FINAL REPORT

Impact of Shear Layer Swirl on Near- and Far-field Noise Emissions from Twin-Engine Military Aircraft

SERDP Project WP19-1288

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14. ABSTRACT
Environmental impact of aviation is measured in emissions and noise. The communities in the vicinity of airports bear the brunt of aircraft noise in takeoff, climb, flyover, approach and landing. The exposure to loud noise is harmful to human physiological and psychological health and welfare. The problem in the military (DoD) is even bigger since there are servicemen working in close proximity of advanced supersonic jets, in takeoff and landing. The research team at The University of Kansas has identified a novel and powerful means of mitigating jet noise by inducing shear layer swirl through embedded vanes near the nozzle exit lip. In this proof-of-concept study, we aim to demonstrate the feasibility of the concept through both high-fidelity computational simulations and experimental investigations.

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Noise Mitigation, Supersonic Jet, Swirl Vane, Circular Nozzle, Shear Layer Swirl

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Table of Contents

List of Tables

List of Figures

List of Acronyms

DOD: Department of Defense

CCD: Conical Convergent-Divergent

LES: Large Eddy Simulation

dB: Decibel

SA: Swirl Angle

SERDP: Strategic Environmental Research and Development Project

SEED: SERDP Exploratory Development

CD: Convergent Divergent

BBSAN: Broadband Shock-Associated Noise

NASA: National Air and Space Administration

CFD: Computational Fluid Dynamics

SST: Supersonic Transport

FR: Flux Reconstruction

CPR: Correction Procedure via Reconstruction

DG: Discontinuous Galerkin

ILES: Implicit Large Eddy Simulation

BDF2OPT: Backward Forward Difference 2 Optimizing

DFT: Discrete Fourier Transform

SPL: Sound Pressure Level

FWH: Ffowcs Williams-Hawkings

NPR: Nozzle Pressure Ratio

TTR: Total Temperature Ratio

LE: Leading Edge

TE: Trailing Edge

Keywords

Noise Mitigation, Supersonic Jet, Swirl Vane, Circular Nozzle, Shear Layer Swirl

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Abstract

Environmental impact of aviation is measured in emissions and noise. The communities in the vicinity of airports bear the brunt of aircraft noise in takeoff, climb, flyover, approach and landing. The exposure to loud noise is harmful to human physiological and psychological health and welfare. The problem in the military (DoD) is even bigger since there are servicemen working in close proximity of advanced supersonic jets, in takeoff and landing. The research team at The University of Kansas has identified a novel and powerful means of mitigating jet noise by inducing shear layer swirl through embedded vanes near the nozzle exit lip. In this proof-of-concept study, we aim to demonstrate the feasibility of the concept through both high-fidelity computational simulations and experimental investigations.

The role of swirl in free turbulent jets is to trigger centrifugal instability, set up a radial pressure gradient and thus promote mixing by both means. However, large-scale swirl in the exhaust jet creates thrust penalty. Thus, a targeted approach to limited swirl induction in the nozzle inner and outer shear layer is proposed that injects the benefits of centrifugal instability waves in the nozzle inner and outer shear layers without incurring significant loss of thrust.

A comprehensive approach was taken that uses 1) Computational simulation track that involves high-order Computational Fluid Dynamics (CFD) and Computational Aero-Acoustics (CAA) and 2) Experimental track that involves a free-jet facility for jet noise/acoustic measurement. A benchmark supersonic nozzle problem was selected as the base-line, which was also used to verify and validate the present computational and experimental results. After that, swirl-inducing vanes were added to the nozzle, and many vane configurations were investigated both computationally and experimentally for jet noise mitigation.

When the vanes were added in the subsonic converging section of the nozzle before the throat, no noise reduction was found. When the vanes were added near the nozzle exit in the supersonic region, noise reduction of various degrees were discovered depending on the configuration of the vanes: height, swirl angle and solidity. Eight design iterations were performed using 3D-printed nozzles, and the best design was able to achieve over 3db reduction in noise. The results were reproducible in our free-jet facility.

Benefits

If the swirl-inducing vanes are demonstrated to be effective in a real-world military aircraft engine, advanced fighters will operate with significantly reduced noise at takeoff and landing. With civil supersonic flight on the horizon, the same noise mitigation idea may be also applicable. The scientific community benefits from a novel noise mitigation tool that may be used as an element of a smart aircraft engine component.

Executive Summary

1. Introduction

This project directly addresses aircraft engine noise reduction problem. Noise generated by high-performance military aircraft can be deafening. The main noise source is from the jet engine with a low bypass ratio. According to Tam [15] and Martens [11], the noise of a supersonic jet comprises three basic components: the turbulent mixing noise, the broadband shock-associated noise (BBSAN), and the screech tones.

Jet noise reduction for military aircraft continues to be a severe challenge. Finding solutions that reduce the noise significantly while minimizing cost and performance penalty continues to be a goal for many researchers, e.g., [6-10,12-14]. Two promising solutions were evaluated under support of the SERDP program: mechanical chevrons and fluidic chevrons/injection [8,12]. So far neither has been implemented in military aircraft. The search for a practical solution for supersonic jet noise mitigation is still ongoing.

In the present feasibility, proof-of-concept phase I study, we have investigated the concept of introducing embedded shear layer swirl in the exhaust nozzle for noise reduction, as shown in Figure 1. The role of swirl in free turbulent jets is to trigger centrifugal instability, set up a radial pressure gradient and thus promote mixing by both means [2-4]. The strength of the swirl is dictated by the vane height, the vane swirl angle, and the solidity. It appears this concept has the potential to significantly promote mixing, and reduce noise. In this Phase I study, we only investigated the influence of swirl angle and solidity. An investigation of the vane height is suggested to achieve the full benefits. A further study at the full scale is also needed to understand the noise mitigation capability and its cost and performance penalty.

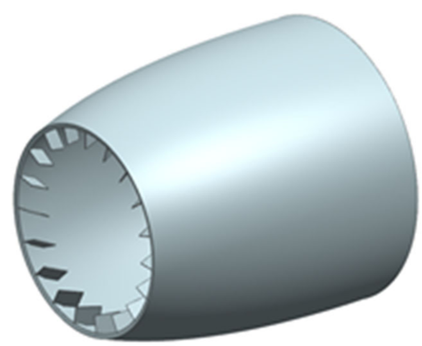



Figure 1. Schematic of swirl vanes near the nozzle exit(s) for noise reduction (not-to-scale)

2. Objectives

The principal objective of this project was to develop a new and innovative way to mitigate the excessive noise pollution generated by current supersonic military aircraft exhaust systems, thereby improving the Department of Defense's (DOD) ability to protect its flight deck personnel from auditory damage. Accordingly, this proof-of-concept project aimed to develop shear layer swirl vanes for convergent-divergent (CD) nozzles to reduce the noise of supersonic jets at far-field observer locations. The tested parameters included vane location, blockage, and swirl angle (SA). In addition to observing the acoustic response of the jet to different vanes configurations, thrust differentials were computationally extracted for configurations.

