Noise Suppression of a Supersonic Model Twin Jet Nacelle

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ABSTRACT

This paper summarizes on-going experimental research associated with efforts to achieve aero-performance efficient noise reduction of supersonic jet mixing and shock noise for military style supersonic nozzle exhausts. The baseline supersonic nozzle under investigation is one that is designed with a sharp throat radius of curvature and conical convergent and divergent sections with flat seals. Relevant baseline geometries are defined by the supersonic nozzle exhaust ducts on the F101, F110, F414, and F119 engines. Acoustic suppression technology being investigated utilizes corrugated surface topology for the divergent section of a supersonic nozzle, divergent sections with bevelled exhaust, and high pressure water drop injection from the nozzle nacelle trailing edge. Acoustic measurements were acquired for a small scale model, nominally 10 % scale, supersonic nozzle with baseline and suppressed configurations. These nozzles have a nominal exhaust diameter of 5 cm. The suppression concepts are all aero-performance efficient designs that achieve substantial jet mixing noise reduction and elimination of shock generated noise. In the current round of testing, a twin jet nozzle nacelle was designed and fabricated. The twin jet model scale experimental measurements have indicated that corrugated divergent surface topology can suppress mixing noise by 4 dB relative to the baseline and completely eliminate shock generated noise. The reduction in jet mixing noise improves to 5.5 to 6 dB when bypass flow is ported through the interior of the corrugated seal.

1.0 INTRODUCTION

The team at the National Center for Physical Acoustics has developed a retrofit noise suppression concept (U.S. Patent 7,240,493 B2) for the F/A-18 E/F Super Hornet aircraft that demonstrated noise reduction capability and thrust augmentation on a GEAE F404-400 engine at NAWCADLKE [1]. The concept involves application of a corrugated surface to the current flat engine seals, where only every other flat seal requires corrugation. The engine test results corroborated those results obtained earlier with a 1/10'th scale model obtained in the NCPA Jet Noise Laboratory [2]. The success of the engine and model scale studies shows the utility in the design and evaluation of noise suppression concepts in this model scale size.

One of the fundamental goals associated with optimization of the surface topology for a corrugated seal is to maximize the strength of counter-rotating vorticity generated by the corrugated engine seal. Enhanced mass flow entrainment into the jet plume is directly related to the strength of the counter-rotating vorticity. Increased mass entrainment into the jet from low speed surrounding cold air leads to lower jet static temperatures and lower jet velocities (lower noise emission). Lower noise emission is also achieved by reduction of turbulent kinetic energy and elimination of large-scale coherent-like turbulent structure [3]. In order to optimize this noise suppression concept cross plane Particle Image Velocimetry (PIV) measurements were acquired at several axial stations of a model baseline nozzle with flat seals and one with 6 corrugated seals. These measurements, previously reported at the 19'th ONR Propulsion Meeting [4], related measured counter-rotating vortex strength to level of noise suppression. Supersonic jets, like the exhaust plume from a military engine nozzle also contain shocks that lead to the generation of shock-generated noise when turbulence is convected through a shock [5]. Consequently, in addition to the generation of counter-rotating vorticity for eddy-Mach wave emission, the corrugated engine seal described in references 1 and 2 was also designed to produce a shock free engine exhaust plume. That part of the design process is aided by the Method of Characteristics design procedure.

The corrugated surface topology represents one possible method to achieve, with fixed geometry, nearly shock free flow over a wide range of operating nozzle pressure ratios for nozzles with sharp throat radii of curvature. The boundary layer along the interior wall of the divergent nozzle section is always separated due to the sharp throat radius of curvature and consequently has a thick boundary layer at the nozzle exit. Noise suppression concepts that are utilized to enhance mixing of the high speed jet exhaust plume with surrounding ambient air by generation of counter-rotating vorticity are not as effective with a thick subsonic boundary layer. Thus the fundamental concept behind the corrugated surface topology for supersonic nozzle design is to decrease the potential for separation at the throat thereby reducing the nozzle exit boundary layer thickness. This in turn increases the static pressure along the divergent section inner wall leading to thrust augmentation.

Since these new and exploratory tests were completed, we have additionally evaluated the corrugated engine seal concept with a single nozzle nacelle of 1/5'th scale with simulated forward flight in the Boeing LSAF. These results indicated improved noise suppression in flight over prior static testing. In addition, studies with this scale model were conducted with a concept introduced by Boeing, the beveled exhaust nozzle. The beveled exhaust nozzle represents a major reconfiguration to the design and manufacture of a military exhaust nozzle. The concept would require that both the primary and secondary flaps with seals have different lengths. To minimize flap attachment part count, the outer nozzle nacelle would necessarily have an unequal boatail angle azimuthally. This would lead to a significant increase in aircraft drag in flight. In addition, one must factor in the length of the flaps and seals to avoid ground strike on take-off and landing. However, the concept can produce noise reduction without any additional loss of thrust and thus requires that the noise reduction potential of this concept be established. There is a slight loss in axial thrust since the flow becomes vectored with a beveled exhaust.

In this paper we will show the design used for the dual podded nozzles with corrugations and beveled exhaust. The acoustic measurements with twin nozzle nacelles will be compared to results obtained with single nacelles and single nacelles in simulated forward flight at a speed of 150 knots. Comparisons will also be made to evaluate if the concepts result in additive suppression levels. Consequently results from high pressure water droplet injection will also be included in this paper.

