Noise Reduction for Gas Turbine Powered Military Vehicles

Steve Martens
One Research Circle
K1 ES503
Niskayuna, NY 12309 USA

Steven.Martens@GE.com

ABSTRACT

Jet noise has been an environmental issue since the advent of jet aircraft. The past 5 decades have seen much research into solving this very difficult challenge for a variety of applications. More recently jet noise from high performance military aircraft has received growing attention. With the continuous drive to higher specific thrust, jet noise levels continue to rise. Compounding that is the fact that many military bases, Naval in particular, are located in very desirable locations on the coasts, and the surrounding communities are growing closer and closer to these bases. Another serious issue is the ground personnel around this military aircraft, both at bases and on carrier decks. Ground crew are in very close proximity to the very high power jet plume and hearing loss is a growing personal health, safety, and cost issue. In this paper a brief survey will be presented of some of the jet noise reduction technologies for tactical aircraft systems investigated by GE. Some of the specific technologies aimed at changing the mixing characteristics of the jet plume after it leaves the nozzle will be discussed in detail including chevrons and fluidic injection. The fluid shield and inverted velocity profile will also be included, which arrange the various engine exhaust streams to minimize noise. Measured data will be presented to show the effect these technologies have on high-speed jets.

1. INTRODUCTION

Reducing jet noise is difficult because the dominant noise production region is located outside of the engine, typically near the end of the potential core of the exhaust jet. This is in contrast to other dominant engine noise sources like fan noise, where noise is generated internally. In this case, it is possible to affect noise in the generation process (source reduction), or use treatment after noise generation to reduce noise levels before noise leaves the engine nacelle (noise attenuation). For jet noise reduction, modifying the jet plume before it leaves the exhaust system is one of the only feasible ways to reduce noise. Beyond the jet noise reduction problem itself lies the aircraft integration challenge, as maintaining aircraft system performance remains paramount. A further hurdle to noise reduction technology implementation is that most viable supersonic exhaust systems must be equipped with variable geometry to provide optimum performance over the wide range of pressure ratios required in these systems.

Jet noise reduction for high-speed applications continues to pose a challenge. Finding solutions that have significant jet noise reduction while minimizing the cost and performance impact to the aircraft system continues to be a goal for many researchers.

1.1 SUPERSONIC JET NOISE SOURCES

There are four main sources of noise in supersonic jets: turbulent mixing noise, broadband shock associated noise, Mach wave emission, and screech. Turbulent mixing noise is found in both subsonic and supersonic jets and is caused by the turbulence in the mixing or shear layer of the jet. Turbulent mixing noise is the dominant noise source in the downstream direction. Broadband shock associated noise is essentially generated by turbulent eddies passing through the shock cell system of an imperfectly expanded supersonic jet plume. Mach wave emission is the noise generated by turbulent eddies in the shear layer traveling with a supersonic convection speed relative to the ambient. Finally, screech is a resonant feedback phenomenon created by the interaction of large-scale turbulent structures and shock cells, with the generated noise traveling to the trailing edge of the nozzle and reinforcing the turbulent structures. Screech generally does not occur in non-laboratory exhaust systems, and if it does occur, is eliminated with well-known engineering solutions, and will not be discussed further. Tam [1,2] provides a more detailed explanation of these supersonic jet noise sources.

1.2 SUPERSONIC JET NOISE REDUCTION

In this paper a number of supersonic jet noise reduction technologies will be discussed. The technologies can be divided into two groups, passive and active. The passive or active identifier is used to indicate whether the technology is operating under all conditions or whether it can be turned on and off. Active technology includes feedback-based control of noise, but is not limited to this narrower group of actuators. The majority of noise reduction technologies are passive, e.g., some mechanical device to enhance mixing that is always in the flow. Passive technology is the simplest to implement, but both negative and positive effects are typically present. Possible aerodynamic losses associated with passive technology will be incurred at all operating conditions, including cruise, where fuel burn is of prime importance. Passive noise reduction technologies discussed below include mechanical chevrons and the inverted velocity profile (IVP).

For the majority of missions, low noise is only required for a couple of minutes, during low altitude flight, e.g., during take-off and landing operations in the vicinity of an airport and surrounding communities. This clearly motivates the development of active noise reduction technologies that can be turned on for noise sensitive operations and then turned off to minimize any negative performance impact. The two active noise reduction technologies discussed below are fluidic chevrons, or fluidic injection, and the fluid shield.

1.3 ACOUSTIC FACILITY

The acoustic results discussed in this paper were obtained at GE Aviation test facilities. The GE Aviation Engines Cell 41 anechoic free-jet noise facility, shown in Figure 1, is a cylindrical chamber 43 feet in diameter and 72 feet tall. The inner surfaces of the chamber are lined with anechoic wedges made of fiberglass wool to render the facility anechoic above 220 Hz. The facility can accommodate single and dual flow model configurations, where the dual flow configuration is used to represent the core and fan streams of a typical high-bypass ratio, separate flow exhaust system. The two streams of independently heated air making up the dual flow arrangement flow through silencers and plenum chambers before entering the test nozzle. Each stream can be heated to a maximum temperature of 1960 ^{o}R with nozzle pressure ratios as high as 5.5, resulting in a maximum jet velocity of 3,000 ft/sec, with maximum throat areas of 22 in^2 and 24 in^2 for the core and fan streams, respectively. For the tests discussed in this paper, the nozzle temperature, nozzle pressure ratio, and mass flow requirements to achieve meaningful real world operating conditions are well within the capabilities of the facility.