Specific research objectives were to:

- ❖ **Objective 1:** Test influence of vane location, SA, and blockage effect on jet flow-field and acoustic noise
- ❖ **Objective 2:** Establish thrust differentials for the vaned nozzle configurations
- ❖ **Objective 3:** Validate and verify computational and experimental testing procedures to ensure high confidence in results

In addressing these objectives, criteria for success of the SEED project were established as follows:

- ❖ **Criteria 1:** Establish agreement between experimental/computational results and a well-documented baseline reference case
- ❖ **Criteria 2:** Ensure that the far-field acoustic noise of jet is able to be decreased by ~3dB without significant impact to thrust differential
- ❖ **Criteria 3:** Develop reproducible testing protocols so results may be reviewed by other researchers

To date, the researchers which took part in this project have executed an experimental and computational plan that successfully achieved each of these objectives and met each of the established criteria for project success. In doing so, the researchers have acquired sufficient proof-of-concept data to establish that shear layer swirl-generating vanes are indeed effective in noise reduction of supersonic jets. Finally, the overarching implications and outcomes of this SEED project include:

- ❖ Development of innovative noise mitigation technique for current/future military and civilian supersonic aircraft
- ❖ The potential for reduced acoustic noise through the reduction of far-field turbulent mixing noise
- ❖ The potential for increased auditory safety of near-by flight deck personnel, primarily on aircraft carriers and airbases

3. Technical Approach

In order to test the effectiveness of swirl-inducing vanes in noise reduction, we selected a well-known supersonic jet noise problem as the baseline configuration without the vanes. This supersonic jet noise configuration has been studied in the literature with well-documented computational and experimental data [9,10], and is shown in Figure 2. A summary of the case parameters can be found in Table 1.

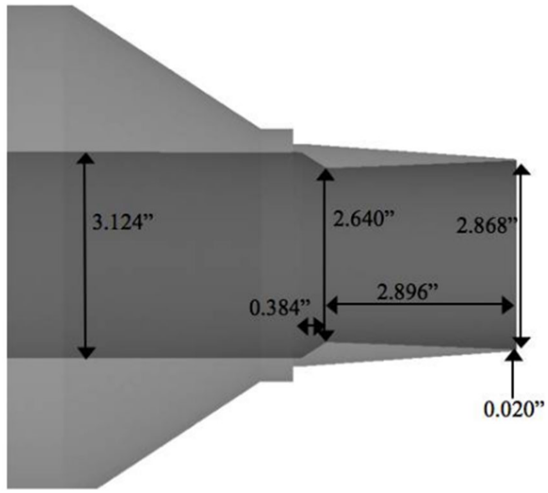


Figure 2. Geometrical dimensions of convergent-divergent baseline nozzle from [10].

Table 1: Operating conditions for the convergent-divergent baseline (CDB) test case

M_d	NPR	M_j	U_j(m/s)	D_j(mm)	Re_j	TTR
1.5	3.515	1.47	425.8	72.05	3.5 M	1.0

Both experimental and computational studies were performed for the baseline configuration in the verification and validation (V&V) stage. An experimental facility was established in KU's Flight Research Laboratory. A schematic of the experimental setup is shown in Figure 3. Acoustic treatment was applied on all exposed surfaces in the experimental chamber to reduce wall reflections.

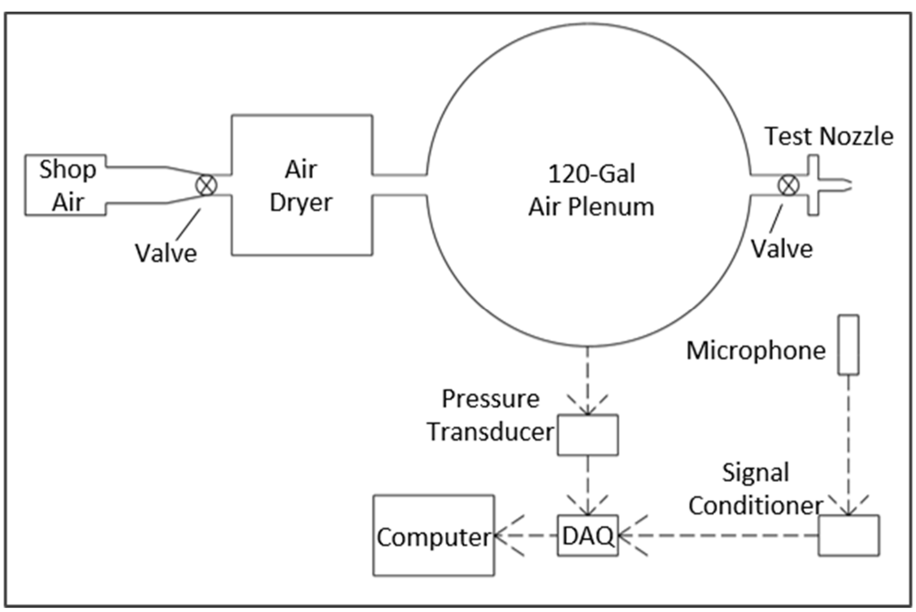


Figure 3. Schematic drawing of the jet noise research facility

A high-order large eddy simulation (LES) tool called hpMusic [17] was employed for computing the turbulent jet flow. HpMusic has been verified and validated on a wide variety of test problems, including aero-acoustic noise generated by a generic car mirror and the three-element airfoil problem. The near field acoustic noise can be computed from the pressure histories, while the far-field noise was extracted using a newly developed tool based on the Ffowcs-Williams and Hawkings (FWH) acoustic analogy [5,1]. A sample computational mesh for the baseline configuration is shown in Figure 4.

