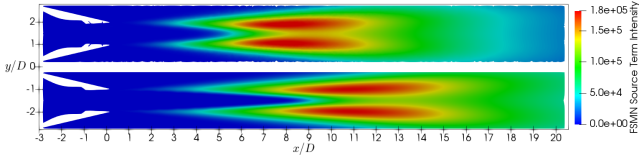


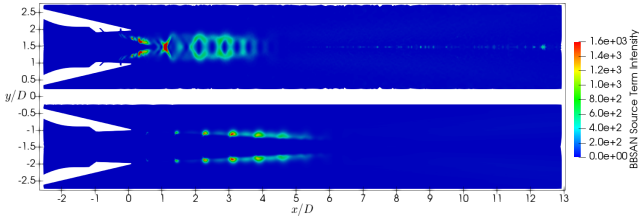
[9] Morris, P. J., et al., "Noise Reduction in Supersonic Jets by Nozzle Fluidic Inserts," *Journal of Sound and Vibration*, Vol. 332, No. 17, 2013.

Results for NPR = 2.750 and TTR = 3.00



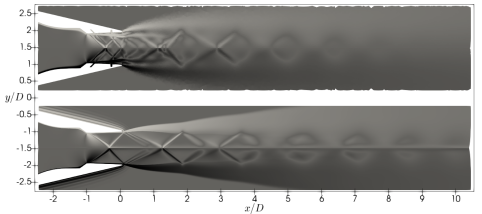


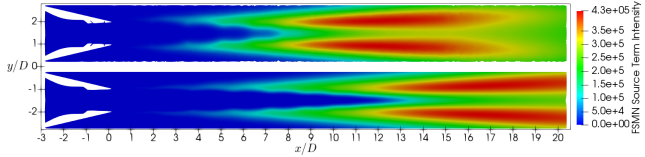


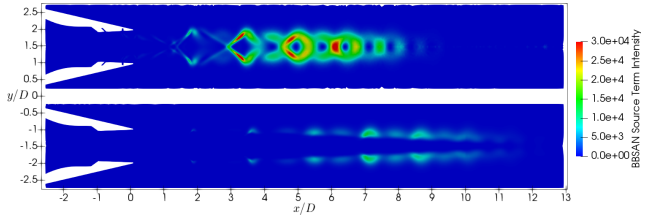


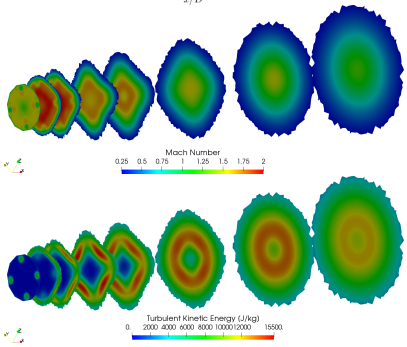
Clockwise starting from the top-left: Numerical schlieren comparison, FSMN source location comparison, BBSAN source location comparison of the fluidic insert nozzle with the faceted nozzle, and Mach no. and TKE contours at different cross-sections

Results for NPR = 5.200 and TTR = 3.00





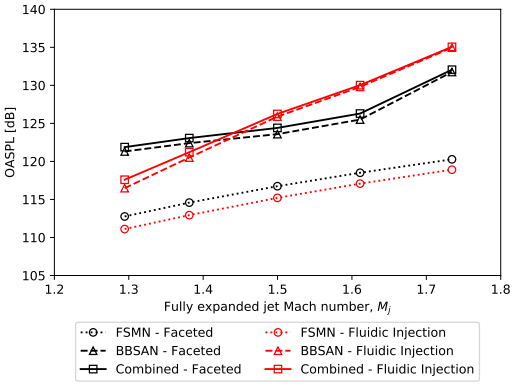


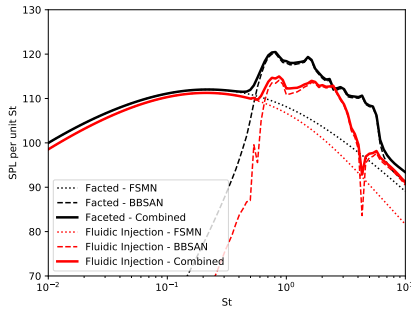


Clockwise starting from the top-left: Numerical schlieren comparison, FSMN source location comparison, BBSAN source location comparison of the fluidic insert nozzle with the faceted nozzle, and Mach no. and TKE contours at different cross-sections

Acoustic Results

- BBSAN reduces at over-expanded condition and increases at under-expanded conditions
- BBSAN OASPL reduces by 6 dB at NPR = 2.750 and increases by 4 dB at NPR = 5.200
- FSMN OASPL reduces bv 1.75 dB at all operating conditions





Summary and Future Work

- Identified the FSMN and BBSAN source term from the Navier-Stokes equations
- Developed statistical models for FSMN and BBSAN
- Noise radiating from different nozzle geometries were compared using the identified source term
- Fluidic injection noise reduction technique was analysed using the identified source terms
- Approximately similar noise reduction is obtained in the present work when compared to the experiments of Morris et al.[10]
- The identified source terms can be used for quantifying noise reduction due to different noise reduction techniques in the future

[10] Morris, P. J., McLaughlin, D. K., and Kuo, C.-W., "Noise Reduction in Supersonic Jets by Nozzle Fluidic Inserts," *Journal of Sound and Vibration*, Vol. 332, No. 17, 2013.

Thank You for your Attention!
Questions?