

High Speed Jet Noise Mitigation Using Microjet Injection

Brenton Greska and Anjaneyulu Krothapalli

Florida State University
Department of Mechanical Engineering
2525 Pottsdamer Street, Room A229
Tallahassee, Florida 32310

akrothapalli@fsu.edu

ABSTRACT

This paper serves as a review of the experimental results that have been obtained using microjet injection to reduce the noise produced by a high-speed jet. This technique utilizes high pressure (400 – 800 psig) air/water microjets that are injected into the main jet just downstream of the nozzle exit to create streamwise vortices, which alter the turbulence characteristics in the noise producing region of the jet to result in substantial reductions in the far-field noise. Developed at the laboratory scale using a 1/10th-scale nozzle, reductions of up to 6 dB have been observed in the peak radiation direction. The dominant parameter that determines the magnitude of the noise suppression has been found to be the momentum ratio between the microjets and the main jet. The laboratory results were validated on a full scale F404-GE-402 engine at static conditions. Forward flight simulation results obtained utilizing a 1/5th-scale nozzle at the Boeing Low Speed Aeroacoustic Facility (LSAF) suggest that the technique is viable for practical implementation for the purpose of full-scale fighter jet noise mitigation. Addressing the twin engine nature of some carrier-borne fighter aircraft, microjet injection was employed on a 1/10th-scale twin nozzle configuration and it produced reductions of almost 5 dB and 8 dB in the peak radiation direction and forward quadrant, respectively. As a result, the best application of water microjet injection is the substantial mitigation of the jet noise on the flight deck of an aircraft carrier.

1.0 INTRODUCTION

Almost sixty years after the introduction of the first jet engine powered carrier-borne fighter, the XFD-1, the U.S. Navy finds itself in a precarious situation with its most recent carrier-borne fighter, the F/A-18E/F Super Hornet. Producing almost 35% more thrust than its previous variant, the F/A-18C/D, the engines utilized by the Super Hornet produce jets that generate significantly more jet noise. Once romanticized as “the sound of freedom”, the jet noise from fighter airplanes is now considered by the general public to be a detriment to their quality of life. And while this noise is a nuisance to the general public, it can be harmful to those who must work within close proximity to it on a daily basis, such as the people who work on the flight deck of an aircraft carrier. Unfortunately, the solution employed on commercial airplanes, the high bypass ratio turbofan engine, cannot be used on supersonic military fighter airplanes due to the required large inlet areas. As such, there currently exists a need for the development of jet noise reduction techniques that do not adversely affect the jet engine performance, most notably the thrust.

Since the early days of jet noise research,^{1,2} a vast knowledge of jet noise control techniques has been acquired, with some of the methods contributing to reductions in jet noise. One such example is the subdivision of a normal circular jet into numerous elements that would promote rapid mixing. Such an approach results in the reduction of the sound pressure level (SPL) for the high-energy, low frequency noise, accompanied by increasing SPL at higher frequencies. The practical problem of subdividing the jet,

High Speed Jet Noise Mitigation Using Microjet Injection

with minimal performance loss, led to a number of concepts such as nozzle exit profile variations through the insertion of chutes or corrugations around the periphery and multi-lobed nozzle in conjunction with lined ejector suppressors, just to name a few. Although the objective of these concepts was to produce the maximal low frequency sound reduction, the aerodynamic performance was vastly different for the different designs. The performance losses associated with these devices are due to the external drag resulting from the air flowing over the complex geometries and the thrust losses due to more complicated gas passages. For most suppressor designs, the magnitude of noise reduction against take-off thrust loss, increased weight and external drag are unacceptable for their implementation. Recently, Seiner et al.^{3,4} successfully introduced a novel method referred to as “internal corrugations” to achieve significant noise suppression (~5 dB) of heated axisymmetric supersonic jets. This method refined the design of corrugations, cleverly utilizing the internal aerodynamic features of the converging-diverging nozzle geometry to avoid any thrust losses that are commonly associated with such approaches.

In order to develop an effective jet noise reduction technique, one must have an understanding of the sources of noise that are present in the high-speed jets that are produced by supersonic military airplanes, such as the Super Hornet. Based on a review of the relevant literature, Crighton⁵ determined that high-speed jet noise consists of turbulent mixing noise, similar to that generated by subsonic jets, as well as the additional noise sources of Mach wave radiation and shock-associated noise, which can be avoided by operating the engine at the condition near the nozzle design condition. In order to reduce the turbulent mixing noise, one would have to develop a reduction technique that reduced the turbulence levels in the jet, an attempt that has eluded researchers for the last few decades because it is difficult to do without negatively affecting the thrust. On the other hand, in order to reduce the Mach wave radiation, one would simply have to develop a technique that affected the large-scale structures that are responsible for the generation of Mach wave radiation. However, the maximum noise reduction that could be obtained using this approach would be at best about 5 dB.⁵

Bishop et al.⁶ suggested that the most important noise sources of a high-speed jet are confined to the mixing region that surrounds the jet potential core. As such, the near-field will be dominated by the noise generated by the supersonically convecting large eddies that have yet to become indistinct and stretched into the random motion that is commonly associated with turbulent mixing layers. Therefore, these sources are associated with an unsteady flow on a scale that is of the order of the shear layer width. Bishop et al.⁶ suggested that the introduction of strong axial vortices to impede the large eddy structure may help mitigate the noise. However, for the design of effective noise control schemes, it is important to determine the location and the extent of the noise producing region with the varying jet parameters of nozzle pressure and temperature ratios. Due to limitations of measurement techniques to obtain flow data for heated supersonic jets, pressure fluctuation measurements were made in the near-field, within a few nozzle diameters (ND) of the jet centreline, to determine the extent of the noise producing region. For a description of the experiment, reference can be made to a recent paper by Greska et al.⁷ Figure 1 depicts the variation of the overall sound pressure level (OASPL) with downstream distance, covering from the nozzle exit to 30 ND, at a transverse location of $y/D = 5$. A peak in the magnitude of the near-field pressure fluctuations is seen at the location corresponding to the end of the potential core. Also, it can be seen that an increase in the jet temperature has a minimal effect on the rate of increase of the observed OASPL values beyond a temperature ratio (stagnation temperature/ambient temperature) of about 2.5. In fact, the sharp rise in OASPL values has been attributed to the generation of high intensity Mach waves. For example, the exit velocity of the jet at a temperature ratio (TR) of 4 is about 1125 m/s as compared to a value of 515 m/s for the TR = 1 jet. The figure also suggests that the heated jets have a shorter potential core than the cold jet. The rapid mixing of the shear layer at elevated temperatures will result in a shortened potential core length followed by rapid centreline velocity decay.⁸ As a result, it appears that the extent of the maximum pressure fluctuations region of the heated jets extends from the end of the potential core to about 20 diameters downstream. Beyond this region, the OASPL drops precipitously until it is about 10 dB less than the peak value at $x/D = 30$. Hence, any control technique must be able to affect the peak noise producing region that is located beyond 10 nozzle diameters. For example, a recent study by