2.0 MODEL HARDWARE AND FACILITIES

2.1 NCPA Facility

Figure 1 illustrates the exhaust portion of the jet model geometry installed in the NCPA Jet Anechoic Facility (1/10'th scale) and the Boeing LSAF (1/5'th scale). The system contains a centerbody, whose shape from the exit of the turbine casing is exactly scaled, as is it position to the nozzle throat. The model does not contain a system for mixing by-pass engine air and thus is considered premixed in this model. The NCPA is currently designing a bypass nozzle for these studies. Also the model does not contain scaled thrust augmenter tubes.

All internal and external dimensions of the nozzle section have been scaled. As can be observed the model can accept either flat or corrugated seal inserts. The upstream NCPA section of the model, not shown, contains a swirl can propane combustor and seeding tubes for SPIV measurements. The NCPA model system was designed to maintain working pressures of 300 psig at temperatures to 20000R. The NCPA air charging system enables continuous testing. As can be observed in Figure 1, the nozzle is extended from the main air feed to minimize acoustic reflections and line of sight blockage to microphone sensors located in the inlet arc. The LSAF facility can accommodate operation at military exhaust power.

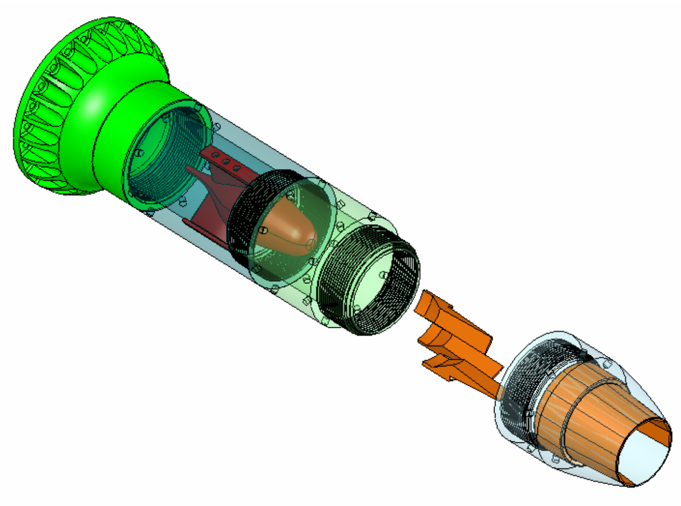


Figure 1: Design of Jet Rig for Testing of Single Stream Small Scale Supersonic Nozzles.

Figure 2 shows a solid model drawing of the fully assembled twin nozzle nacelle. It is important to note that each nozzle is inclined 2^0 toward the center. The model is designed with a rotation part to set azimuthal angles. After the rotation feature, the flow is directed into a plenum that contains 2 honeycomb ceramic flow straightener as illustrated in Figure 3.

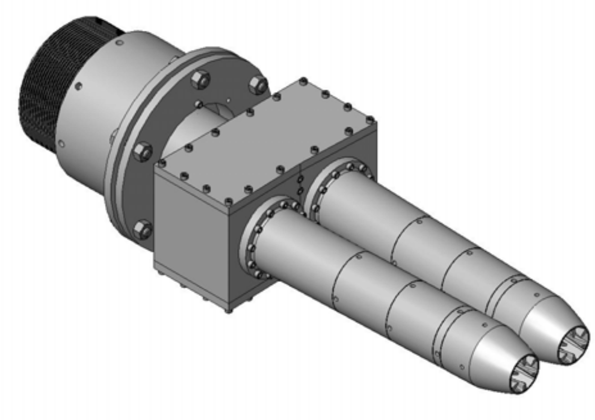


Figure 2: Design of twin nozzle nacelle.

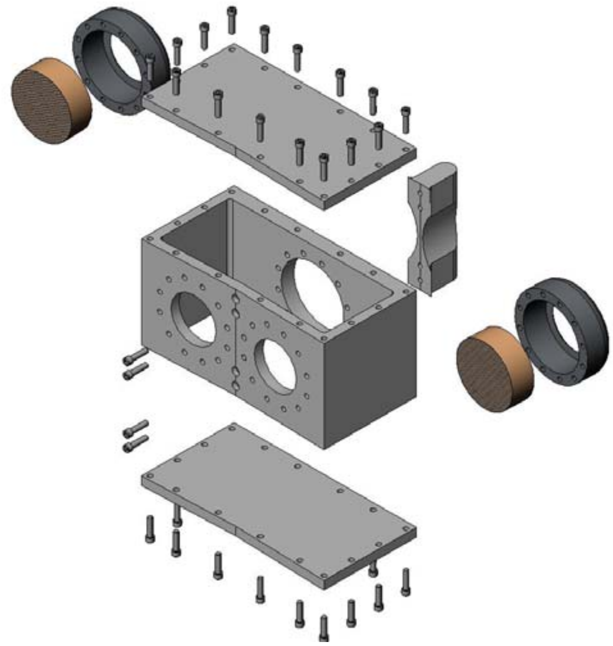


Figure 3: Exploded view of twin nozzle plenum chamber with ceramic flow straighteners.

Figure 4 shows a solid model drawing of one of the bevel nozzles. These nozzles were fabricated from smooth bore conical internal geometry and have a bevel angle of 35^0 at the nozzle exit. The longest divergent section is equivalent to the non-beveled nozzles shown in Figure 3. These nozzles were also designed for the military power setting. Since this research is conducted statically, no attempt was made to fabricate an outer nacelle with a constant trailing edge lip thickness. Each beveled nozzle could be rotated about its axis to study optimal orientation for noise reduction.