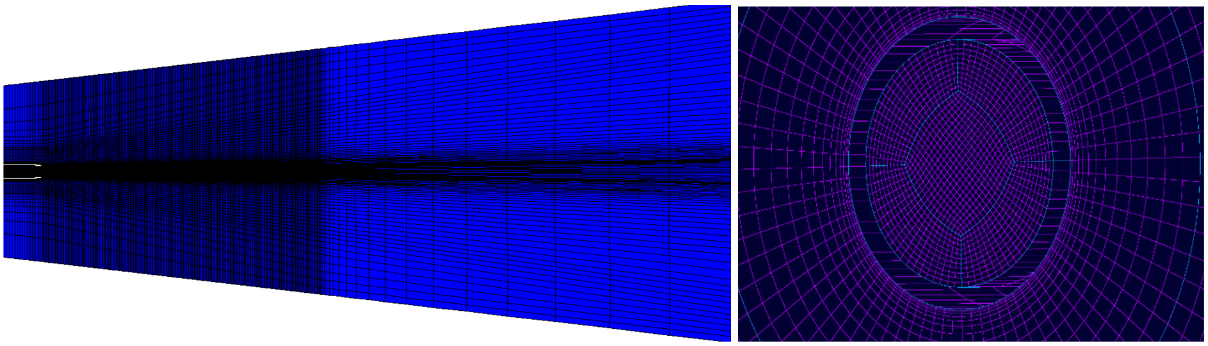
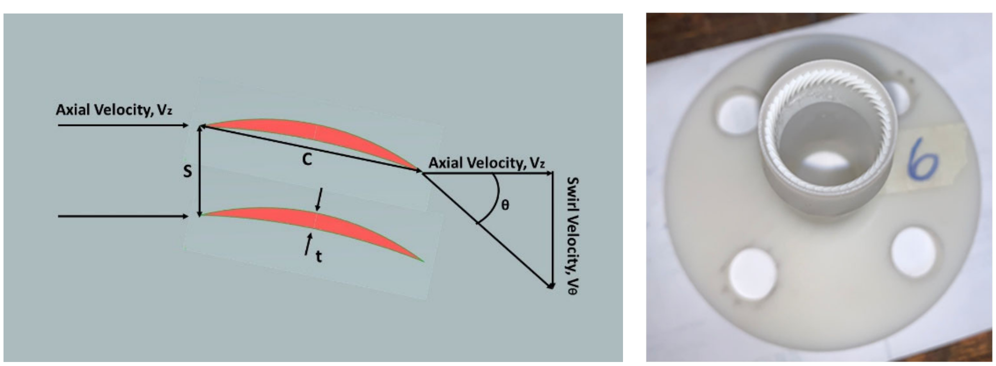


Figure 4. Mid-plane view of baseline nozzle mesh and a cross-section grid utilizing hexahedral discretization topology

After the V&V study, swirl-inducing vanes were then added inside the nozzle. A total of 10 configurations were studied experimentally using 3D printed nozzles, and 5 configurations were studied computationally. The LES studies turned out to be very expensive, and some cases took months to complete on our local cluster with 480 cores. Through trial and error, we decided to use low-profile, double-circular arc-based swirl vanes, as shown in Figure 5a. The parameters for the vanes include the chord length, vane height, solidity and swirl angle. The solidity of the configuration is defined as,

$$\sigma = \frac{c}{s}$$

where 'c' is the chord length and 's' is the spacing between the vanes as referenced from the leading edge.



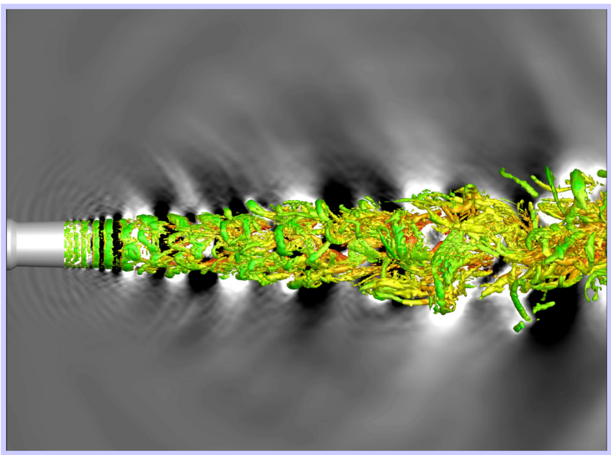
(a) (b)

Figure 5. (a)Vane schematic showing double-circular arc configuration. (b) Front view of a 3D-printed nozzle (patent pending)

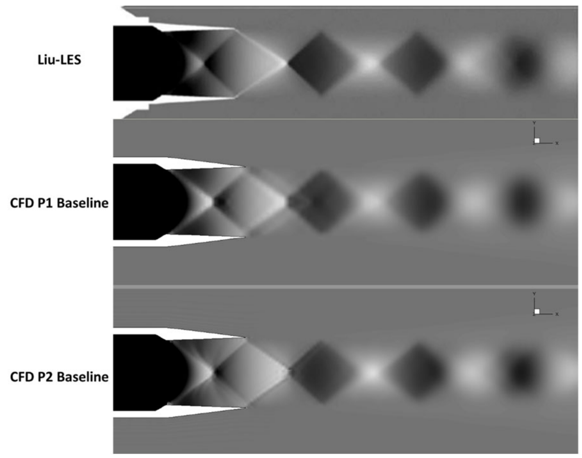
4. Results and Discussions

Verification and validation

The baseline configuration was used as a V&V case for our experimental and computational investigations. Both 2nd (p = 1) and 3rd (p = 2) order simulations were conducted to assess the mesh and order sensitivity. A computational flow field is shown in Figure 6a, which displays the iso-surfaces of the Q-criterion colored by the streamwise velocity with the pressure distribution in the background. Note that fine turbulent eddies were captured and one can clearly see down-stream and upstream traveling acoustic waves. The computed mean pressure distributions on the center cutting plane are compared with that in the literature [10]. There is a good qualitative agreement on the shock patterns, and the 3rd -order simulation showed visibly sharper shock waves.



(a)



(b)

Figure 6. (a) Iso-surfaces of the Q-criterion colored by the streamwise velocity with the pressure distribution in the background (gray), 3rd order computation. (b) Comparison of the mean pressure between the present simulations and the literature [10]

Next, we compare the far-field noise results between the present computation and experiment at an angle of 150°. An overall good agreement was achieved as shown in Figure 7.

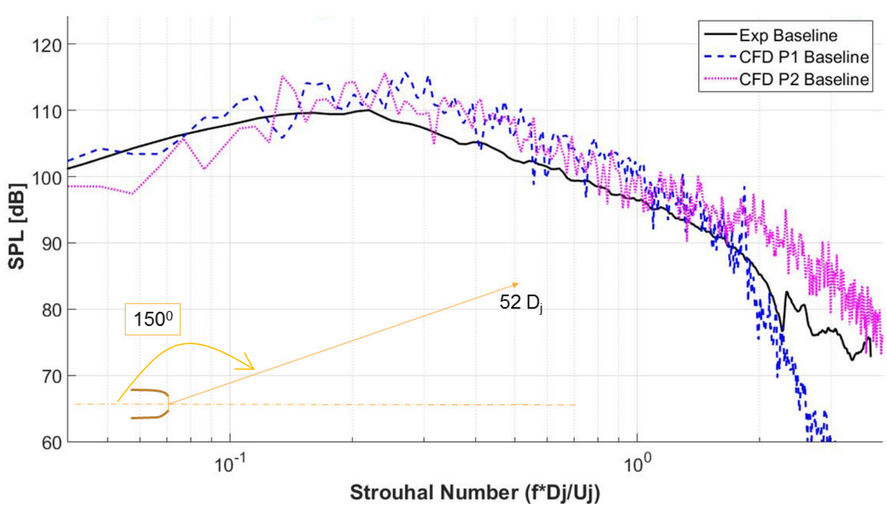


Figure 7. Comparison of far-field noise results between the present computation and experiment