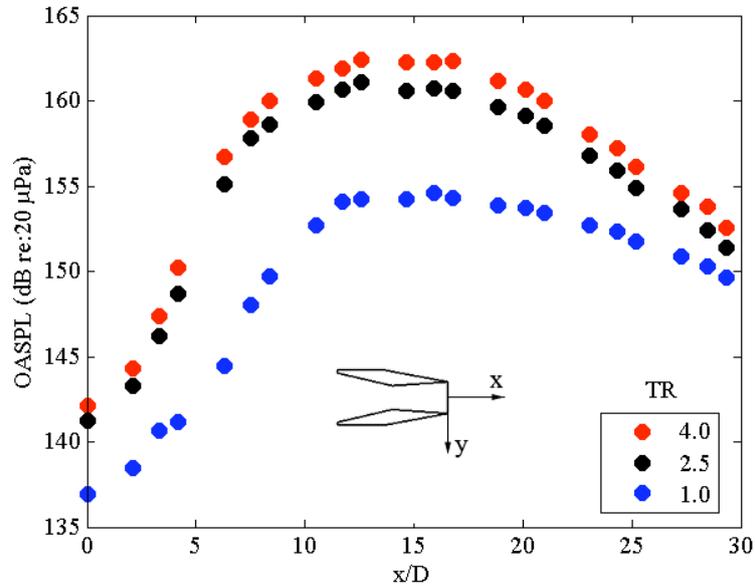


Figure 1. Near-field OASPL values for different temperature ratios (TR) at a distance of $y = 5D$ from the jet centerline. $M_j = 2:0$.

Alkislar et al.⁹, using a $M=0.9$ cold jet, has shown that the commonly suggested use of “chevrons” generates streamwise vortices that decay rapidly with downstream distance, thus limiting their influence to a small region of the jet. In contrast, the counter-rotating streamwise vortex pairs generated by microjet injection, located primarily on the high-speed side of the initial shear layer, last longer and possess the ability to affect the jet in the peak noise generating region. Alkislar et al.⁹ also showed that the measured far-field OASPL illustrates that microjet injection provides relatively uniform noise suppression for a wider range of sound radiation angles when compared to that of a nozzle utilizing chevrons. As shown by Seiner et al., the effectiveness of chevrons in high-speed jets can be enhanced with increased penetration into the jet, thereby producing long lasting streamwise vortices, albeit with a significant thrust penalty.³

As mentioned, high pressure microjet injection is one method of introducing axial vortices in high-speed jets and it has been successfully demonstrated in subsonic and cold supersonic jets.^{9,10,11} It has also been shown to be effective at reducing the far-field noise produced by both heated laboratory scale jets and full-scale jet engines.^{12,13,14} Another benefit of microjet injection is the ability to vary the operating medium. By using a medium such as water, the Mach wave radiation and turbulence levels can be reduced simultaneously without affecting the mean flow properties of the jet. In the case of water injection, the microjets reduce the size of the large eddies and the shear breakup of the microjet into micron size droplets in the shear layers helps to reduce the magnitude of the turbulence shear stress.¹¹ When the droplets reach a minimum size of about $4 \mu\text{m}$ or less, they are unaffected by the high temperature of the jet stream; a phenomenon that is related to time scales of droplet evaporation and convection. As a result, the droplets can exist in the noise producing region of the jet (10 or more diameters downstream of the nozzle exit), which can result in mixing noise reduction through the suppression of turbulence.

The effectiveness of microjet injection has been found to be dependent on a number of parameters. Figure 2 illustrates these parameters, which consist of the micro-nozzle diameter, d , the main nozzle radius, R , the angular spacing between micro-nozzles, θ_s , and the angle of microjet injection, θ_i . Based on a limited parametric optimization, the optimal microjet spacing ratio was found to be $d/s=0.04$, where $s = R\theta_s$ is the arc length affected by a single microjet. The optimal angle of injection, θ_i , was found to be 60 degrees. The momentum ratio, which quantifies the penetration depth of a jet into a crossflow, was also found to be

High Speed Jet Noise Mitigation Using Microjet Injection

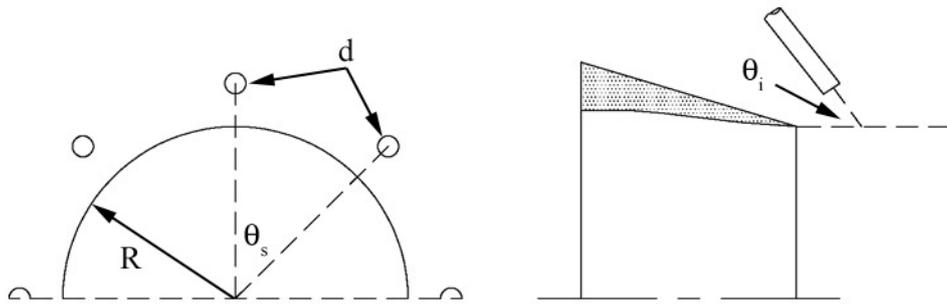


Figure 2. Schematic illustrating the micro-nozzle configuration around the main nozzle. Left: nozzle exit; Right: nozzle exit profile.

