# Flow Control of Large-Scale Coherent Turbulence to Reduce Jet Noise

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## Overview

- This project represents a joint experimental and computational effort to reduce supersonic Jet Noise.
- Noise from an off-design supersonic jet has unique statistics that allow for promising opportunities in active flow control. In the upstream direction the broadband shock associate noise is dominant at higher frequencies, but at mid to low frequencies there is a combination of both fine and large-scale mixing noise of similar amplitude. This mixing noise can be further separated due to the fact that the large-scale noise in the upstream direction is highly correlated to the large-scale noise that dominates the acoustic radiation in the downstream direction. The signal extracted from the large scale noise can be used in a feedback control system to alter the large scale coherent turbulence within the jet and reduce downstream noise radiation.
- An analytical aeroacoustic model will be combined with LES simulations to extract the large-scale associated noise in the upstream direction.
- The identification of the statistics related to the large-scale noise will allow for an educated way to leverage the flow instabilities within the jet shear layer to actively control the large-scale coherent turbulence which is the dominant noise generation mechanism.
- Active flow control will be performed using Local Arc Filament Plasma Actuators placed in the diverging section of the nozzle to seed a thermal perturbation within the developing boundary layer.
- A feedback control system will be developed using a microphone placed upstream at an inlet angle of 45 degrees to capture the radiated acoustic signal, which will be separated in real time using a LabVIEW control system and fed to the plasma actuators.
- The combination of analytical theory, large eddy simulations, and experimental efforts will allow for a decomposition algorithm to be developed to target the structures that dominate noise generation in an off-design supersonic jet.

## Instability Wave Theory

- The theory calculates the jet noise from the large-scale turbulent structures.
- The governing equations are the linearized equations of motion[1][2].
- The instability wave formula is express as:

$$p'(r,\theta,x,t)=\sum_{n=0}^{\infty}\delta_n(\varepsilon)\hat{p}_n(r,x)exp\left[i\left(\int\alpha(x)dx+m\theta-\omega t\right)\right]$$

- In the inner region, the governing equations are transformed to an ODE of pressure via the method of multiple scale analysis.

$$\frac{\partial^2\hat{p}_n}{\partial r^2}+\left[\frac{1}{r}+\frac{2}{\omega-\alpha\bar{u}}\frac{\partial\bar{u}}{\partial r}-\frac{1}{\bar{\rho}}\frac{\partial\bar{\rho}}{\partial r}\right]\frac{\partial\hat{p}_n}{\partial r}+\left[\bar{\rho}M_j^2(\omega-\alpha\bar{u})^2-\frac{m^2}{r^2}-\alpha^2\right]\hat{p}_n=G_n(r,s),$$

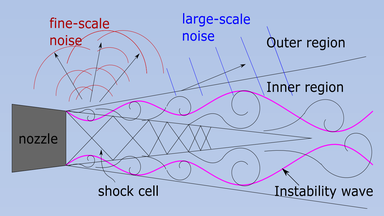
- In the outer region, the governing equations are solved in frequency-wavenumber space[2].
- The inner and outer solutions are obtained after applying the method of matched asymptotic expansions in the overlapping region[3].

$$p_0^{inner}(r,\theta,x,t)=A_0(x)\hat{p}_0exp\left[i\left(\int\alpha(x)dx+m\theta-\omega t\right)\right],$$

$$p_0^{outer}(r,\theta,x,t)=\int_{-\infty}^{\infty}\hat{A}\hat{g}(\eta)H_m^1[i\lambda(\eta)r]\,exp[i(\eta dx+m\theta-\omega t)]d\eta.$$

- The amplitude of the instability wave is determined by the stochastic theory. The power spectrum density in the far-field region is[3]

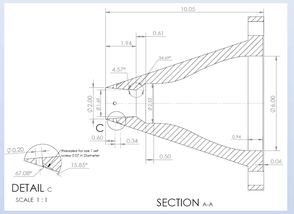
$$S(R,\psi,\theta,t)=10\log_{10}\left[\frac{\rho_j^2u_j^2R_j^3}{p_{ref}^2R^2}\sum_{n=-\infty}^{\infty}\frac{8\pi\hat{D}\left|g_n\left(\rho_\infty^{0.5}M_j\omega\cos\theta,\omega\right)\right|^2}{|\hat{p}_n(r_{0.5},0,\omega)|^2}\right].$$



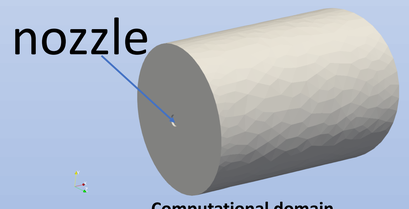

Ref:
[1] Tam, C. K. W., and Burton, D. E., "Sound Generated by Instability Waves of Supersonic Flows. Part 1. Two-dimensional Mixing Layers," *Journal of Fluid Mechanics*, Vol. 138, No. -1, 1984, p. 249.
[2] Tam, C. K. W., and Burton, D. E., "Sound Generated by Instability Waves of Supersonic Flows. Part 2. Axisymmetric Jets," *Journal of Fluid Mechanics*, Vol. 138, No. -1, 1984, p. 273.
[3] Tam, C. K. W., and Chen, P., "Turbulent Mixing Noise from Supersonic Jets," *AIAA Journal*, Vol. 32, No. 9, 1994, pp.1774–1780.
[4] H. Tanna, "An experimental study of jet noise part I: Turbulent mixing noise," Journal of Sound and Vibration, vol. 50, no. 3, pp. 405–428, 1977.
[5] M. Samimy, J.-H. Kim, and M. Kearney-Fischer, "Active Control of Noise in Supersonic Jets Using Plasma Actuators," Volume 1: Aircraft Engine; Ceramics; Coal, Biomass and Alternative Fuels; Controls, Diagnostics and Instrumentation; Education; Electric Power; Awards and Honors, 2009.
[6] J.-H. Kim, M. Nishihara, I. V. Adamovich, M. Samimy, S. V. Gorbatov, and F. V. Pliavaka, "Development of localized arc filament RF plasma actuators for high-speed and high Reynolds number flow control," Experiments in Fluids, vol. 49, no. 2, pp. 497–511, 2010.