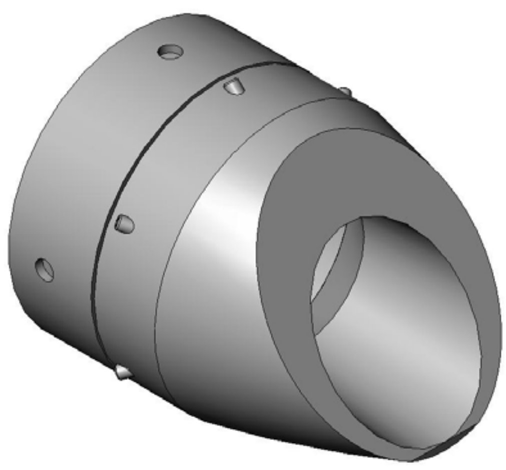


Figure 4: Beveled Mil-Power Nozzle with 35^0 Inclined Exit Lip.

Figure 5 shows the twin jet rig with the scale model nozzles with corrugated seals mounted in the NCPA anechoic room. The NCPA anechoic room has a low frequency cut-off limit of 200 Hz, which is adequate for noise assessments with small-scale models. The anechoic room has flow through wedges on the entrance and eductor walls. The eductor is connected to a powered exhaust fan to enable flow through the anechoic test section. This design was adopted to maintain low room temperatures during hot jet model studies, an absolute necessity for accurate refraction free far field acoustic measurements. When operating hot jets in this facility, room temperatures rise only a few degrees with continuous hot jet runs. The room has an 11-element microphone array with a radius of 55 jet exhaust nozzle diameters for 2-inch diameter exit nozzles. One requires a radius of 50 jet diameters to be in the jet acoustic far field. With respect to the inlet arc microphones are mounted at the following angles of ψ = 45, 52.5, 60, 75, 90, 105, 120, 127.5, 135, 142.5, and 150 degrees. All microphone sensors are calibrated with a pistonphone. Floor wedges in this room are removable to permit operation of jet flow measurements with a traversing rig. All microphone data was sampled at 250 kHz with a total of 1048576 points per channel to allow 256 averages of 4096 points with a ▲f = 61:0352 Hz.

All acoustic measurements were acquired with a power setting of the F414-400 engine at military power. The nozzle system was rotated to azimuthal angles of ϕ = 0, 30, 60 and 90 degrees. The $\phi = 90^0$ angle is representative of a direction directly below an aircraft toward the ground.

Figure 5: Twin Nozzle Nacelles Mounted in NCPA Anechoic Room

3.0 ACOUSTIC MEASUREMENTS

3.1 Overview

Acoustic studies with a single nozzle nacelle were conducted using the following nozzle set:

- MOC designed nozzle
- Smooth bore conical sharp throat radius
- Faceted
- Corrugated (6)
- Beveled

All nozzles were operated at the military power. Except for the 1/5'th scale beveled nozzle, all other nozzles were 1/10'th scale. The faceted and corrugated nozzle was also tested at 1/5'th scale. The 1/5'th scale nozzles were studied statically and simulated forward flight at 150 knots. The MOC nozzle should produce the maximum acoustic energy for Mach wave emission which dominates the rear jet arc and minimum shock noise for acoustic radiation in the forward jet arc. Thus the MOC nozzle is a good reference nozzle. The faceted nozzle is the baseline nozzle in its use of flat seal inserts.

Figure 6 shows a comparison of the far field acoustic overall sound pressure level at R/D = 55 between the baseline nozzle and one with corrugated surface topology. The data has been corrected to STP atmospheric conditions. The faceted nozzle produces nearly the same acoustic Mach wave energy as the MOC nozzle and produces considerable shock noise. The nozzle with corrugations shows a reduction 3 to 3.5 dB relative to the baseline faceted nozzle. The noise emission at angles less than 90^0 are dominated by shock-generated noise. As can be observed by comparing the corrugated seal nozzle to the baseline nozzle the noise is reduced by nearly 6 dB in this region. Thus the MOC design of the corrugated seals appears to be effective at eliminating shock noise. The corrugated seals appear to be effective at eliminating shock noise. In the peak jet noise mixing direction near 135^0 the corrugated topology reduces noise by 4 dB.

