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Assessment of Low-Noise Nozzle Designs for Fighter Aircraft Applications

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The aeroacoustic performance of three noise reduction ideas for fighter aircraft has been evaluated in one-fifth model scale testing, in stand-alone mode, and in combinations thereof in the Low Speed Aeroacoustic Facility at The Boeing Company. These three concepts consist of microjet injections of air and water, corrugated nozzle inserts, and beveled nozzles. Several bevel angles of 20, 24, 28 and 35° at typical military takeoff power, and 24 and 32° at reduced power, were considered with two representative geometric models. The static thrust performance of all the modified nozzles is superior or comparable to that of the baseline nozzle. The model scale noise measurements have been extrapolated to full-scale conditions. The salient results of the acoustic performance at typical military takeoff power, assessed over a range of freestream Mach numbers from 0.0 to 0.32, are as follows. First, the water injection produces a larger benefit at the lower polar angles (measured from the nozzle inlet axis) where the shock component is dominant; the magnitude of the benefit in the dBA metric varies from ∼2 to ∼3 dBA at a polar angle of 60° and drops to ∼1 dBA at 90°. The benefit at large aft angles is ∼1 dBA. Second, the corrugations provide the largest benefit at the lower polar angles. The dBA benefit is ∼4 dBA for a range of freestream Mach numbers from 0.16 to 0.32. As for the water injection, the benefit drops to ∼1 dBA at 90°. At the aft angles, there is a benefit of ∼3 to ∼3.5 dBA. Third, the beveled nozzles provide little modifications to the spectra at the lower polar angles. All of them provide a benefit in the dBA metric in the peak radiation sector: the magnitude of the benefit increases with the bevel angle and reaches a value of ∼4 dBA for bevel 35. Fourth, the addition of water in conjunction with the corrugations and the bevels augments the noise benefit ∼1 dBA at the lower angles and reduces the benefit in the aft angles. Fifth, all the concepts provide a benefit in the effective perceived noise level metric. At the reduced cutback power, the magnitude of the noise benefit is larger in the forward quadrant. The reasons for the observed noise reduction are examined for the different nozzle configurations.

I. Introduction

THE operations of fighter jets pose a significant noise problem. The United States Navy is interested in finding technical solutions that can reduce source noise and thereby alleviate the problem of noise exposure due to the operation of these aircraft. There are two situations with high noise impact: 1) for the communities surrounding naval air bases, where fighter pilots carry out training missions that mimic actual operations on an aircraft carrier deck; and 2) for the crew on aircraft carriers who are positioned very close to the fighter aircraft, which takeoff at maximum power. The first situation pertains to noise in the far field, while the second represents noise in the near field. Both problems are severe and noise mitigation is necessary for both scenarios. The dBA metric is used in noise exposure studies and is important for the operations of the fighter aircraft both on carrier decks and at naval air stations. The jet engines that power the fighter aircraft are often operated at off-design conditions, thereby producing shocks in the jet plume. Consequently, the component of broadband shock-associated noise is produced in addition to the turbulent mixing noise. The Office of Naval Research (ONR) has sponsored efforts to develop noise reduction concepts that do not degrade thrust performance. As part of this program, Seiner et al. [1–3] proposed and evaluated a design, termed the "corrugated inserts," that completely eliminates shock formation at takeoff conditions. Experimental investigations were carried out, both at one-tenth scale in the anechoic facility at the University of Mississippi and on a GE F404 engine at the Lakehurst Naval Warfare Center. Good noise reduction was demonstrated in these tests. Krothapalli et al. [4,5] and Greska et al. [6] have evaluated the microjet technique with air or water injection for the reduction of jet noise at the operating conditions of interest. They experimented with various gases and water, and optimized the angle of microjet injection, the number and location of the microjets, etc. These studies

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showed that there is a large reduction in the overall sound pressure levels with water injection at the forward radiation angles, where broadband shock-associated noise is the dominant component. Again, this concept was tested at both one-tenth scale in the anechoic facility at the Florida State University and in the full-scale engine test at Lakehurst.

Viswanathan [7–9] has carried out detailed aeroacoustic tests of both single-stream and dual-stream beveled nozzles. To gain better insights into the modifications to the flow and radiated noise, large eddy simulations for the same nozzle geometries have been carried out (see [10]). In these studies, the nozzle geometries corresponded to those of high-bypass-ratio turbofan engines that power commercial aircraft. It was demonstrated that significant noise reduction is achieved in the azimuthal directions below the longer lip of the beveled nozzle, principally in the polar angular range of ~110 to ~150°. All polar angles are measured from the jet inlet axis. Furthermore, this reduction is observed at all frequencies. The magnitude of the noise reduction is a strong function of the jet velocity, with progressively higher reductions as the jet velocity is increased.