Additionally, a tertiary air system is available for flight simulation that consists of a 250,000 scfm (at 50" of water column static pressure) fan driven by a 3,500 horsepower electric motor. Such a capability is nearly indispensable for proper jet noise reduction technology evaluation. The transition ductwork and silencer route air from the fan discharge through a 48 inch diameter free-jet nozzle. The silencer reduces the fan noise by 30 to 50 dB. Tertiary airflow at its maximum delivery rate permits flight simulation up to a free jet Mach number of approximately 0.4. Mach number variation is achieved by adjusting the supply air fan inlet guide vanes. The combined model, free jet, and entrained airflow is exhausted through an exhaust "T" stack silencer positioned inline above the model in the ceiling of the chamber. The exhaust "T" stack is acoustically treated to reduce noise transfer from the facility to the surrounding community.

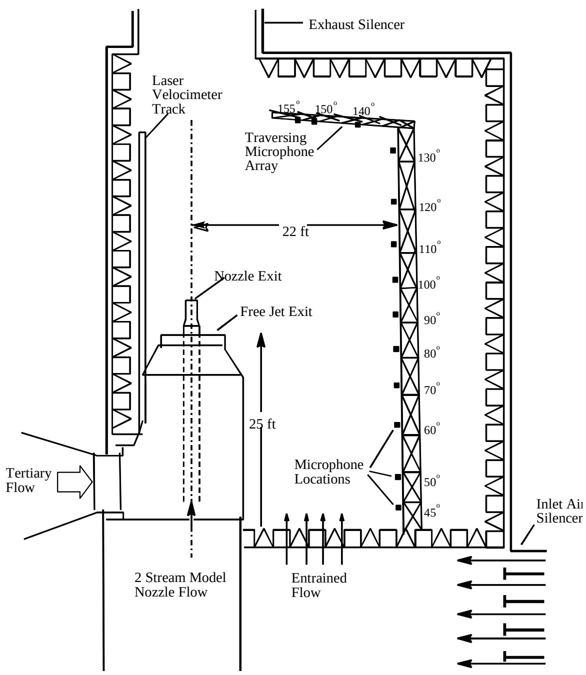


Figure 1. Side view schematic of GE Aviation's Cell 41.

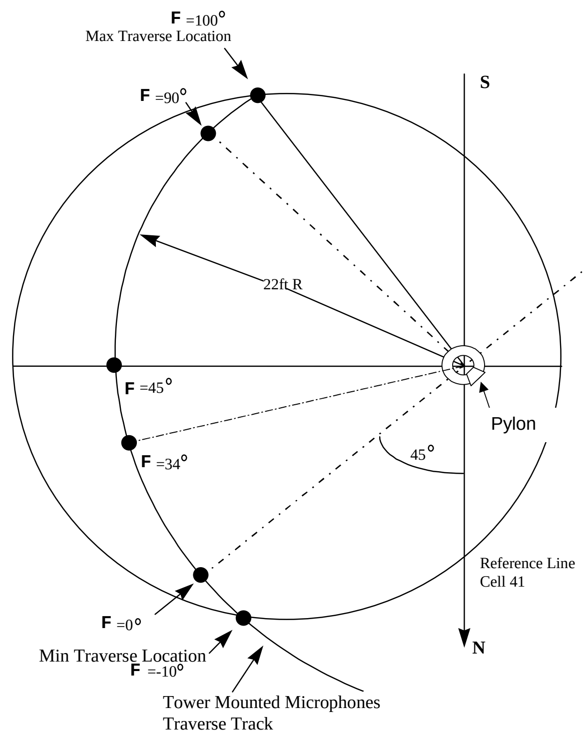


Figure 2. Plan view of GE Aviation's Cell 41 showing microphone locations and measurement orientation.

The facility is equipped with a traversing tower containing 13 microphones, mounted at polar angles from 45^{o} to 155^{o}, shown in Figure 1, and provides measurements at a minimum distance of 22 feet from the nozzle reference location (see Figure 2) to measure the acoustic characteristics of the test models in the far-field. Figure 2 also shows a layout of the facility, indicating the orientation of the model hardware and the microphone locations. The tower can be physically positioned at any azimuthal angle noted in Figure 2. However, to ensure no measurement interference between the anechoic wedges and the tower in its extreme position, data acquisition is normally limited to the 0^{o} to 90^{o} locations identified in Figure 2.

The acoustic data shown in this paper was all scaled to a relevant full-scale engine exhaust size. Since external flow simulation was used for all of the data shown here the data was also corrected for shear layer refraction and extrapolated to a 1000 ft straight and level flyover condition. The acoustic spectra are shown in third octave band. The specific geometries, pressures and temperatures for each case may not be exactly identified but the nozzle geometries and operating conditions are typical for typical noise sensitive operating conditions, typically take-off.