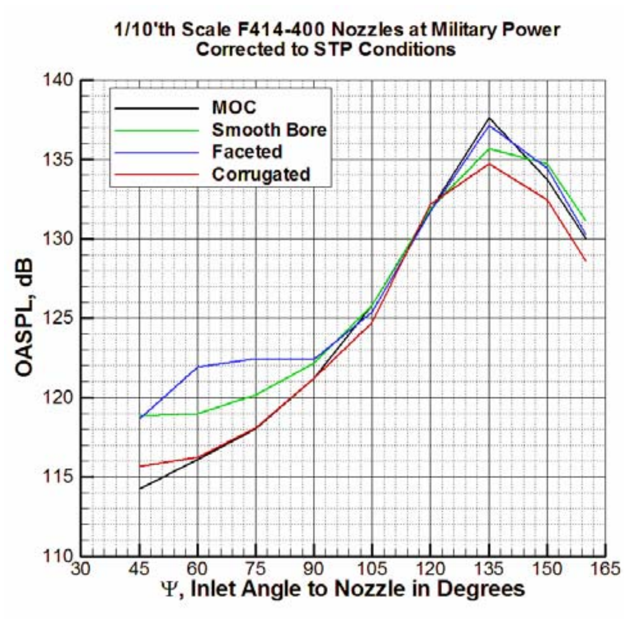
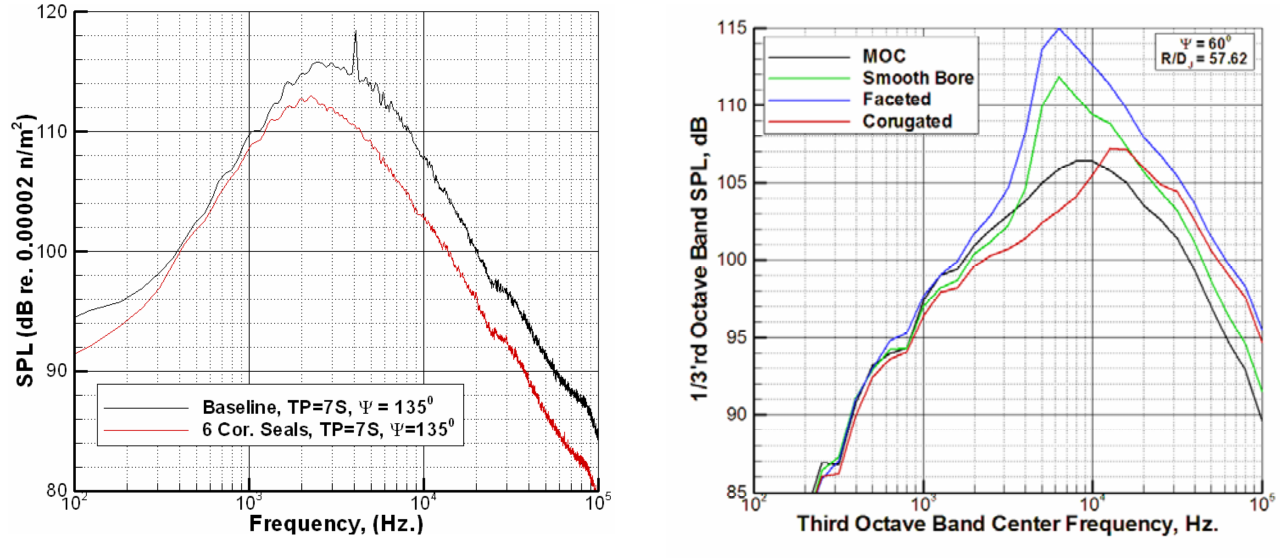


Figure 6: Model OASPL for Baseline and Corrugated Divergent Section Topology.

To more clearly observe the noise suppression characteristics of the corrugated divergent section topology, consider the third octave spectra of Figures 7 which is corrected to STP conditions. Figure 7a shows the peak acoustic energy direction ($\Psi = 135^0$) for jet mixing noise or eddy Mach wave emission for the baseline and nozzle with corrugated engine seals. Figure 7b shows a similar comparison in the peak shock noise direction ($\Psi = 45^0$). Evidently the corrugated engine seal design concept works effectively to remove shock noise. Figure 8 provides a summary for the noise suppression obtained by the corrugated seal nozzle design relative the faceted nozzle. The suppression levels have been corrected to STP conditions and are in dBA. Figure 8 shows that shock noise elimination leads to a reduction of 4.5 dBA using corrugations and a reduction of 2 dBA in the Mach wave emission direction.



a. Noise suppression in Mach wave direction

b. Noise suppression in peak shock noise

Figure 7: Third octave band spectra for baseline and corrugated topology at military power (1/10'th Scale).

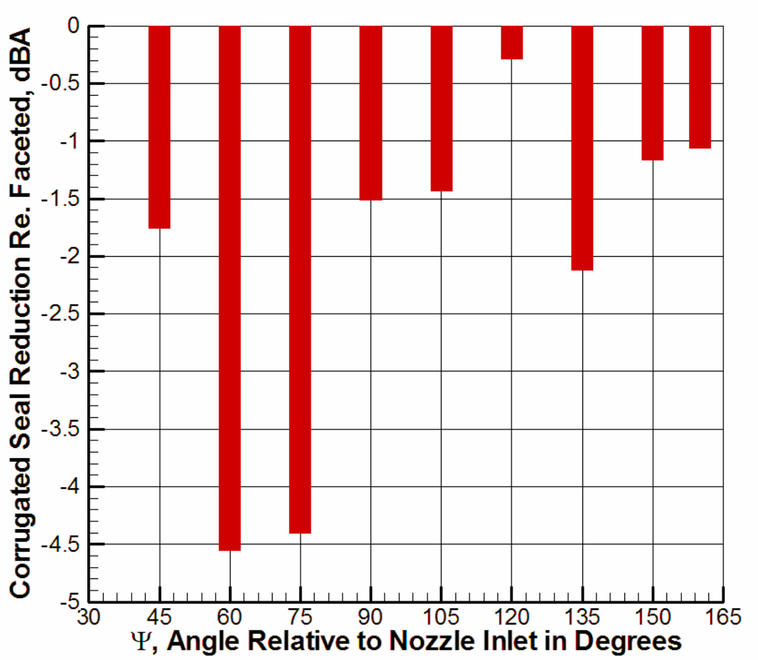


Figure 8: Noise suppression for corrugations with single nacelle (static 1/10'th scale).

Figure 9 contains a summary of the noise suppression obtained in 1/5'th scale and simulated forward flight at 150 knots for both the corrugated seal and beveled single nacelle nozzles at military power. Note that at a few rear arc angles the beveled nozzle has slightly greater attenuation than the corrugated nozzle. In the shock noise direction the bevel nozzle is ineffective. Comparing the suppression results for corrugated seals in 1/10'th scale (Figure 8) and 1/5'th scale in simulated flight (Figure 9) one sees that the peak eddy Mach wave suppression is increased from 2 dBA to nearly 4 dBA. This improved suppression comes as a result of forward flight, not scale sine our prior full scale static results were similar to the 1/10'th scale results.