an important parameter. The momentum ratio, J , is defined as:

$$J = \frac{\rho_{mj} U_{mj}}{\rho_j U_j}$$

where U and ρ are the fully expanded jet velocity and density, respectively, and the subscripts mj and j are indicative of the properties for the microjets and the main jet, respectively. Figure 3 illustrates the effectiveness of microjet injection in the peak radiation direction as a function of the momentum ratio. According to the figure, reductions of up to 6 dB can be achieved if the momentum ratio is sufficiently high. It is important to note that the plot includes the data obtained from two full scale jet engines.^{13,14}

This paper serves as a review of the experimental results that have been obtained using microjet injection to reduce the noise produced by a high-speed jet. The first results that will be discussed are those that were obtained using microjet injection on a single 1/10th-scale laboratory nozzle. These will be followed by the results obtained using microjet injection on a F404-GE-402 jet engine operated at mil-power. The single nozzle results will conclude with a discussion of the results obtained for a 1/5th-scale model test based on the nozzle from an F414-GE-400 jet engine operating with and without simulated forward flight. These single nozzle results will be followed by the results obtained using a 1/10th-scale twin-nozzle

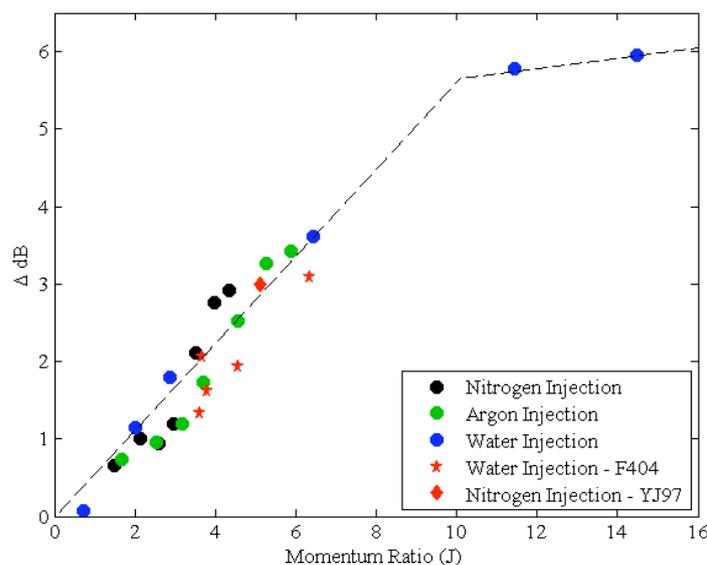


Figure 3. Effect of momentum ratio on jet noise reduction in the peak radiation direction.

configuration based on the aft end of an F/A-18E/F Super Hornet.

2.0 SINGLE NOZZLE RESULTS

2.1 1/10th-scale Laboratory Simulation

The 1/10th-scale experiments were conducted in the High Temperature Supersonic Jet Facility at the Florida State University (FSU). This blow-down facility is capable of generating the high-pressure, high temperature airflows that are necessary for an accurate simulation of the jets that are produced by jet engines. This is accomplished through the use of a sudden expansion (SUE) burner that combusts ethylene in order to heat the high-pressure air supply, up to stagnation temperatures of 1700 K. The heated jet exhausts into a fully anechoic chamber that is 5.2 m wide, 5.8 m long, 4.0 m high and has a cut-off frequency of 300 Hz. After a distance of 3.4 m, the jet exhausts to the atmosphere by way of an acoustically treated duct. A more in-depth discussion of the facility can be found in Greska.¹⁵

The nozzle for these experiments was based on the geometry of the mil-power condition of the F414-GE-400 jet engine. This engine currently serves as the power plant for the F/A-18E/F Super Hornet, hence the decision to focus on its use. The experimental results discussed here were obtained using operating conditions similar to the mil-power operating condition of the F414. The microjets in the facility at FSU were generated through the use of six 800 μm converging axisymmetric micro-nozzles, as shown in Figure 4. The micro-nozzles were connected to feeder tubes that were bent such that they made an angle of 60 degrees from the upstream jet axis. The feeder tubes set the exit of the micro-nozzles at a downstream distance of 6 mm and a radial distance of 5 micro-nozzle diameters from the inside edge of the main nozzle exit. The feeder tubes were then connected to a toroidal manifold that had four static pressure taps on it for determining the stagnation pressure of the microjets. Water was used as the operating medium of the microjets and it was supplied at a pressure of 800 psig.

Figure 5 illustrates the results that can be obtained using an optimally configured microjet injection scheme. A reduction of almost 6 dB can be seen in the peak radiation direction, as well as a reduction of 3 dB in the forward quadrant. Examination of the frequency spectra in the peak radiation direction reveals that the increased noise reduction is due to a reduction at all of the frequencies, with the biggest increase occurring at the higher frequencies associated with Mach wave radiation. Worthy of note is that the

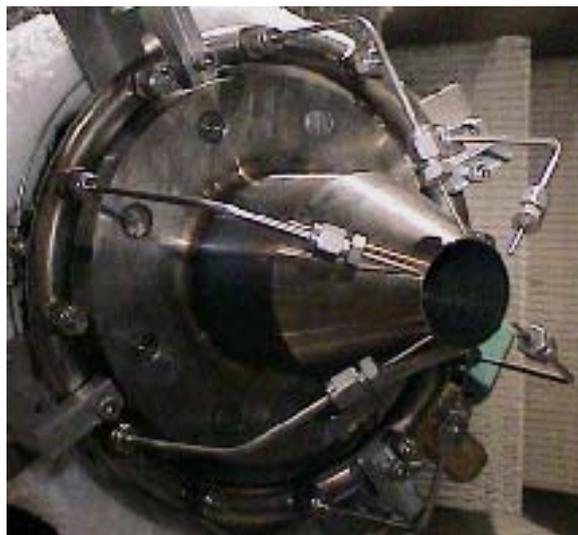


Figure 4. 1/10th-scale FSU laboratory nozzle with micro-nozzle array.