1.0 JET NOISE REDUCTION TECHNOLOGIES

1.1 MECHANICAL CHEVRONS

The chevron exhaust nozzle is the current state of the art for implemented jet noise reduction and mainly applied to commercial aircraft engines. These nozzles have serrated trailing edges where each “lobe” penetrates into or out of the primary flow and generates a secondary flow motion. These secondary vortical flows enhance the mixing of the jet plume and can provide a significant reduction in the radiated jet noise. An appealing aspect of this technology is that the change to the engine is minor in terms of weight, complexity, and performance. This has resulted in deployment of the chevron exhaust nozzle on regional jets in revenue service.

Figure 3 shows a photograph of a scale model of a typical converging-diverging high performance exhaust system with a chevron nozzle. The throat diameter for this model is approximately 4.5”. The chevron nozzle design pictured was chosen after testing design concepts with various permutations of the chevron design parameters. Some of these parameters included the number of chevrons, length, aspect ratio, sweep angle, penetration, shape, and azimuthal contouring. Initial design screening was done using computational fluid dynamics (CFD) analysis to qualitatively compare the mixing characteristics of the jet plume for different chevron designs relative to the baseline configuration. Beyond the acoustic benefit, nozzle performance, engine operability, manufacturability and maintainability were important considerations. Unfortunately, acoustic and aerodynamic performance usually have an inverse relationship, i.e., what’s good for acoustics is generally bad for performance, so the choice of design is a classic engineering trade-off. Comprehensive discussions of chevron nozzles can be found in references [3-11].

Figure 3. Photograph of scale model C-D nozzle with chevrons.

Figure 4 shows perceived noise level (PNL) directivities of a conventional nozzle and a chevron nozzle at a representative full power engine condition with a nozzle pressure ratio (NPR) of 3.5, with a total temperature matching that of the engine cycle. Angles in Figure 4 and hereafter are measured from the model, or engine inlet. The data presented includes the effect of external flow around the exhaust system and shows that chevrons are effective at reducing the noise level at all directivity angles. They are more effective in the forward angles, where broadband shock noise is the dominant noise source.

Figure 5 shows the sound pressure level (SPL) spectra at two directivity angles for the same conditions as

Figure 4. Figure 5a shows the SPL at 60 deg, where broadband shock noise is dominant. It is clear that the chevron has a significant effect on shock noise. However, the chevron is responsible for some modest noise increases at higher frequencies, which is somewhat typical for this technology. Figure 5b shows the SPL at 140 deg, where jet-mixing noise is dominant and again the chevron is effective at reducing noise over a wide range of frequencies.

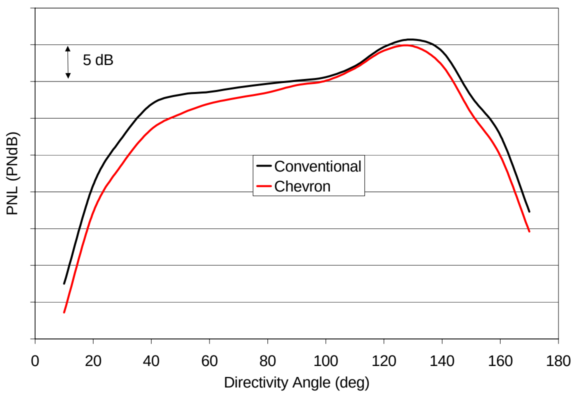


Figure 4. PNL directivity comparing a conventional and chevron nozzle at a nozzle pressure ratio of 3.5 and nozzle

Chevrons are in service on many regional jet engines and will be entering service with the Boeing 787. Chevrons are a good jet noise reduction technology for a broad range of applications. Issues encountered with chevron technology implementation include the possibility of a very modest impact on specific fuel consumption (SFC). Ongoing research is investigating the use of shape memory alloys (SMA) to allow a relatively practical implementation of variable geometry chevrons [12]. In essence, SMA materials are engineered to have two different shapes depending on temperature, allowing a properly engineered SMA chevron to retract from the flowpath when noise reduction is not needed and thereby reduce or eliminate any performance impact.