Noise mitigation study with vanes

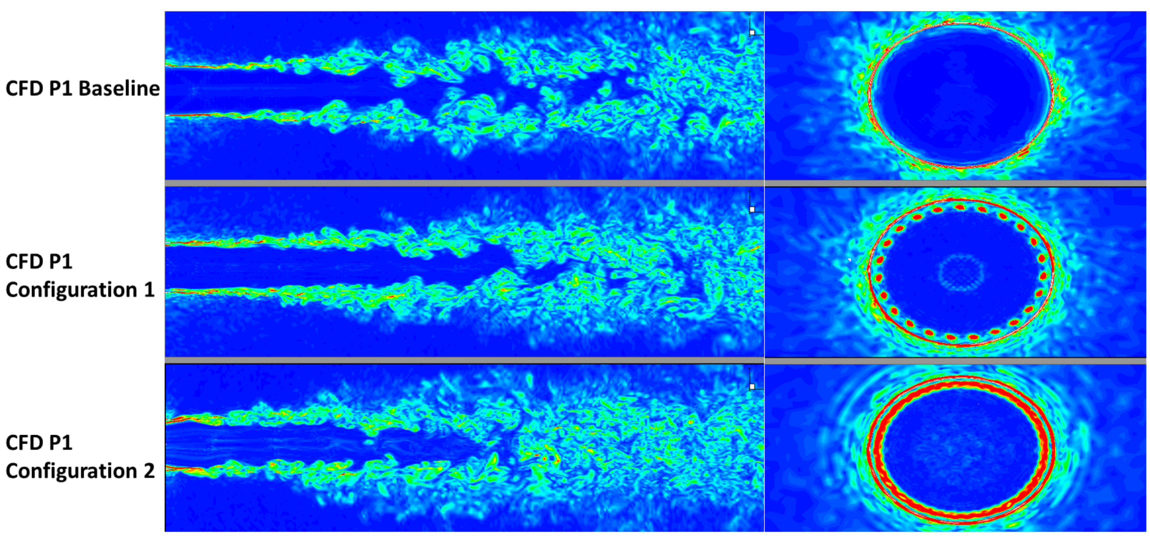
We first tested the impact of vane location. Initially we put vanes in the subsonic region just ahead of the throat. Both the computational and experimental results showed insignificant change in noise levels.

Next, we placed the vanes near the nozzle lip, as shown in Figure 5b. A total of 8 configurations were tested experimentally because of the ease in manufacturing the nozzles using 3D-printing. The computational studies were more time-consuming because of the difficulty in generating high-quality computational meshes with the vanes, and the much-increased computational cost with the vanes present. These configurations were designed to study the influence of various vane parameters: location of the vanes, swirl angle (SA) and vane solidity. Two representative configurations are presented next.

The following three nozzle configurations in Table 2 were tested experimentally as well as computationally. The larger the solidity, the more vanes are placed inside the nozzle. The two vaned configurations significantly enhanced the mixing, as shown in Figure 8, which displays the distribution of the streamwise vorticity magnitude. Note that indeed the vanes added a lot of vorticity in the flow field, promoted mixing, and visibly reduced the jet core length.

Table 2: Vaned nozzle configurations with various blockage specifications

Configuration	X_{LE}/D_e	***Solidity (σ)***	***Swirl Angle (SA)***
CDB (Baseline)	N/A	N/A	N/A
Configuration 1	-0.325	2.000	25°
Configuration 2	-0.325	4.000	60°



(a): Midplane vorticity magnitude (b): Vorticity magnitude at x = 0D

Figure 8. Comparison of computed vorticity magnitude for vaned nozzle configurations

The computed mean Mach number distributions at the meridional plane are shown in Figure 9 for all three configurations. Indeed, the length of the jet core is reduced. In addition, the shock structures are also significantly altered.

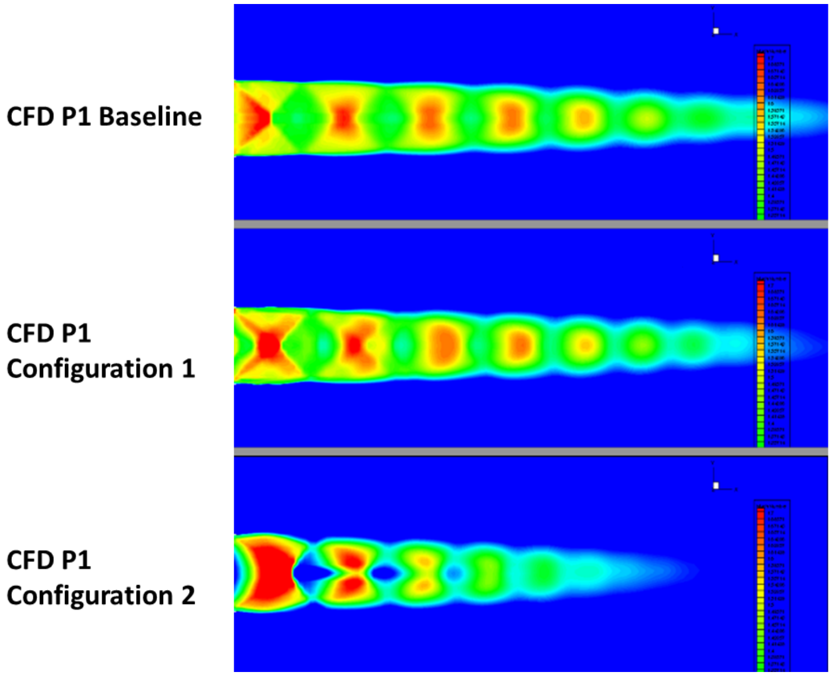


Figure 9. Comparison of computed mean Mach number for different vane blockage configurations