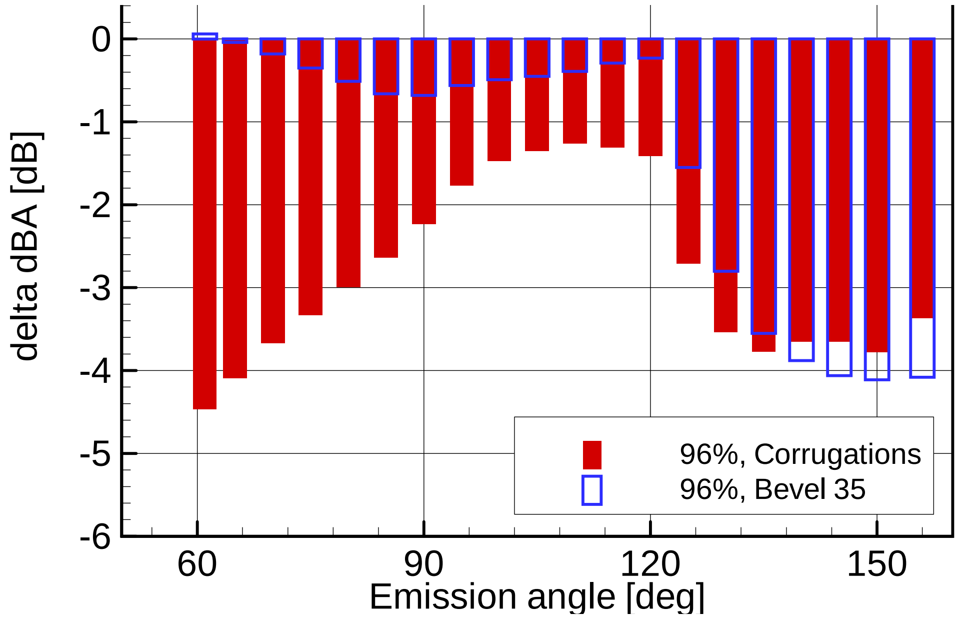


Figure 9: Noise suppression for corrugations and bevel with single nacelle (flight 1/5'th scale).

3.1 Twin Nozzle Results

Figure 10 shows the OASPL levels obtained for the faceted baseline nozzles installed on the twin nozzle nacelle of Figure 2. The acoustic levels have not yet been corrected to STP and are in dB rather than dBA. Figure 10 shows results for azimuthal angles of ϕ = 0, 30, 60, and 90^0. The peak amplitude level directly below the flight path (i.e. $\phi = 90^0$) for Mach wave emission is 140 dB which is 3 dB above the level obtained for the single stream baseline nozzle. This implies that coupling between exhaust plumes is minimal for static conditions. Radiation directed to the sideline is slightly reduced due to shielding of noise by one jet plume from another. The noise radiation at intermediate angles falls in between the noise radiated to ϕ = 90 and 0^0. The remainder of this presentation will concentrate on just these two angles to condense the results. Corrections to STP conditions will not be made at this time.

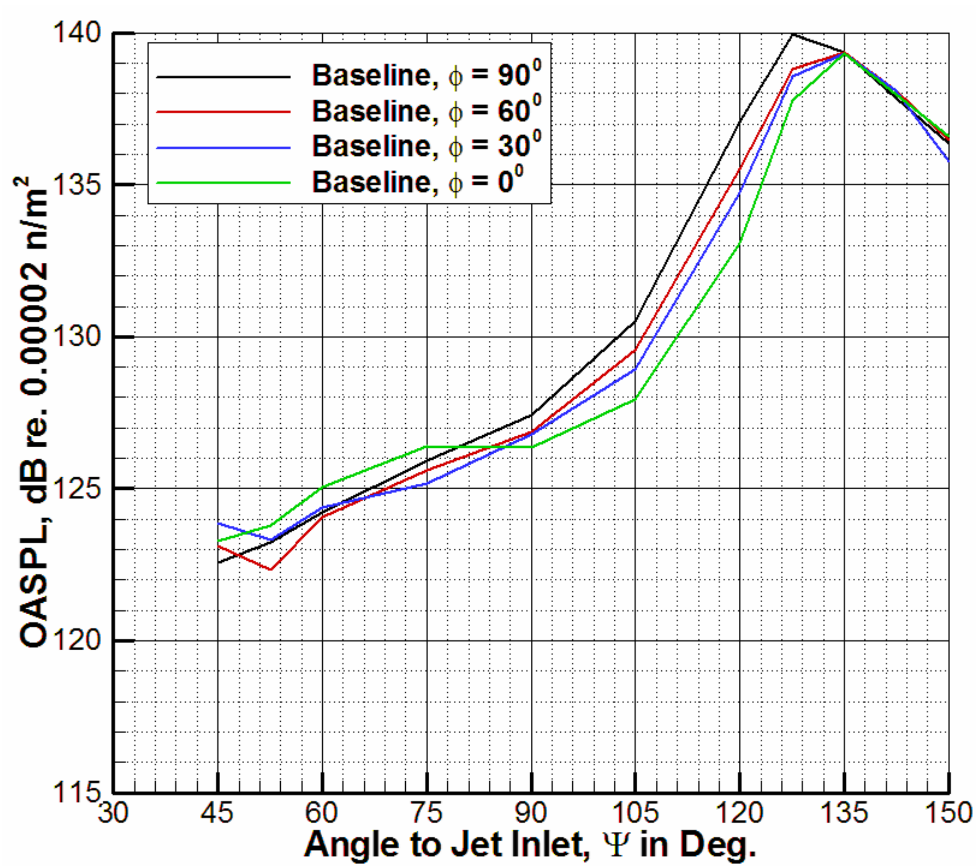
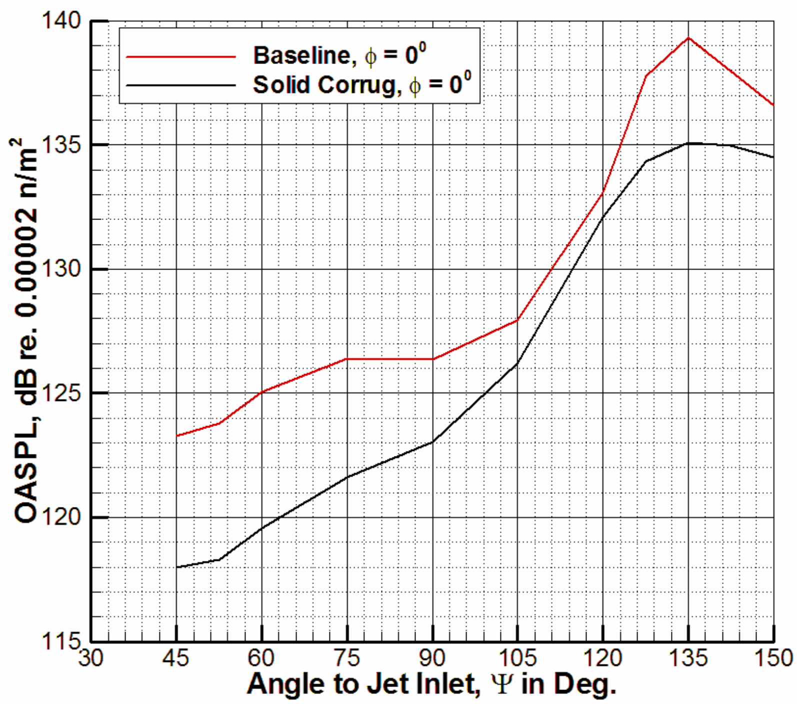