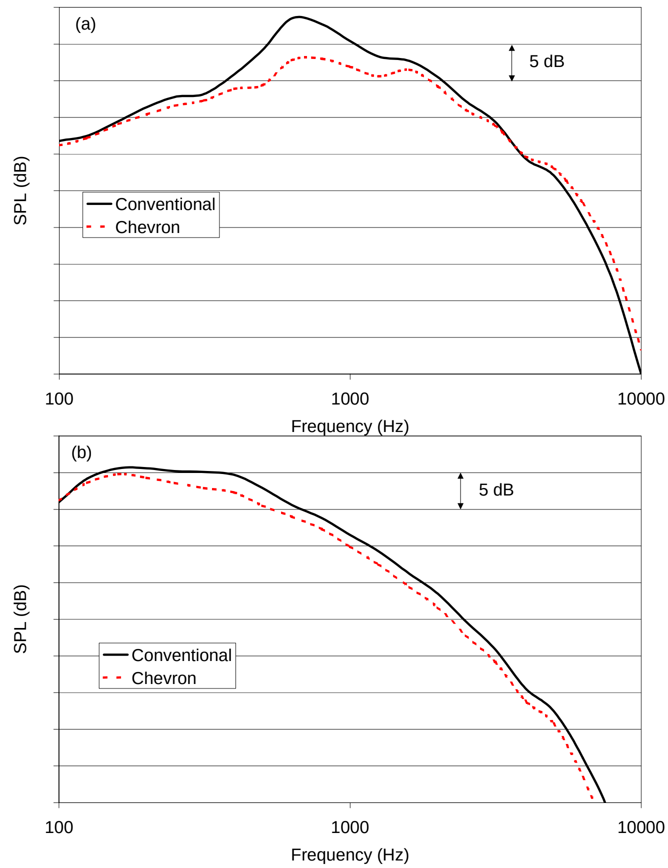


Figure 5. SPL spectra comparing a conventional and chevron nozzle at a nozzle pressure ratio of 3.5 and nozzle area ratio of 1.067 with external flow simulation, Mfj=0.35, (a) 60 deg, (b) 140 deg.

1.2 INVERTED VELOCITY PROFILE

The Inverted Velocity Profile (IVP) occurs when the main high temperature and velocity flow stream surrounds a lower temperature and velocity flow stream. This type of IVP arrangement is shown to reduce the overall measured jet noise relative to a fully mixed stream [13,14], believed to be the quietest type of nozzle, assuming constant thrust. The lower noise level is achieved by promoting higher rates of mixing between the high velocity flow stream and the ambient flow stream, thus reducing the peak velocity faster. The detailed flow path design employed computational fluid dynamics (CFD) to optimize the performance of this exhaust system to reach the necessarily high performance goal at cruise.

Figure 6 shows a photograph of a scale model exhaust system designed for a Mach 2.4 cruise supersonic aircraft. The exhaust system is an annular plug dual stream nozzle with an IVP. The exhaust system employs variable geometry and Figure 6 shows the nozzle in the configuration for take-off. Figure 7 shows the PNL directivity for the take-off configuration with external flow simulation. Noise reduction is seen over much of the directivity, even the aft mixing noise dominated regions. Figure 8 shows the SPL spectra for the IVP nozzle pictured in Figure 6 at the take-off operating condition. Figure 8a corresponds to the broadband shock noise dominated 60 deg directivity angle and very significant noise reduction is achieved. Figure 8b corresponds to the mixing noise dominated 140 deg directivity angle and again noise reduction is observed.

Figure 6. Photograph of a scale model dual stream with annular plug nozzle with an inverted velocity profile exhaust system.

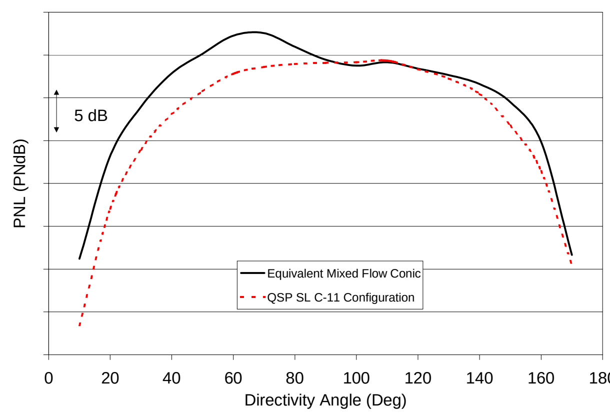


Figure 7. PNL directivity comparing a fully mixed nozzle with a dual flow annular plug nozzle with IVP at the same thrust at a typical take-off condition with external flow simulation. with external flow simulation, Mfj=0.32.

These figures demonstrate that the IVP is a powerful jet noise reduction technology. However, successful application of this technology is possible only in some jet velocity regimes. A trade-off exists in the acoustic performance of IVP nozzles between the benefits of the increased initial mixing rate and the noise generated in this more intense mixing. It is typical to see an increase in high frequency noise, due to higher turbulence in the early development of the jet where turbulence has smaller scales. At the same time the benefit of early mixing is observed by reduced lower-frequency noise emission. (The trade-off is such that for some velocity regimes a conventional separate flow nozzle, with the higher temperature higher speed flow in the inner stream will result in lower noise.) The IVP exhaust system discussed here was developed for a specific cruise Mach number vehicle and was based on an engine architecture that could provide different bypass ratios for different operating conditions, enabling some control of the two streams of flow. The IVP technology implementation discussed here has demonstrated significant acoustic benefits as well as very high aerodynamic performance [15]. The only significant integration issue is the rearrangement of the lower temperature and velocity flow into the center of the exhaust system. For the IVP technology implementation discussed here, the rearrangement concept employed the struts of the bypass duct.