High Speed Jet Noise Mitigation Using Microjet Injection

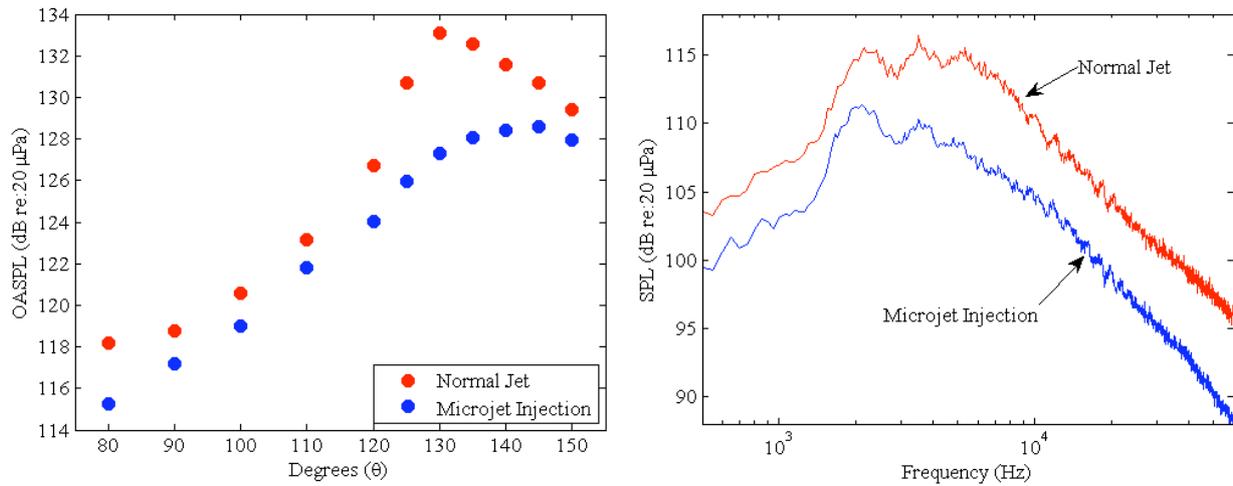


Figure 5. Results obtained using 800 psig microjet injection on a 1/10th-scale laboratory nozzle. Left: farfield directivity; Right: peak radiation direction narrowband spectra.

reduction in the low frequencies is indicative of a reduction in the turbulent mixing noise.

2.2 F404 Jet Engine Results

The F404-GE-402 jet engine test was conducted at the Propulsion Systems Test Facility at the Lakehurst Naval Air Warfare Center. This remotely located outdoor test site consisted of a large concrete pad and infrastructure required for operating the jet engine. The F404 was installed on a static test stand that was located atop a linear thrust balance. This setup resulted in the engine centerline being 5.5 m above the ground, thus reducing any acoustic reflections that might complicate the data analysis. The jet engine controls and the acoustic data acquisition system were located inside the control building that was located at an angle of 90 degrees to the nozzle exit and at a distance of approximately 200 m. More detail about the test facility, experimental setup and results can be found in Greska et al.¹⁴



Figure 6. F404 jet engine with the micro-nozzles installed.

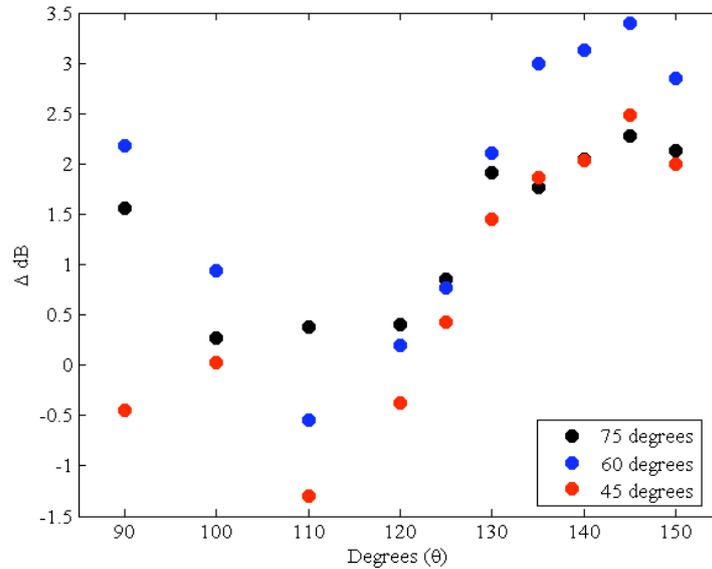


Figure 7. Effect of injection angle on the effectiveness of microjet injection.

The microjets for these experiments were generated through the use of converging axisymmetric micro-nozzles that had exit diameters of 4.0 mm. Micro-nozzle manifolds were installed onto each one of the twelve outer divergent flaps on the F404, as shown in Figure 6. Each of these manifolds had provisions for three micro-nozzles, one inner and two outer, thus allowing for a maximum of 36 micro-nozzles. However, it was found that the optimal results were obtained when using only the inner micro-nozzle. As such, the results presented here involve the use of only twelve microjets. The microjet operating medium was supplied to each of these manifolds by way of a flexible stainless steel hose that was connected to a pressure manifold, where the stagnation pressure of the microjets was monitored. This arrangement allowed for the micro-nozzles to move with the engine flaps, thus maintaining a constant distance of 5 micro-nozzle diameters between the micro-nozzle exit and the shear layer of the main jet without interfering with the operation of the nozzle. It should be noted that the micro-nozzle manifolds were used to set the angle of injection of the microjets. The angle of injection was set at 60 degrees assuming that the engine flaps would be parallel at the operating condition with the largest exit diameter. This turned out not to be the case and instead the angle of injection was closer to 75 degrees. The importance of this difference in injection angle can be observed in Figure 7. The operating medium of the microjets for these experiments was water and, due to facility limitations, the stagnation pressure was limited to 400 psig.