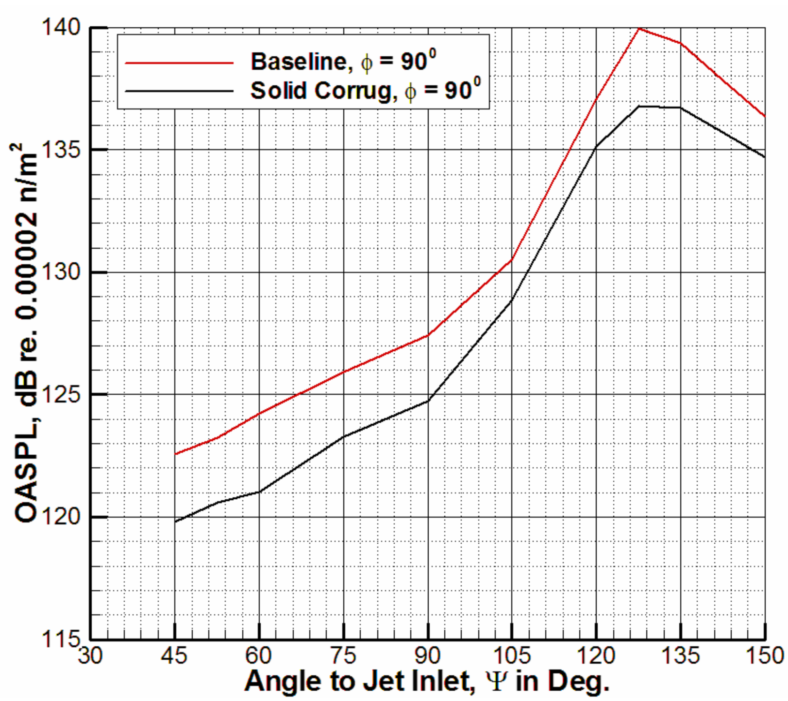
Figure 10: OASPL directivity for several azimuthal angles for baseline faceted nozzle at military power.

Figure 11a and 11b show respectively OASPL levels for the solid corrugated seal nozzle at overhead and sideline angles. These OASPL levels are compared to that obtained by the reference faceted nozzles. As can be observed, under the flight path the corrugated seals provide 3 dB noise reduction and to the sideline 4 dB. These reductions are better than that achieved with 1/10'th scale models and this is attributed to improved interactive effects with twin nozzle nacelles.

Details of the noise suppression for each major noise emission source are shown in the narrow band spectra of Figures 12a and 12b. These figures show the narrow band acoustic spectra at $\Psi = 135^0$ and 60^0 respectively for Mach wave emission and shock noise. Figure 12a shows the results for noise directed to the side and 12b for noise generated directly overhead. From this data the reduction of shock noise is easily observed as well as reductions in Mach wave radiation.