1.3 FLUIDIC CHEVRONS/INJECTION

Fluidic chevrons consist of small steady vortex generator jets (VGJ's) arranged around the exit perimeter of an otherwise conventional exhaust nozzle. The VGJ's enhance the jet mixing and alter the entrainment characteristics of the jet by introducing streamwise vorticity. Fluidic chevrons are intended to replicate the noise benefits obtained using mechanical chevrons. When a properly oriented jet is introduced into a cross-flow, a pair of counter-rotating vortices is created, which enhance the mixing in the primary flow. The strength, orientation and position of these vortices control the entrainment process. Mechanical chevrons produce the same streamwise vortical flows, but fluidic chevrons can potentially activate on-demand at noise-critical stages of the mission for maximum noise reduction and deactivate during noise-insensitive operations for minimum impact on overall engine performance. Therefore, the system trade-offs that limit noise suppression in favor of cruise performance need not be made. VGJ's require a high-pressure source of flow extracted from the engine cycle and therefore have non-negligible impact on engine operation. However, the bleed air required could be extracted in a manner minimizing the impact on available thrust. References [15-18] report a broad summary of the current state of the art in fluidic injection for various applications.

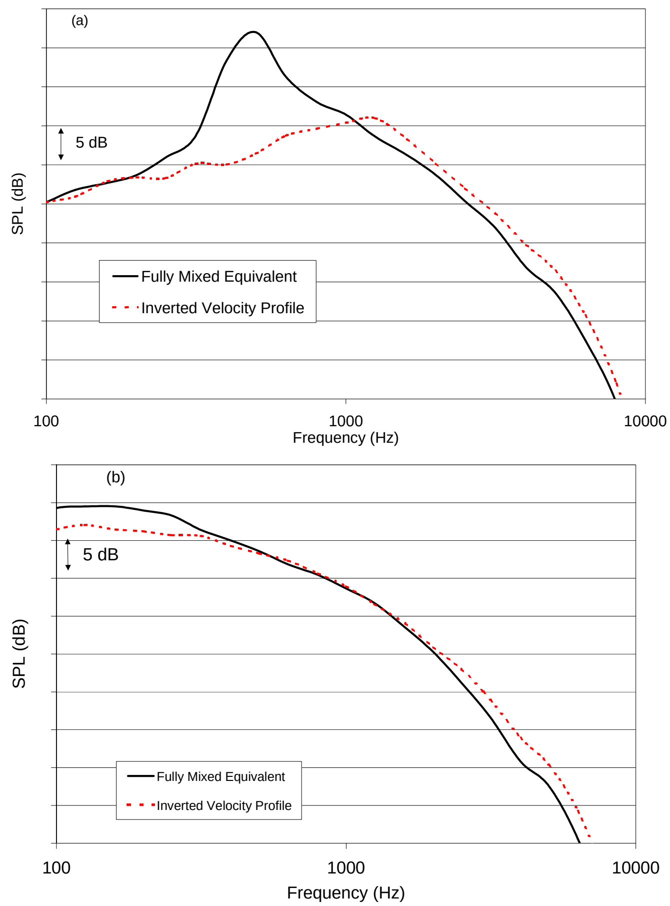


Figure 8. SPL spectra comparing a fully mixed nozzle with a dual flow annular plug nozzle with IVP at the same thrust at a typical take-off condition with external flow simulation. with external flow simulation, Mfj=0.32, (a) 60 deg, (b) 140 deg.

For the fluidic chevron work presented here, the injection pressures were limited to that available from the fan or bypass stream of the target engine cycle. Generally, mass flow ratios of injection flow to engine flow were constrained to no higher than 2%. Imposing these limits on our research helps provide estimates of the available noise reduction for a realistic system implementation. Pressure ratios were limited to respect pressures available from the bypass or fan stream of the target engine cycle. Very high-pressure injection, although attractive from a potential noise reduction standpoint, results in prohibitively high cycle penalties.

Figure 9 shows a photograph of a converging-diverging nozzle with 12 pairs of fluidic chevrons arranged around the circumference of the nozzle's trailing edge. The fluidic chevrons have a specified pitch and yaw angle into the flow. The individual jets comprising each fluidic chevron are yawed to point towards each other. Figure 10 shows the variation of maximum PNL benefit as a function of injection pressure at two NPRs: 2.5 and 3.5. Figure 10 shows that noise reduction potential at a given injection pressure decreases with

Figure 9. Photograph of scale model C-D nozzle with fluidic chevrons and a fluid shield.

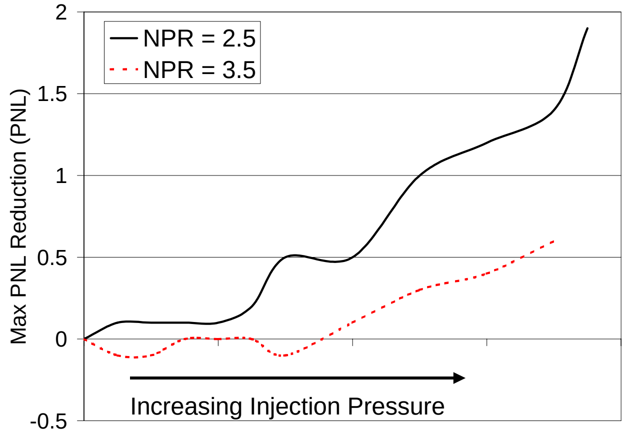


Figure 10 Maximum PNL reduction with fluidic injection for two NPRs with a nozzle area ratio of 1.067 with different injection pressures. With external flow simulation, Mfj=0.35.