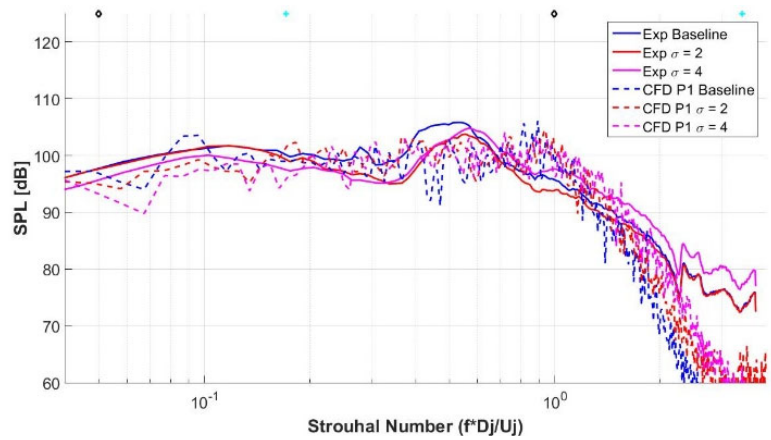
In the present study, we were not able to measure the thrust experimentally. Instead, computations were used to estimate the gross thrust according to the following formula:

$$F_g = \iint_{A_{exit}} \rho(\vec{V} \cdot \hat{n})^2 dA + \iint_{A_{exit}} (P - P_\infty) dA. \quad (1)$$

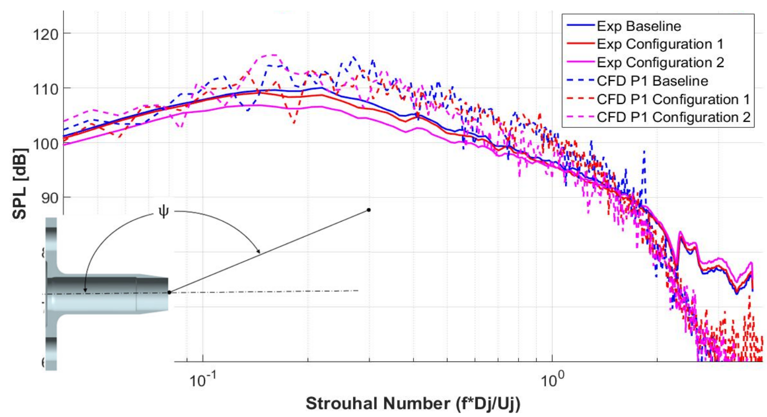
The thrust for the three configurations were estimated, and the thrust penalties for Configurations 1 and 2 with respect to the baseline are 0.8% and 3.5% respectively.

The far-field results in both the experiment and the computation at the angles of $\psi = 70°, 150°$ are displayed in Figure 10. Because of the limited duration of the computation, the computational results are quite noisy, and we are unable to make definite conclusions. The experimental results, however, clearly showed that the vaned configurations reduced noise over a wide range of frequencies. From here on, we will focus on the experimental results.

Next, we present the experimental results varying the swirl angle (SA) only with other geometric parameters being exactly the same. Figure 11 shows the sound pressure level (SPL) of the far-field noise (i.e., 52 D_e) at $\psi = 140^o$ for CD nozzles with swirl angles of 25^o, 60^o and 75^o respectively with all vaned nozzles having a solidity of four. The reference 3 dB scale is shown to facilitate SPL comparisons over the range of Strouhal numbers corresponding to the audible range (20 Hz-20 kHz). As expected, swirl inhibited jet noise between 3-5 dB over the baseline configuration at 140^o in the far-field (52 D_e). The results for other far field locations at different angles are similar and therefore not repeated here.



(a) ψ = 70°



(b) ψ = 150°

Figure 10. Comparison of computed and experimental SPL at two angles for various vane blockage configurations

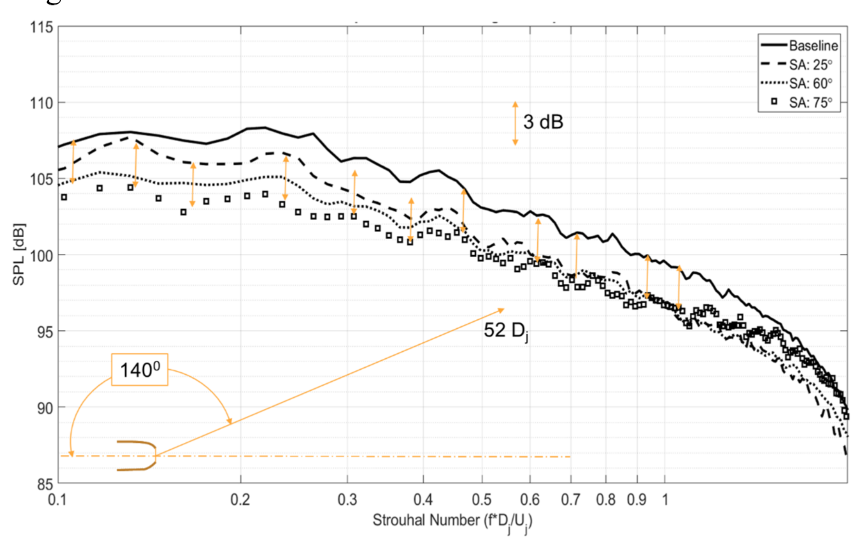


Figure 11: The effect of shear layer swirl angle on far-field supersonic jet noise spectra

Finally, we show the effects of the nozzle location on noise reduction. The swirl vanes were near the nozzle exit plane and at the nozzle exit plane. Figure 12 shows the far-field noise at $\psi = 90^o$. The baseline CD nozzle shows the screech followed by the broadband shock-associated noise (BBSAN). Again, the reference 3 dB scale is used to facilitate viewing the results in Figure 12. The vanes produce three profound effects, namely:

1) eliminates the screech (note the 6 dB reduction)
2) reduces jet noise by 3 dB over a broad range of Strouhal number
3) shifts the jet noise spectra to higher frequencies

5. Implications for Future Research and Benefits

Over the past year of the SERDP support, we have executed an experimental and computational plan that successfully achieved the objectives outlines in our original SEED proposal. Via this proof-of-concept investigation, we have demonstrated that embedded swirl in a supersonic shear layer through the use of vanes can be used to reduce the acoustic noise of an unheated supersonic jet. More importantly, results show that a ~3dB (50% acoustic power) reduction can be obtained through the use of these vanes, thereby greatly enhancing the auditory safety of personnel that operate within close proximity to these high-speed jets. As a result, our hypothesis of supersonic jet noise mitigation using shear layer swirl is validated. Our multi-facetted research indicates that swirl

- ❖ Impacts turbulent mixing noise
- ❖ Reduces the jet core length
- ❖ Eliminates screech
- ❖ Mitigates jet noise by 3 dB+, over a broad range of Strouhal number
- ❖ Low-profile, embedded device may be used to generate the centrifugal instability
- ❖ Through nozzle and vane shape optimizations, we may be able to further reduce the thrust penalty