## LES Simulation Setup

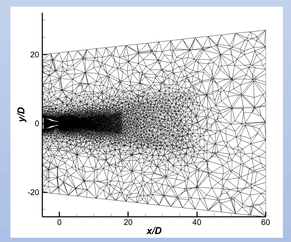
- The testcase for the simulation is selected from the Tanna Matrix[4]. Details of the simulation are as follows:
  - Design Mach number: $M_d$=1.76
  - Nozzle pressure ratio: NPR=4.645
  - Jet Mach number: $M_j = 1.675$
  - Total temperature ratio: TTR = 3.346
  - Polynomial basis order: 2
  - Total number of elements: 2.32 millions
  - Running on 2048 cores




Nozzle profile



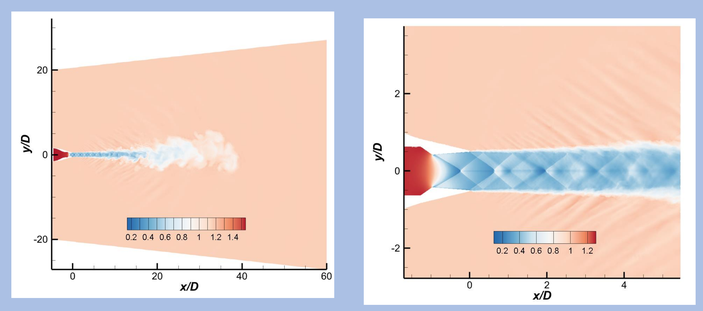

Computational domain




Computational mesh

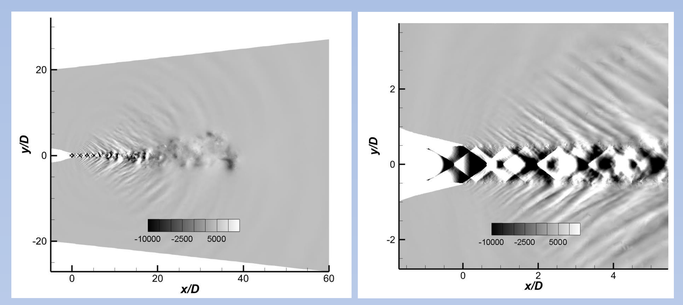
## Preliminary Results

- Transient density and fluctuating pressure are presented.
- The complex shock cell structure due to the biconic nozzle can be clearly observed.




Transient density and zoom in view near nozzle outlet

- The Mach wave radiation is generated by supersonically convecting disturbances in the shear layer.

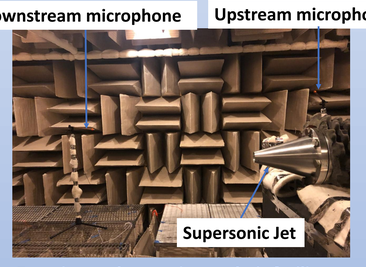



Transient fluctuation pressure and zoom in view near nozzle outlet

## Experimental Setup

- The experiments are performed on an unheated supersonic jet in the UF Anechoic Wind Tunnel, which has a cutoff frequency of 100 Hz. The jet design parameters are as follows:
  - Exit diameter: D = 2in
  - Area ratio: AR = 1.4
  - Design jet Mach number: $M_d$=1.76
  - Nozzle pressure ratio: NPR= 5.4
  - Reynolds Number: $Re_D$ = 1.6x10$^6$
- Two microhomes are used to analyze the correlation between upstream and downstream noise statistics. Also to evaluate the effectiveness of the control authority for reducing the large-scale jet noise.

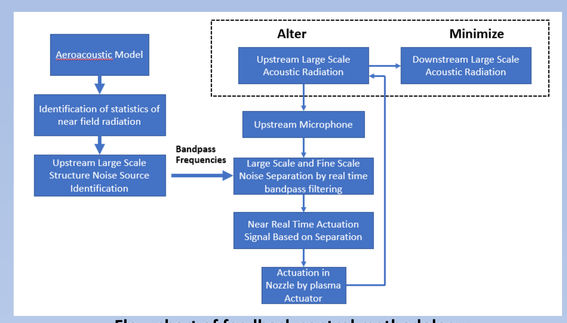
Side view of supersonic jet




Experimental set up in anechoic facility

## Flow Control Method

- Samimy[5] has shown that Local Arc Filament Plasma Actuators (LAFPA) can be used to alter supersonic jet noise through exciting azimuthal modes of the jet with localized thermal perturbations at the jet exit.
- The LAFPAs in the current study have the benefit of a large bandwidth and control authority acting as RF modulators for the input actuation signal similar to the work performed by Kim et al.[6]
- The LAFPAs are held by ceramic tubes located in the diverging section of the nozzle to seed a perturbation within the growing boundary layer.
- A closed loop feedback control system will be applied with a LabView Code which filters the signal from the upstream microphone to separate out the large scale associated noise. This signal acts as the actuation signal for the LAFPAs in order to break up the large scale coherent structures.




Flow chart of feedback control methodology

Front view of nozzle without actuator (left) and with actuator (right)