nozzle pressure ratio. Similarly, continued increase in injection pressure increases noise reduction. Figure 11 shows the PNL directivity with and without fluidic injection for a typical take-off engine condition (NPR = 3.5) and a nozzle area ratio of 1.067. Figure 11 indicates that modest noise reduction is achieved over a wide range of directivity angles. Figure 12 shows the SPL spectra for the same conditions at directivity angles of 60 deg in Figure 12a, and 140 deg in Figure 12b. At 60 deg there is some broadband shock noise reduction and at 140 deg, noise reduction is confined mostly to higher frequencies, indicating that injection benefits are likely limited to noise produced in the nozzle exit's immediate vicinity. These results show that some modest noise reduction is achievable with fluidic chevrons, but all of the benefits described previously in this section for mechanical chevrons were not achieved. The limited magnitude of low-frequency mixing noise reduction achieved indicates that when using the realistic pressure ratios and mass flow rates employed in this study, injection likely can't act like a mechanical chevron but instead achieves noise reduction through different phenomena. Callender et al. [16] propose some theories on how fluidic injection interacts with the jet plume and the shear layer to reduce noise. Due to the limited level of noise reduction achieved and given the complexity of extracting air from the engine cycle for fluidic injection, the technology, in its current state, is not attractive to implement on a product high-speed exhaust system.

1.4 FLUID SHIELD

Given the trade-offs and noise characteristics regarding mechanical chevrons discussed in Section 2.1, focused high frequency attenuation would prove an attractive complement to the low frequency noise reduction offered by mechanical chevrons. One technology that offers these potential benefits is the fluid shield. The fluid shield is a thin layer of flow that partially surrounds the main jet and is characterized by a proper combination of velocity and speed of sound. High-frequency noise, whether from jet mixing or due to internal sources, can be both attenuated and reflected by the fluid shield. The shield design determines the low-frequency limit above which the shield is effective. Above this frequency, it is effective on all sources of aft-

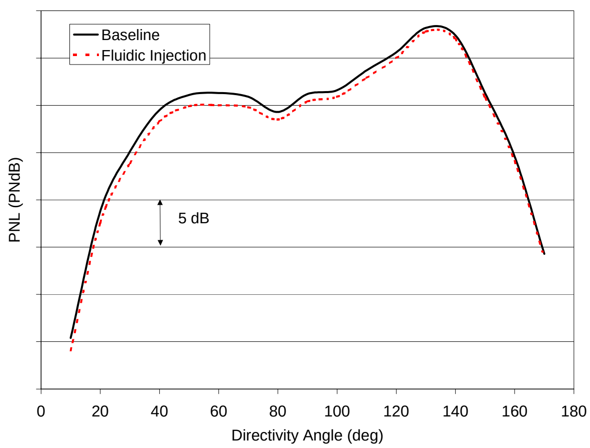
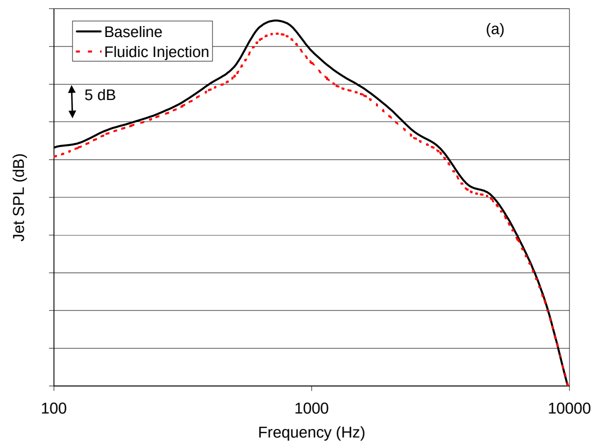


Figure 11. PNL directivity with and without fluidic chevrons/injection at a typical take-off condition (NPR = 3.5) with external flow simulation, Mfj=0.32.



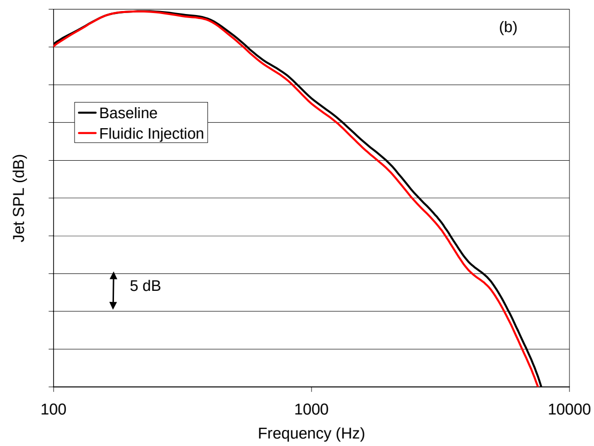


Figure 12. SPL spectra with and without fluidic chevrons/injection at a typical take-off condition with external flow simulation. with external flow simulation, Mfj=0.32, (a) 60 deg, (b) 140 deg.

radiated noise.