Figure 8 illustrates the effect of 400 psig water injection on the directivity of the F404 jet engine operated at the mil-power operating condition. The effect of the injection is negligible at the angles less than the peak radiation direction, $\theta = 130$, where a reduction of 2 dB can be observed. This reduction continues into the cone of relative silence where it increases slightly to 3 dB. An examination of the narrowband frequency in the peak radiation direction is also presented in Figure 5. The spectra illustrates that the effect of the water injection is a reduction of both the high frequencies attributed to Mach wave radiation and the lower frequencies attributed to the mixing noise in the jet. It should be noted that the mass flux of the water microjets that were used to obtain these results was 8% of the mass flux of the main jet.

Following the F404 test, a laboratory scale simulation was conducted at FSU in order to determine if it would be possible to obtain similar results. A 1/10th-scale nozzle, based on the F404 geometry, was utilized for these tests and the angle of injection was increased to 75 degrees while the injection pressure was limited to 400 psig. Figure 9 illustrates the effect of 400 psig water injection obtained using the 1/10th-scale nozzle in the laboratory. The operating conditions for these experiments were similar to the

High Speed Jet Noise Mitigation Using Microjet Injection

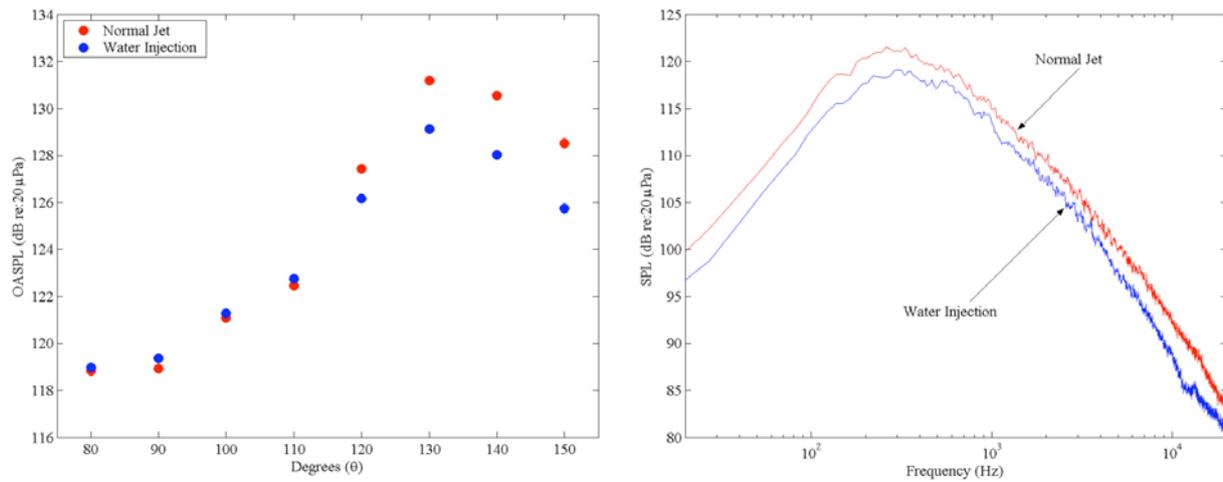


Figure 8. Results obtained using 400 psig microjet injection on an F404 jet engine. Left: farfield directivity; Right: peak radiation direction narrowband spectra.

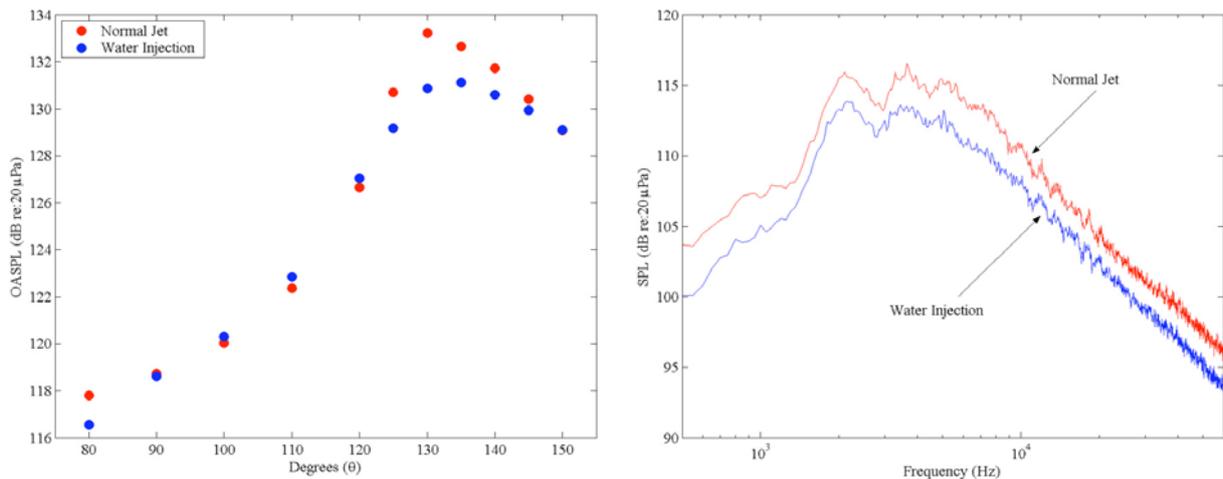


Figure 9. Results obtained using 400 psig microjet injection on a 1/10th-scale laboratory nozzle. Left: farfield directivity; Right: peak radiation direction narrowband spectra.

mil-power operating conditions for the F404 test. At the sideline angles and in the peak radiation direction, where a reduction of 2 dB is observed, the effect of water microjet injection appears to be the same as what was observed in Figure 8 for the F404 jet engine. However, the reduction in the cone of relative silence all but disappears in the laboratory measurements, a phenomenon that is believed to be an artifact of the anechoic chamber. Figure 9 also presents the narrowband frequency spectra in the peak radiation direction for the 1/10th-scale tests. The effect of water injection appears to be the same as what was observed in Figure 8. These results suggest that the noise reduction results can be simulated relatively accurately. It should be noted that the mass flux of the water microjets at the laboratory scale is 14% of the main jet mass flux. As noted previously, the mass flux of the water microjets on the F404 at this operating condition was 8%. This suggests that the observed reductions are not a function of the percentage of water used, but rather the momentum ratio and micro-nozzle spacing.