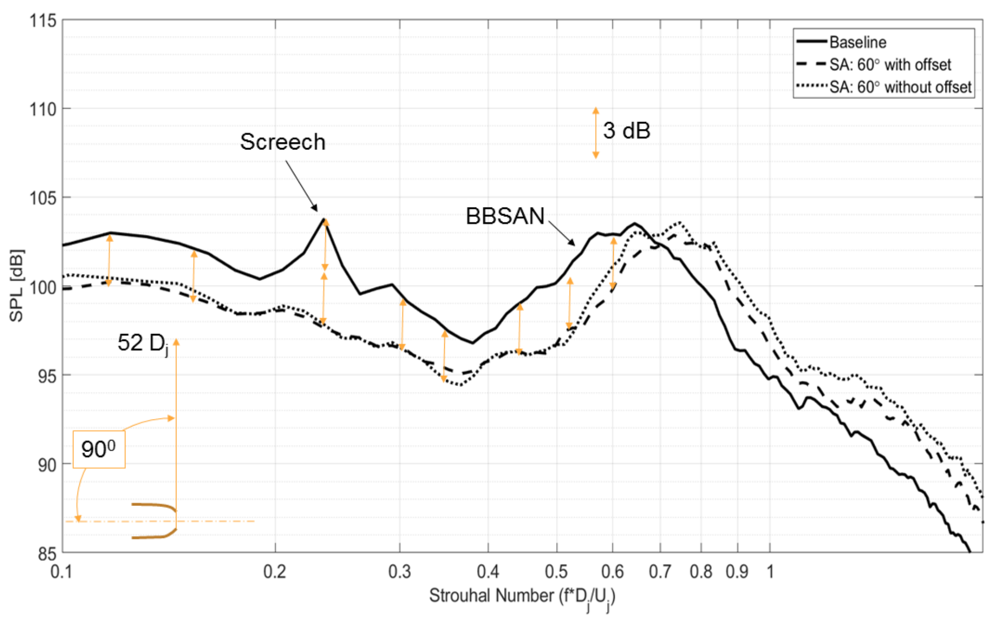


Figure 12. The effect of vane axial location on far-field supersonic jet noise spectra

While the results so far have been very promising, more work is needed to realize the full potential of swirl-generating vanes in jet noise reduction in actual supersonic military aircraft. Although a 3+dB noise reduction has been achieved at the laboratory scale, a similar level of noise reduction must be demonstrated for a nozzle matching the size of a supersonic fighter aircraft before a practical implementation can be carried out. In addition, real world nozzles are "heated" nozzles. Therefore, it would be prudent to also demonstrate the noise reduction capability for heated nozzles. We therefore suggest the following topics for a follow-up study (either Phase I or Phase II):

1. Optimize the vane chord length, height and shape for swirl generation and thrust. Preliminary calculations put the thrust penalty for Configuration 1 and 2 between 0.8-3.5%. Through optimization, we believe the thrust penalty can be significantly decreased.
2. Examine the performance of vaned nozzle in heated jet configurations. A verification and validation of the present vaned configurations will boost our confidence in the capability of the vanes for a wide range of flow conditions.
3. Verify the present study in a scale comparable to the real world. This is a critical step which is necessary before an implementation.

The KU team can perform topics 1 and 2, and will team up with another university, an engine manufacturer such as the General Electric Company and the US government to perform topic 3.

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Appendices

Appendix A.1:

Additional results regarding vaned nozzle configurations

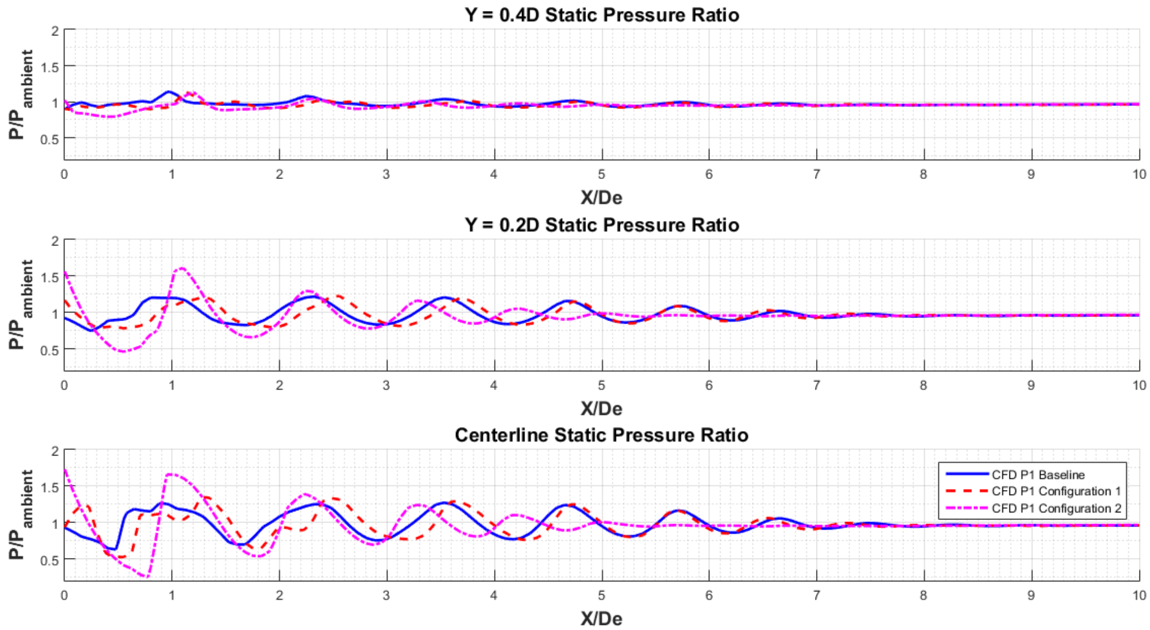


Figure 13. Comparison of computed static pressure ratio at three different radial extents for various vane blockage configurations