Since the fluid shield is an active device, it can be applied only during operations around noise-sensitive areas and turned off for all other operations to minimize the thrust and efficiency penalties normally associated with passive noise reduction hardware. Furthermore, if the benefits of mechanical chevrons could be replicated by an active flow technology (such as fluidic chevrons), then this entirely on-demand supersonic jet noise suppression system could achieve significant broadband jet noise reduction when required and have minimal impact on cruise performance when turned off.

As discussed previously, the fluid shield provides a method to reduce high-frequency noise generated by mixing devices such as chevrons. This synergy allows chevrons to provide a higher level of low-frequency noise reduction because the increased high-frequency noise emission potentially associated with mechanical chevrons is mitigated by the fluid shield. Another feature of a fluid shield is that its azimuthal (circumferential) position can be configured depending on the noise emission direction requiring the most noise attenuation, thus potentially reducing the shield flow required. For example, the fluid shield can be configured to reduce sideline noise during takeoff roll and reconfigured to reduce flyover noise during climb-out.

The fluid shield is described in Gliebe et al. [20] as a “high temperature, low velocity gas stream surrounding the principal jet and which yields noise suppression because of the wave refraction and reflection that occurs due to the impedance change at the interface between the principal jet and the fluid shield.”

Some of the factors that govern the effectiveness of a fluid shield are:

- High frequency sources are more amenable to "suppression" by the fluid shield than low frequency sources and effectiveness increases as the ratio of shield thickness to sound wavelength increases.
- Sources located close to the nozzle exit are more effectively shielded relative to those located far downstream because near nozzle sources are characterized by higher frequency content relative to sources located farther downstream.
- Increased shield thickness, temperature, and velocity are beneficial in increasing shield effectiveness. However, the mass flow needed to *create* the shield as well as the self-noise generated by the fluid shield are factors that prevent the use of a very thick or high velocity fluid shield.
- A fluid shield is most effective at relatively shallow angles to the shield axis. Attenuation at angles which are small relative to the inlet jet axis can be improved by inclining the shield away from the jet axis.

Figure 13 shows a side view of a scale model high-speed exhaust system with a C-D chevron nozzle and a fluid shield on the backside of the nozzle. Figure 14 shows a view of the same model, aft looking forward, with the shield located under the nozzle. Figure 15 shows the maximum PNL benefit for different fluid shield pressure ratios at two nozzle pressure ratios. Clearly significant noise reduction potential exists for this technology. Figure 16 shows the PNL directivity for the shield pressure ratio case of 1.7 and NPR = 2.5 conditions. A fairly consistent noise reduction of 2 – 2.5 PNdB is seen over most of the directivity angles. Finally Figure 17 shows the SPL spectra for two directivity angles, 60 and 140 deg, with reduction observed for most frequencies.

Figure 13 Photograph of C-D chevron nozzle with shield on backside of the nozzle.

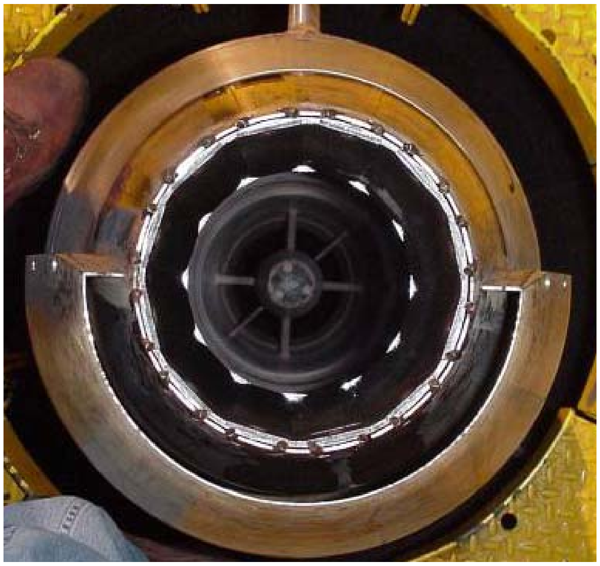


Figure 14 Aft looking forward photograph of C-D nozzle showing fluid shield on the bottom.

These results show that the fluid shield is an effective jet noise reduction technology. However, implementation of a fluid shield represents a fairly significant change to the propulsion system and is difficult to incorporate into an existing propulsion system. Implementation of this technology has to be part of the initial design for a new exhaust system and requires a significant amount of the engine flow, up to 20%, for the noise reduction levels seen here. A variable bypass ratio engine architecture would represent a near ideal candidate for application of fluid shield technology. Such an architecture could provide the additional mass flow required for shield operation during noise-sensitive parts of the mission and return to a performance optimized operating condition once noise reduction is no longer required.