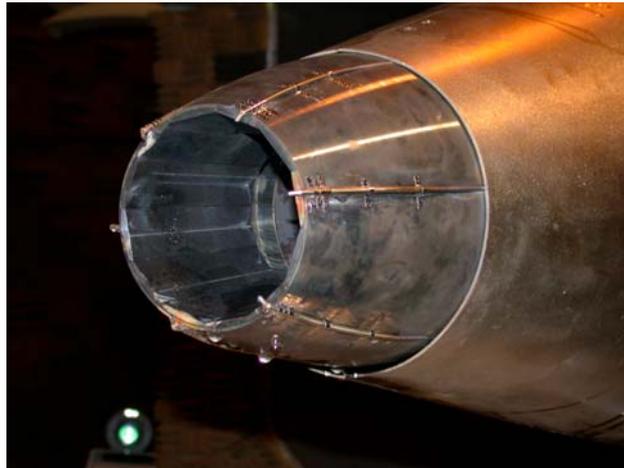


Figure 10. 1/5th-scale LSAF nozzle with micro-nozzles installed.

2.2 1/5th-scale Laboratory Flight Simulation

The 1/5th-scale forward flight simulation experiments were conducted at the Boeing Corporation's Low Speed Aeroacoustic Facility (LSAF). For the purposes of this paper, the significant components of this facility are the large fully anechoic chamber (19.8 m long x 22.8 m wide x 9.1 m high), the jet simulator, and the free-jet wind tunnel. The jet simulator, which is capable of heating the air supply to a stagnation temperature of 1083K, is embedded in the free-jet wind tunnel. The wind tunnel can provide a maximum free stream Mach number of 0.32, which is adequate to simulate the takeoff speeds of most aircraft, thus allowing for the quantification of the effects of forward flight on the jet noise. More details of this test facility may be found in Viswanathan.¹⁶

Like the previous laboratory experiments discussed here the nozzle for these experiments was based on the geometry of the mil-power condition of the F414-GE-400 jet engine. As before, The experimental results discussed here were obtained using operating conditions similar to the mil-power operating condition of the F414. The microjet installation for these experiments was similar to that employed in the previous laboratory experiment. As before, six micro-nozzles were employed, as can be seen in Figure 10, but due to the larger nozzle size, the micro-nozzles for these experiments had an exit diameter of 1.2 mm. The same toroidal manifold was utilized except it was installed under an aerodynamic fairing due to the forward flight aspect. Long feeder tubes, which were set in grooves that were machined into the external surface of the nozzle, were used to feed the micro-nozzles. As can be seen in Figure 10, these tubes were held in place by tack-welded straps. The angle of injection for these tests was set at 60 degrees. Due to facility limitations the maximum injection pressure was limited to 400 psig.

The effects of 400 psig water microjet injection in a simulated Mach 0.233 flight environment can be seen in Figure 11. The results shown in the figure suggest that microjet injection is still effective in the presence of forward flight. A 2 dB reduction is observed in the peak radiation, which is similar to what was observed using 400-psig injection on the 1/10th-scale nozzle in the facility at FSU. Examination of the narrowband spectra in the peak radiation direction, also shown in Figure 11, reveals a noise reduction similar to what was previously observed with the larger reductions occurring at the lower frequencies associated with jet mixing noise. Reductions of up to 3 dB can also be seen in the forward quadrant. Also worthy of note is that the noise reduction in the cone of relative silence diminishes as one moves away from the peak radiation direction. This is similar to what was observed in the facility at FSU in Figures 5 and 9.

High Speed Jet Noise Mitigation Using Microjet Injection

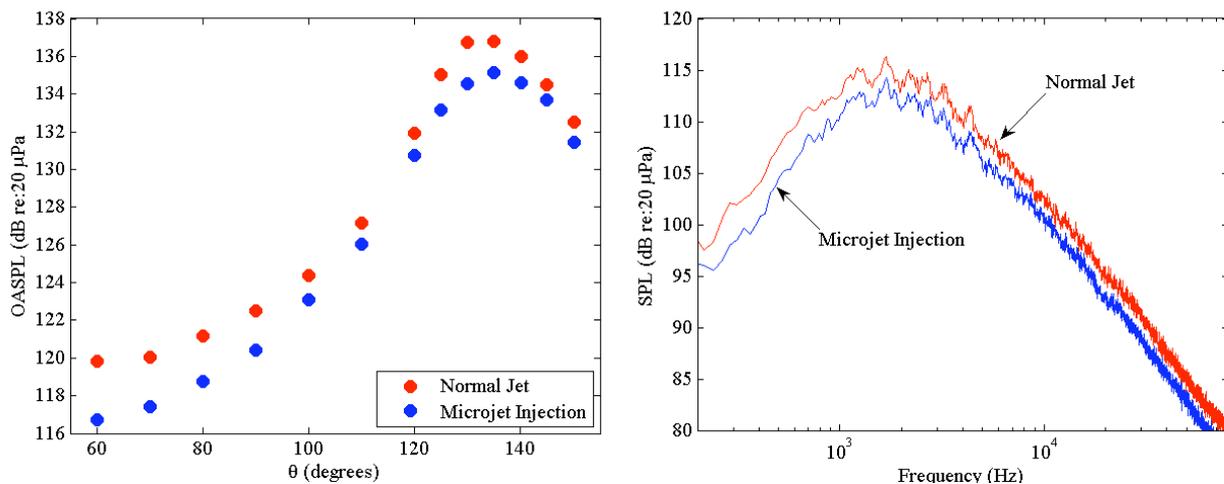


Figure 11. Results obtained using 400 psig microjet injection on a 1/5th-scale laboratory nozzle in a Mach 0.233 free stream. Left: farfield directivity; Right: peak radiation direction narrowband spectra.