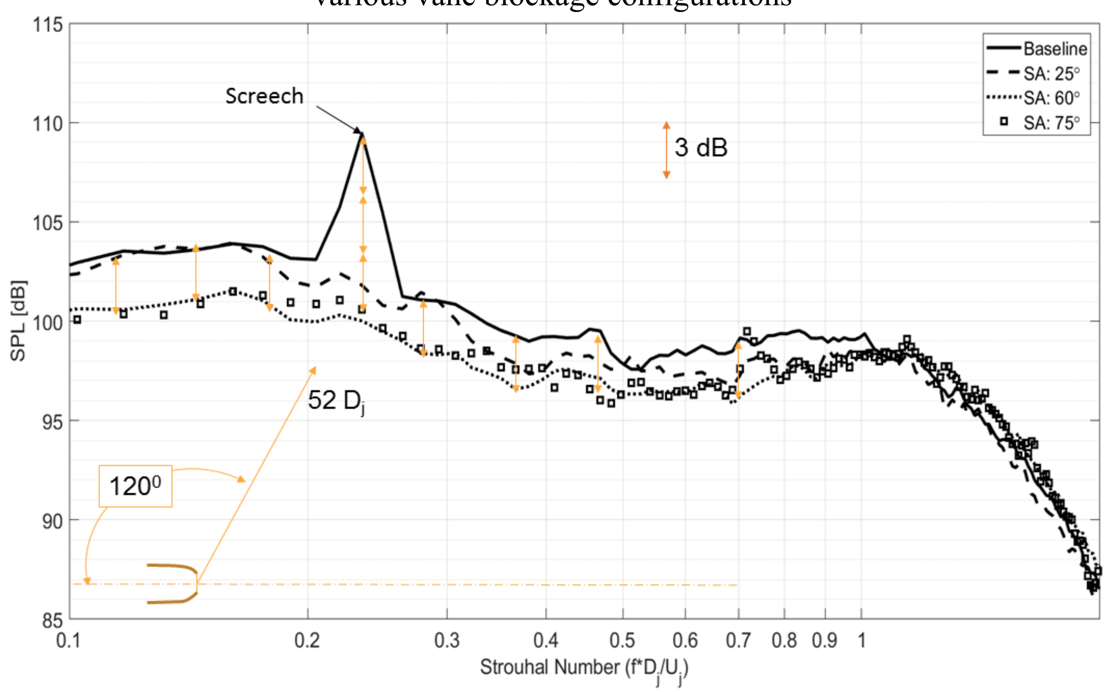


Figure 14: The effect of swirl angle on far-field supersonic jet noise spectra at $\psi = 120^{o}$

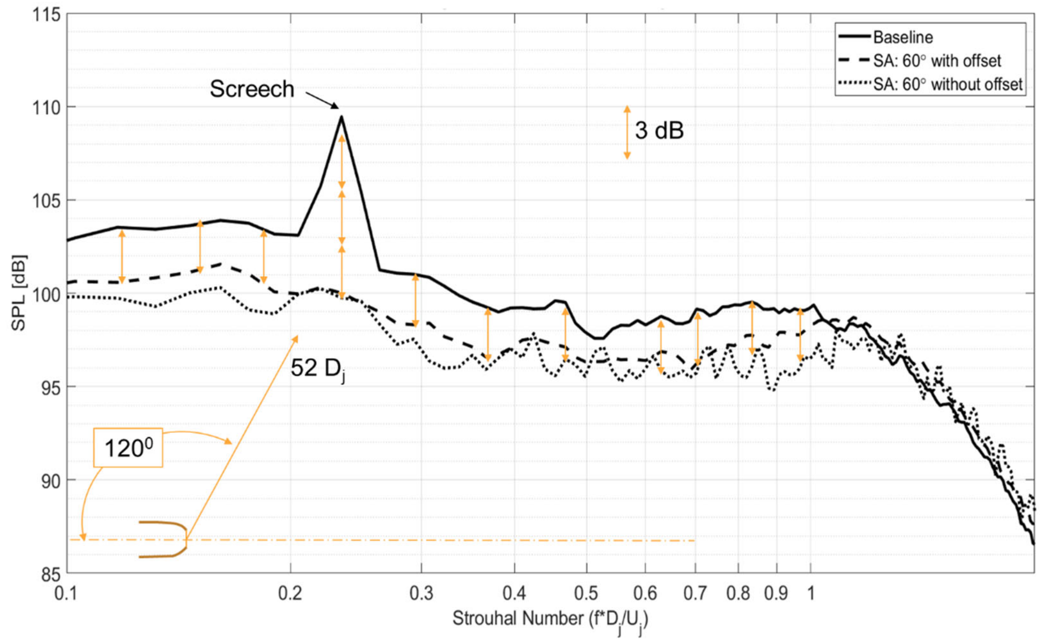


Figure 15. Far-field noise spectra at ψ = 120º for vaned nozzle configurations with and without axial offset

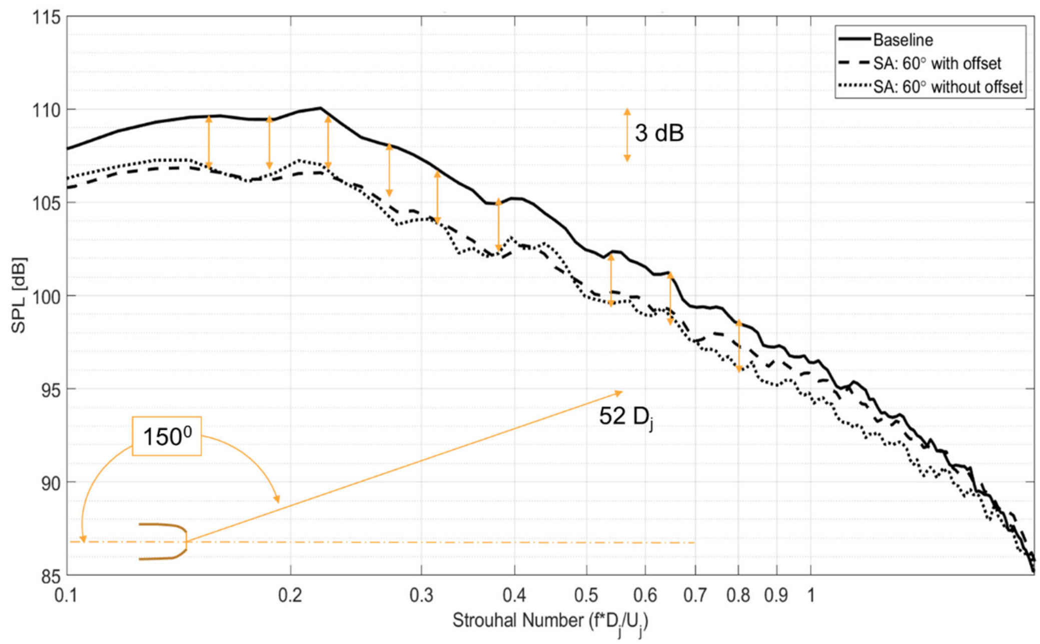
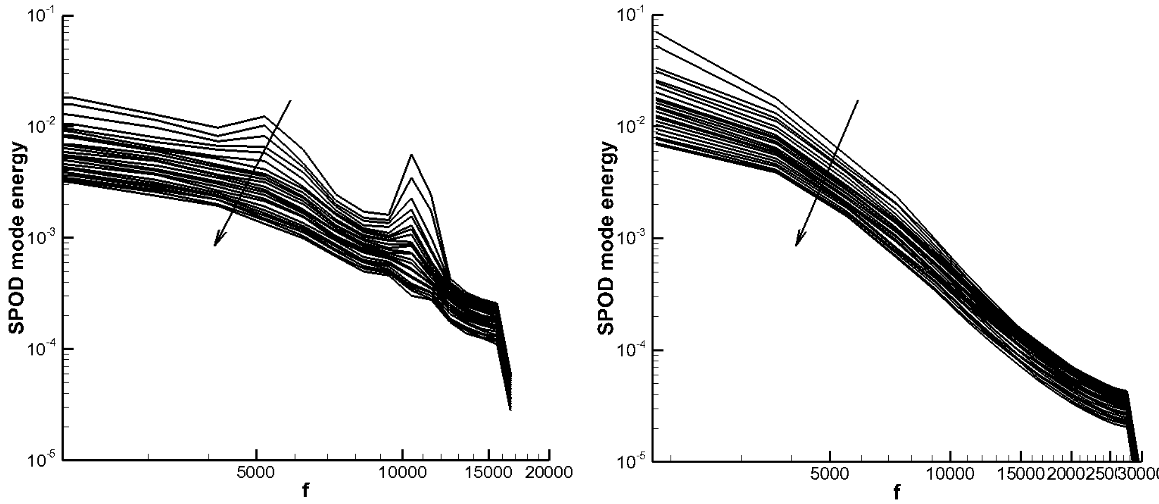