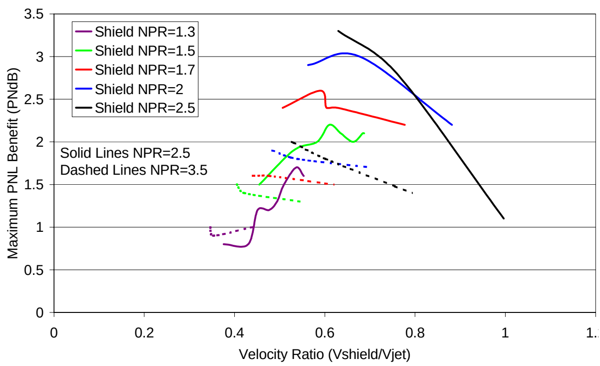


Figure 15 Maximum PNL benefit for the fluid shield with different shield pressure ratios for NPRs of 2.5 and 3.5. With external flow simulation, Mfj=0.35

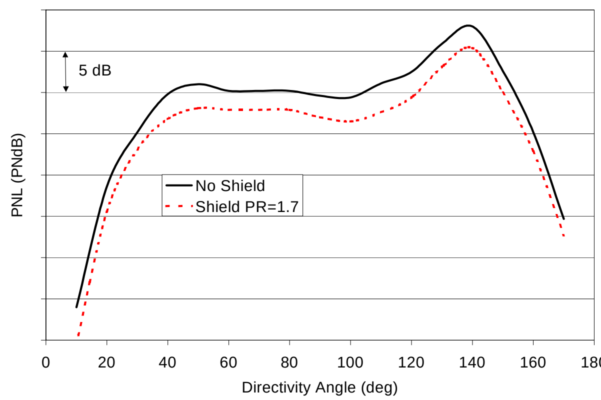


Figure 16 PNL directivity with and without a fluid shield with a pressure ratio of 1.7, NPR = 2.5, and nozzle area ratio = 1.067. With external flow simulation, Mfj=0.35.

2.0 SUMMARY AND CONCLUSIONS

This paper has briefly described a number of passive and active jet noise reduction technologies appropriate for high speed exhaust systems. The technologies discussed include the mechanical chevron, the inverted velocity profile, the fluidic chevron/injection, and fluid shield. Some of these technologies are applicable to a broad range of exhaust systems, such as the mechanical chevron and others are best suited to specific engine architectures. For example, an engine cycle offering the capability to vary bypass ratio can be employed to efficiently provide flow to a fluid shield for noise reduction when required.

For single stream exhaust systems, as found in high performance military aircraft applications, mechanical chevrons appear to be the most practical solution in the near term. For future applications where an engine with variable bypass ratio capability could be considered, all of the technologies discussed here could be used in some combination.

This paper has demonstrated that there are a number of jet noise reduction technologies that can reduce noise in high speed exhaust systems while retaining the required high performance characteristics at cruise conditions. These technologies have been developed to varying levels of technology readiness levels and their noise reduction potential and initial system impacts have been demonstrated.

ACKNOWLEDGMENTS

The authors would like to acknowledge the Office of Naval Research and NASA for their support of some of the research results presented here.

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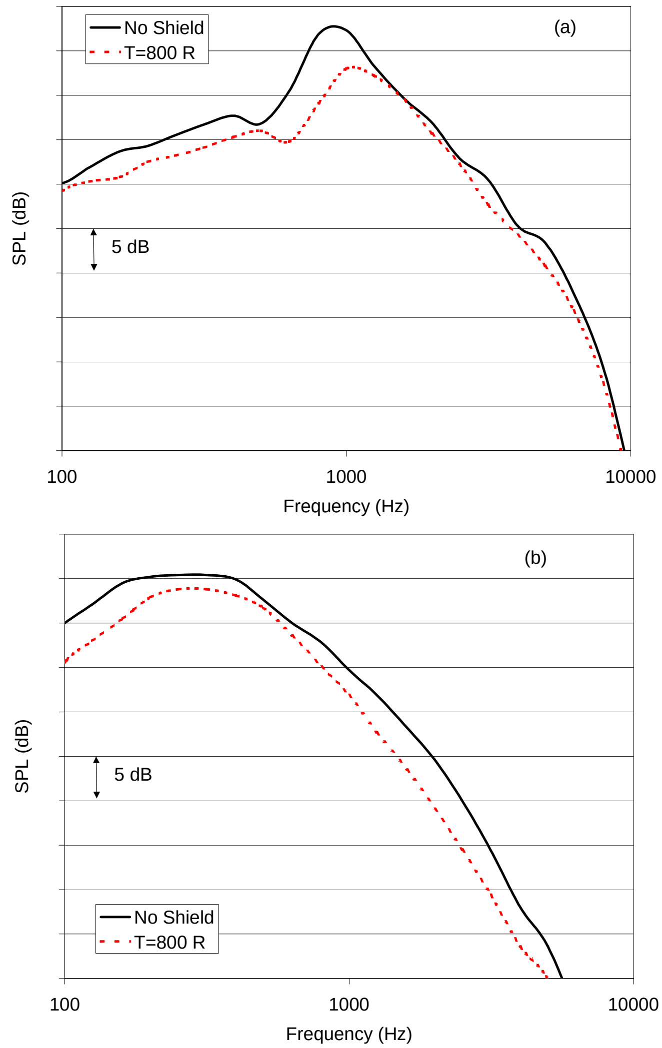

Figure 17 SPL spectra with and without a fluid shield, same conditions as Figure 16, at (a) 60 deg, and (b) 140 deg. With external flow simulation, Mfj=0.35

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