3.0 TWIN NOZZLE RESULTS

The twin jet results discussed here were obtained using the Jet Anechoic Facility at the National Center for Physical Acoustics at the University of Mississippi. This facility is similar to the one at FSU in that it is capable of producing heated jets in a static anechoic environment. Instead of a SUE burner, this facility employs a swirl-can propane combustor for producing heated airflows up to 1100K. This facility is also capable of very long duration runs using 1/10th-scale nozzles. The size of the fully anechoic chamber is similar to the one at FSU and it has a cut-off frequency of 200 Hz. More detail regarding this facility can be found in Seiner et al.¹⁷

The twin nozzle configuration, shown in Figure 12, utilized 1/10th-scale nozzles based on the geometry of the mil-power operating condition of the F414 jet engine. The nozzles are canted together such that their centerlines are each two degrees from parallel. The center to center distance at the exit of the nozzles is 1.7 nozzle diameters. Also shown in Figure 12 is the micro-nozzle arrangement around the twin nozzle configuration. It can be seen that there are six micro-nozzles around each of the nozzles. Each of the micro-nozzles for these experiments was a converging axisymmetric nozzle with an exit diameter of 800

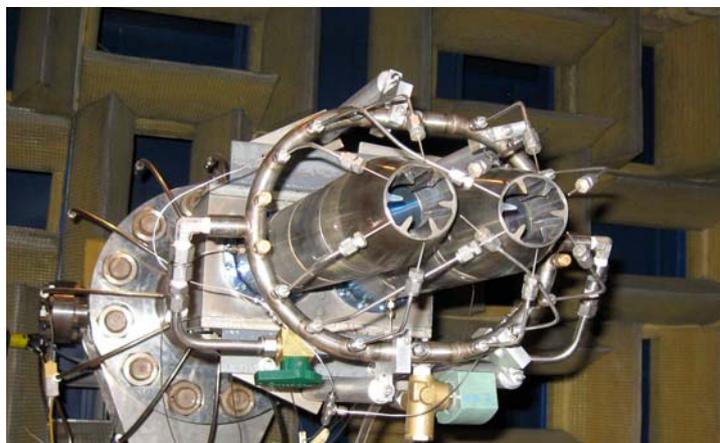


Figure 12. 1/10th-scale twin nozzle configuration with micro-nozzles.

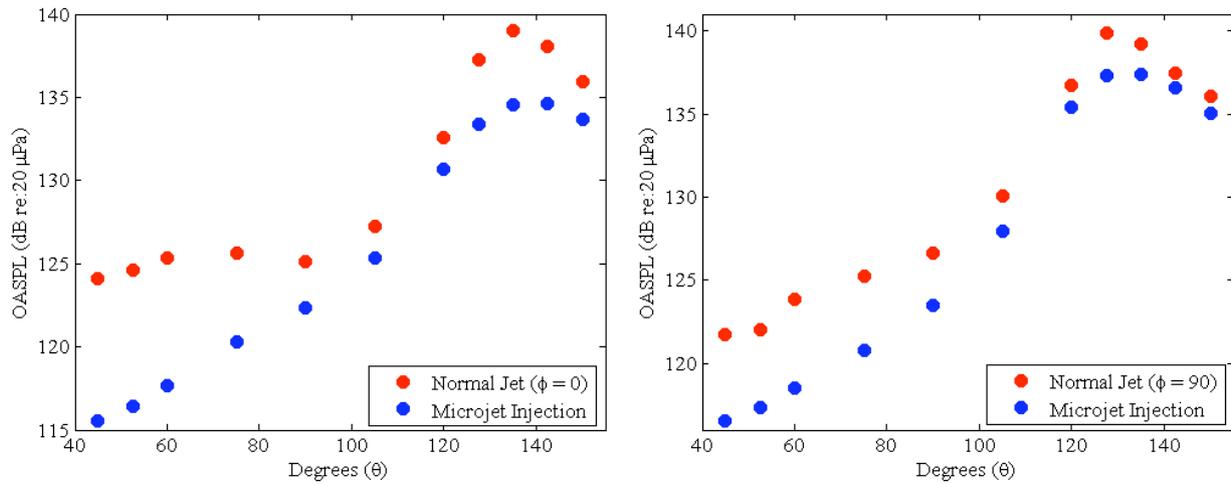


Figure 13. Directivity plots illustrating the effect of 800 psig microjet injection on a 1/10th-scale twin nozzle configuration. Left: $\phi = 0$; Right: $\phi = 90$.

μ m. The same manifold/feeder tube arrangement was employed for these tests and the injection pressure was 800 psig.

Shown in Figure 13 are the results that were obtained using 800-psig water microjet injection on the two orientations of the twin nozzle configuration. In the $\phi = 0$ orientation the noise is measured in the plane containing both nozzle axes and in the $\phi = 90$ orientation the noise is measured normal to this plane. The $\phi = 0$ orientation is what would be experienced by personnel in close ground proximity to the aircraft while the $\phi = 90$ orientation is what would experience as the aircraft was flying overhead. As can be seen in the figure, microjet injection is effective at reducing the jet noise in both orientations. In the $\phi = 0$ orientation there is a reduction of 5 dB and 9 dB in the peak radiation direction and forward quadrant, respectively. The reductions in the $\phi = 90$ orientation are less impressive, with a reduction of only 3 dB in the peak radiation direction and 6 dB in the forward quadrant.