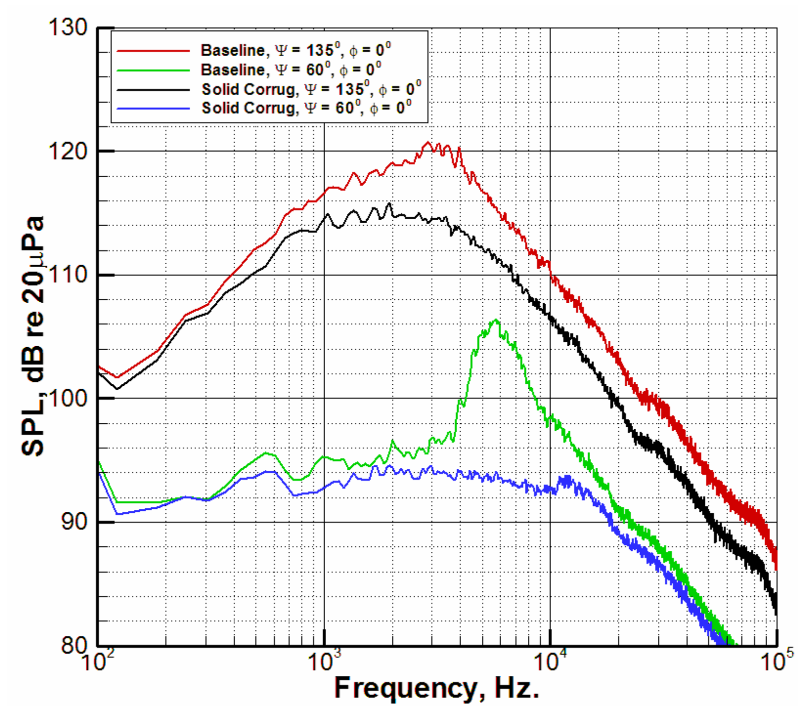


a). acoustic suppression to sideline

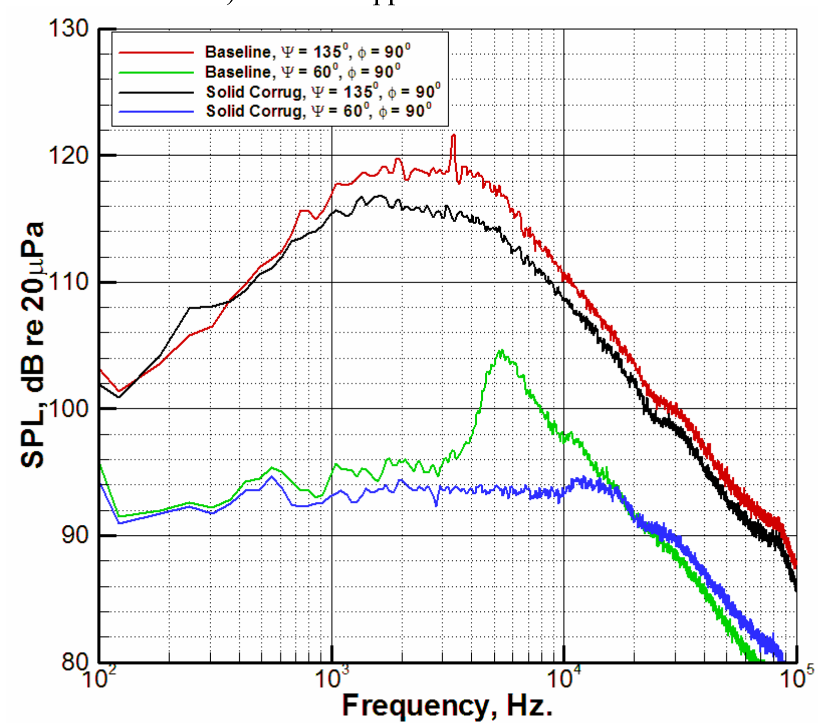


b). acoustic suppression to overhead

Figure 11: Comparison of OASPL between baseline and corrugated seal nozzles.



a) acoustic suppression to sideline

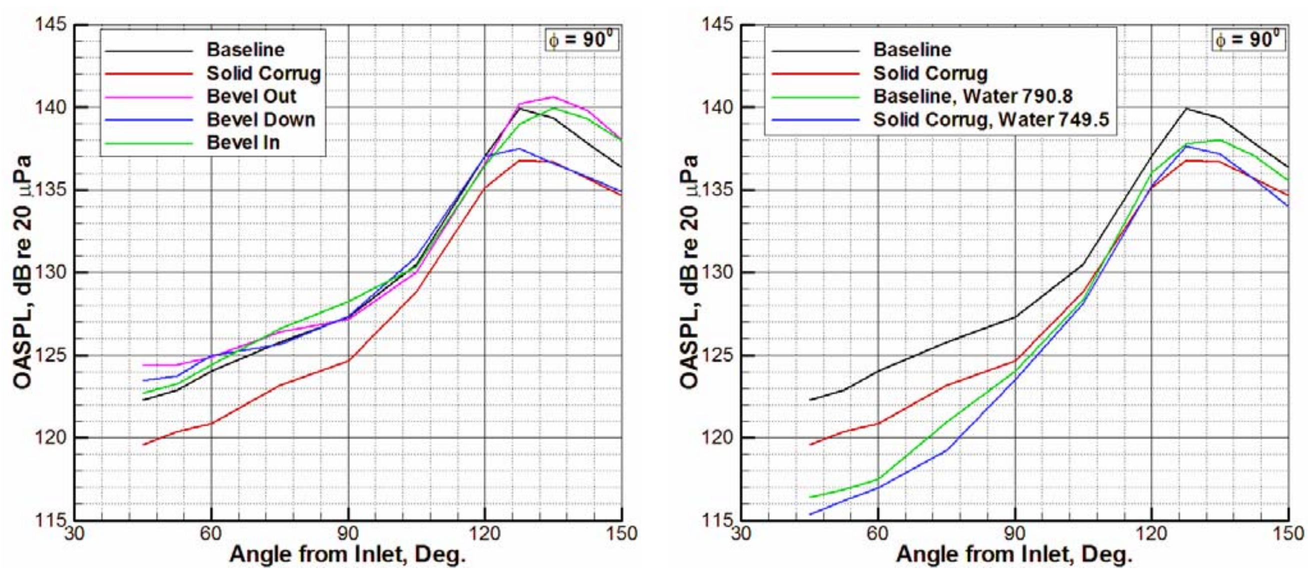


b) acoustic suppression to overhead

Figure 12: Comparison of narrow band spectra between baseline and corrugated seal nozzles.