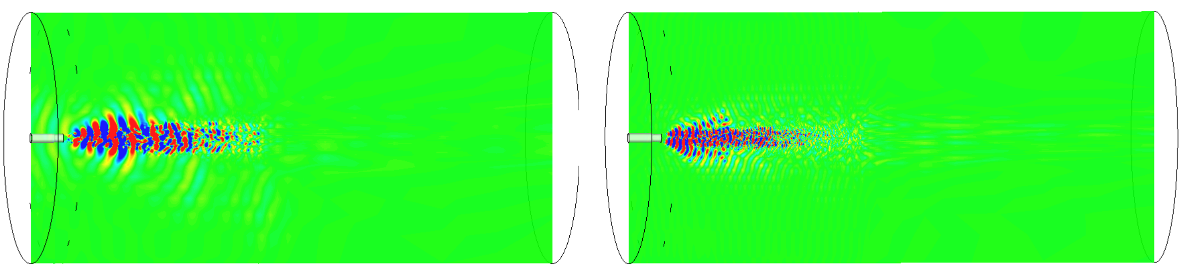
Figure 16. Far-field noise spectra at ψ = 150º for vaned nozzle configurations with and without axial offset

Appendix A.2:
SPOD analysis and flow-field reconstruction

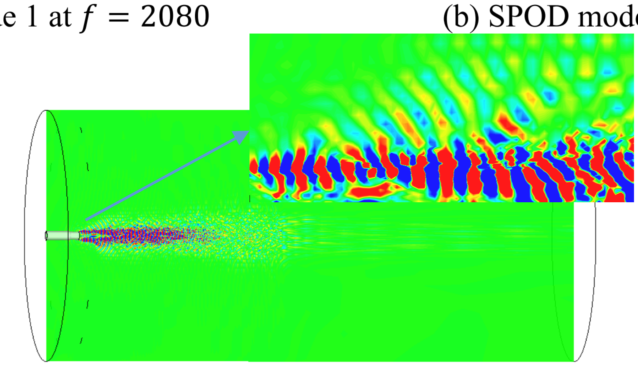


(a) Baseline Nozzle (b) Configuration 2

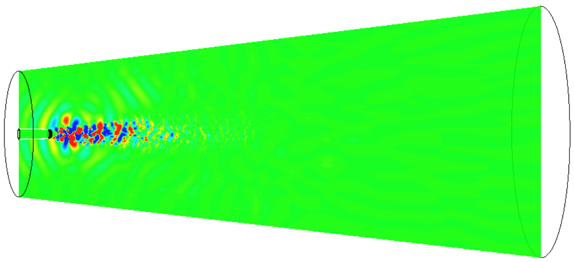
Figure 17. SPOD energy distribution with frequency



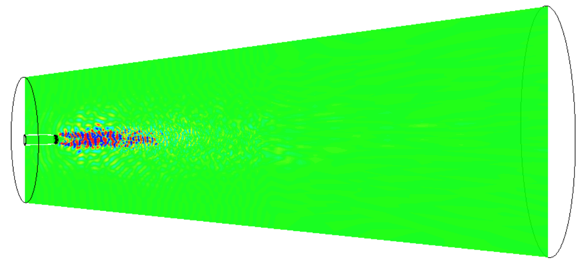
(a) SPOD mode 1 at $f = 2080$ (b) SPOD mode 1 at $f = 5208$



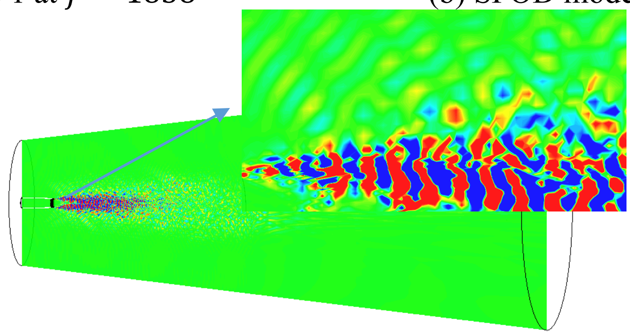
(c) SPOD mode 1 at $f = 10416$
Figure 18. SPOD modes at different frequencies for the baseline nozzle, color from -0.0005 to 0.0005



(a) SPOD mode 1 at $f = 1838$



(b) SPOD mode 1 at $f = 5514$



(c) SPOD mode 1 at $f = 11029$

Figure 19. SPOD modes at different frequencies for Configuration 2, color from -0.0005 to 0.0005

(a) Original flow field

(b) Reconstructed flow field

Figure 20. Original and reconstructed flow field, colored from 8000 Pa to 200000 Pa

Appendix B: Publications

S. Rahmani, M. Alhawwary, Z.J. Wang, J. Phommachanh, C. Hill, B. Hartwell, B. Collicott, J. Swim, S. Farokhi, R. Taghavi, H. Wu, M. Zhang, Z. Zheng, ”Noise Mitigation of a Supersonic Jet Using Shear Layer Swirl,” AIAA SciTech 2020 Forum, AIAA-2020-0499.

Appendix C. Patent Application

PATENT APPLICATION
Docket No.: 20KU022L-01

UNITED STATES PROVISIONAL PATENT APPLICATION

of

Saeed Farokhi

Ray Taghavi

Zhi Jian Wang

Huixuan Wu

and

Zhongquan Zheng

for

METHODS AND SYSTEMS OF MITIGATING JET NOZZLE NOISE