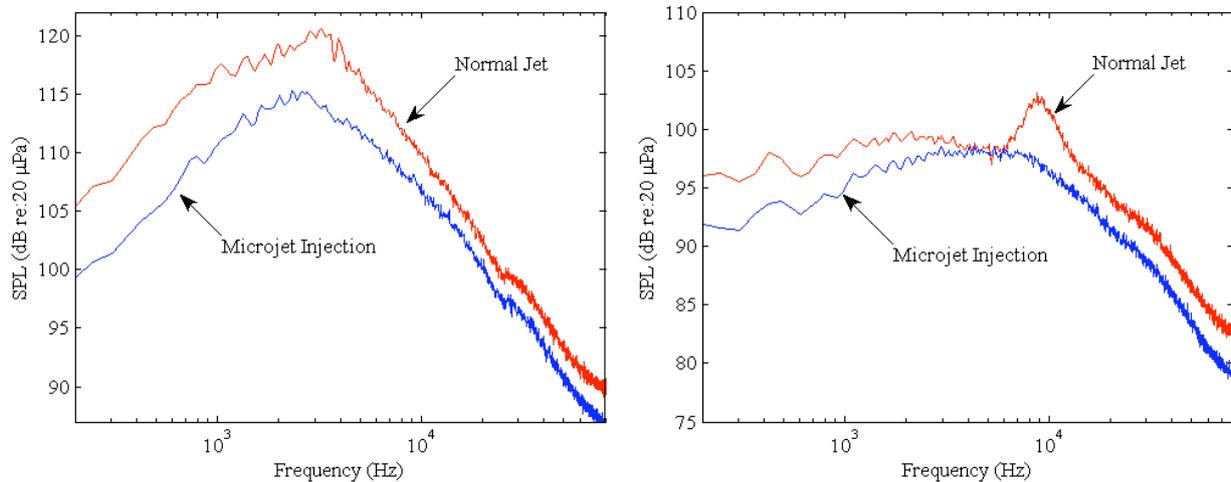


Figure 14. Narrowband frequency spectra obtained using 800 psig microjet injection on the twin nozzle configuration at $\phi = 0$. Left: peak radiation direction; Right: Normal direction.

High Speed Jet Noise Mitigation Using Microjet Injection

A further examination of the effects of microjet injection in the $\phi = 0$ orientation is warranted due to the fact that this orientation is what would be experienced by the personnel on the deck of an aircraft carrier. To this extent, Figure 14 illustrates the effect of the microjet injection on the narrowband spectra in the peak radiation and normal directions at $\phi = 0$. It can be seen that most of the reduction in the peak radiation direction is due to a reduction in the low frequencies associated with mixing noise. A similar phenomenon occurs in the normal direction where it is also seen that the microjet injection has all but eliminated the shock noise that was present.

4.0 CONCLUSIONS

Presented here was a review of some of the results that have been obtained using water microjet injection for the purpose of high-speed jet noise reduction. The technique has been shown to be effective at three different test facilities and on a full-scale jet engine. An optimal configuration for a single nozzle produced reductions of up to 5 dB in the peak radiation direction with reductions of up to 3 dB in the forward quadrant. Even at a less than optimal configuration on a full-scale engine, the microjets produced reductions of 2 dB in the peak radiation direction. An optimal microjet configuration on a 1/10th-scale twin nozzle configuration, oriented in a horizontal configuration, produced a jet noise reduction of 5 dB and 9 dB in the peak radiation direction and forward quadrant, respectively. This suggests that microjet injection would be ideal for producing significant noise reduction in an aircraft carrier environment.

5.0 REFERENCES

- [1] Westley, R., and Lilley, G. M., "An investigation of the noise field from a small jet and methods for its reduction," College of Aeronautics Report No. 53, Cranfield University, 1952.
- [2] Lilley, G. M., "On the noise from jets, noise mechanisms," AGARD CP 131, 1973.
- [3] Seiner, J., Ukeiley, L., Jansen, B., Kannepalli, C. and Dash, S., "Noise Reduction Technology for F/A-18 E/F Aircraft," AIAA Paper 2004-2972, 2004.
- [4] Seiner, J., Ukeiley, L. and Jansen, B., "Aero-Performance Efficient Noise Reduction for the F404-400 Engine," AIAA Paper 2005-3048, 2005.
- [5] Crighton, D. G., "Orderly structure as a source of jet exhaust noise: Survey lecture," Structure and Mechanisms of Turbulence II, Vol. 76 of Lecture Notes in Physics, Springer, 1977, pp. 154–170.
- [6] Bishop, K. A., Ffowcs Williams, J. E. and Smith, W., "On the noise sources of the unsuppressed high-speed jet," J. Fluid Mech., Vol. 50, 1971, pp. 21–31.
- [7] Greska, B., Krothapalli, A., Horne, W.C. and Burnside, N., "A near-field study of high temperature supersonic jets," AIAA Paper 2008-3026, 2008.
- [8] Seiner, J. M., Ponton, M. K., Jansen, B. J. and Lagen N. T., "The effects of temperature on supersonic jet noise emission," DGLR/AIAA Paper 92-02-046, 1992.
- [9] Alkislar, M. B., Krothapalli, A. and Butler, G.W., "The effect of streamwise vortices on the aeroacoustics of a Mach 0.9 jet," J. Fluid Mech., Vol. 578, 2007, pp. 139–169.
- [10] Arakeri, V. H., Krothapalli, A., Siddavaram, V., Alkislar, M. B., and Lourenco, L., "On the use of microjets to suppress turbulence in a Mach 0.9 axisymmetric jet," Journal of Fluid Mechanics, Vol.

- 490, 2003, pp. 75–98.
- [11] Krothapalli, A., Venkatakrisnan, L., Lourenco, L., Greska, B. and Elavarasan, R., “Turbulence and noise suppression of a high-speed jet by water injection,” *J. Fluid Mech.*, Vol. 491, 2003, pp. 131–159.
- [12] Krothapalli, A., Greska, B. & Arakeri, V., “High-speed jet noise reduction using microjets,” AIAA Paper 2002-2450, 2002.
- [13] Greska, B., Krothapalli, A., Burnside, N., and Horne, W. C., “High-speed jet noise reduction using microjets on a jet engine,” AIAA Paper 2004-2969, 2004.
- [14] Greska, B., Krothapalli, A., Seiner, J., Jansen, B. & Ukeiley, L., “The effects of microjet injection on an F404 jet engine,” AIAA Paper 2005-3047, 2005.
- [15] Greska, B. J., Supersonic jet noise and its reduction using microjet injection, Ph.D. thesis, Florida State University, 2005.
- [16] Viswanathan, K., “Jet aeroacoustic testing: Issues and implications,” *AIAA Journal*, Vol. 41, 2003, pp. 1674–1689.
- [17] Ponton, M. K., Seiner, J. S., Ukeiley, L. S. and Jansen, B. J., “A new anechoic chamber design for testing high-temperature jet flows,” AIAA Paper 2001-2190, 2001.

High Speed Jet Noise Mitigation Using Microjet Injection