We examine noise suppression for water injection and beveled nozzle nacelles by examining the OASPL directivity for azimuthal angles 0 and 90^0. Figure 13 shows results for azimuthal angle, $\phi = 90^0$. Figure 13a shows results for beveled nacelles where the longest flap would be oriented facing out on the sideline, facing down to the ground plane, and facing in to the inter-nozzle region. We see from this result that the beveled nacelle provides 2 dB suppression in the direction of the longest flap in the Mach wave direction. The beveled nozzle has no effect on shock noise.

Figure 13b shows the acoustic results for acoustic radiation under the flight path when a high pressure water spray (6 locations) is applied at the nozzle lip trailing edge. The figure shows that water injection combined with corrugated seals is not a good idea since the vortex strength of counter rotating vorticity is diminished in the injection locations used in this study. Even though the mass flow rate of water is equivalent to 30% of the nozzle weight flow, the noise reduction with water injection is about the same as the corrugations in the Mach wave direction but significantly better in the shock noise direction.

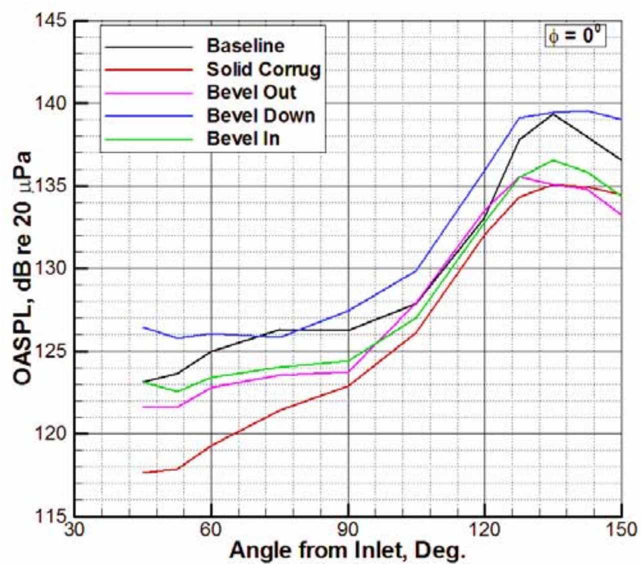


a. Beveled nacelle noise to ground plane

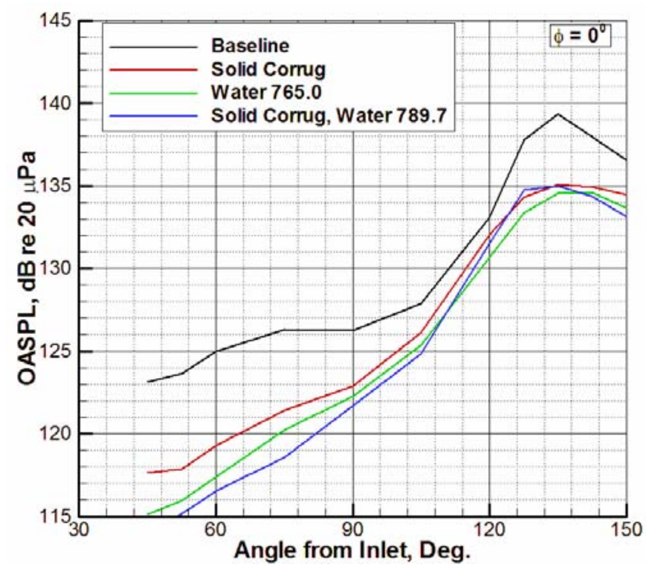
b. Water injection results to ground plane

Figure 13: Acoustic radiation under flight path for baseline and various suppression concepts.

Similar acoustic results are shown in Figure 14 for the radiation to the sideline. Figure 14a is associated with beveled nozzles and 14 b with high pressure water injection. Again the data shows that one only suppresses noise in the direction of the long flap with beveled nozzles. The high pressure water injection reduces noise slightly more effectively than solid corrugations in the sideline direction.



a. Beveled nacelle noise to sideline



b. Water injection results to sideline

Figure 14: Acoustic radiation to sideline path for baseline and various suppression concepts.

4.0 CONCLUSIONS / FUTURE RESEARCH

In this paper we have discussed jet noise suppression associated with corrugated divergent sections of a supersonic nozzle, beveled exhaust nacelles, and to some extent high pressure water injection. The corrugated sections are designed to enhance external stream mixing thereby reducing jet mixing noise, while at the same time achieving fully pressure balanced flow at the nozzle exit to eliminate shock noise. The corrugated topology consequently enhances aero-performance. A scale model supersonic nozzle was constructed with and without the corrugated topology. The noise associated with operation of this model nozzle was obtained in an anechoic facility. The results show that the corrugated topology achieved a noise reduction of 4 dB in the peak eddy Mach wave noise emission direction and 6 dB in the peak shock noise emission direction. The best noise reduction performance was obtained with the use of 6 equally spaced corrugations.

The results obtained in this study clearly indicate relative to prior results that the noise suppression levels associated with the corrugated topology and beveled nacelle improve with forward flight and that associated with a single nacelle. The suppression methods are aero-performance efficient and consequently could be implemented in full scale. The corrugated seals would be retrofit parts. A flight test needs to be conducted to clearly establish the true noise reduction and overall flight characteristics for various missions including cruise.

5.0 ACKNOWLEDGEMENTS

This research was

6.0 REFERENCES

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