A wind-tunnel test is the main component of this project, with the following principal objectives:

1) Evaluate the noise reduction potential of various suppression concepts, individually and in combinations thereof.

2) Quantify the effects of forward flight on baseline and suppression concepts.

3) Assess the thrust performance of the baseline and suppression concepts.

4) Create a database that enhances our current understanding and which satisfies the science and technology goals of the ONR.

A main constraint of this program is the development of noise reduction concepts with zero or negligible thrust penalty. A detailed wind-tunnel test program has been completed to assess the aeroacoustic performance of all these concepts; the salient results are reported in this paper.

II. Facility Description and Test Details

The experiments were performed in the Low Speed Aeroacoustic Facility (LSAF) at The Boeing Company, with simultaneous measurement of thrust and noise. Detailed descriptions of the test facility, the jet simulator, the data acquisition and reduction process, etc., may be found in Viswanathan [11,12]. The jet simulator is embedded in an open-jet wind tunnel, which can provide a maximum freestream Mach number of 0.32. Bruel and Kjaer type 4939 microphones are used for free-field measurements. The microphones are set at normal incidence and without the protective grid, which yields a flat frequency response up to 100 kHz. Since we anticipate significant azimuthal variation, two microphone arrays 30° apart in the azimuthal direction are employed. Figure 1 shows a photograph

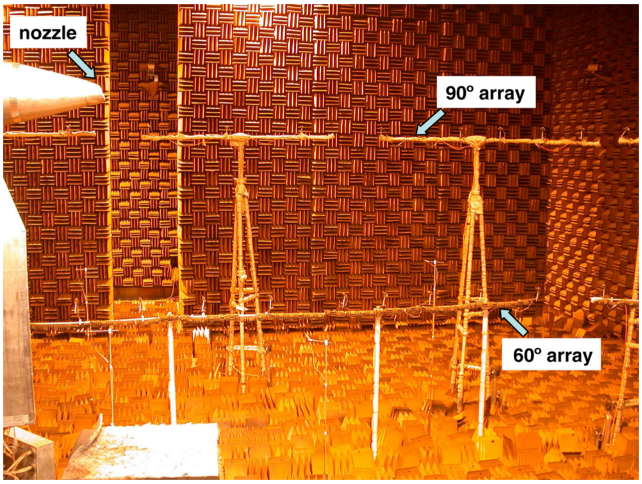


Fig. 1 Photograph of the anechoic chamber with the installed nozzle and the two microphone arrays at azimuthal angles of 60 and 90°.

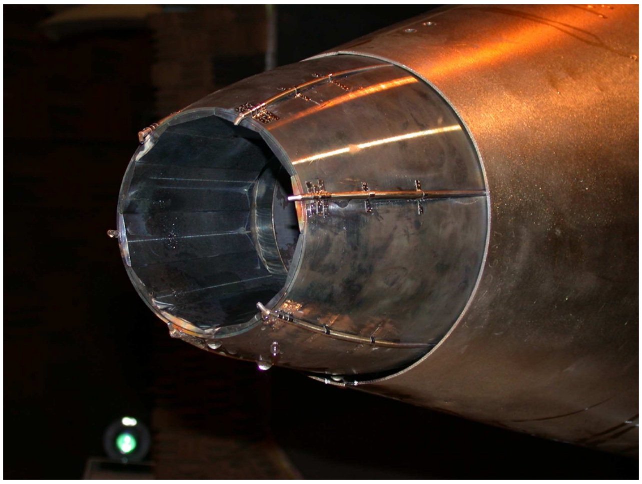


Fig. 2 Photograph of baseline nozzle with external tubes for micro jet injection attached.

of the anechoic facility and the two microphone arrays. The microphones in one array are laid out at a constant sideline distance of 15 ft (4.572 m) from the jet axis; the microphones in the other are on a polar arc at a distance of 25 ft (7.62 m). All angles are measured from the jet inlet axis, with a polar angular range of 50 to 150°. The exit diameter of the nozzle is 4.0 in. (10.16 cm), with a corresponding microphone distance of 75D for the polar array. Note that given the large distance to the microphones, the discrepancy in polar angle between the top and bottom of the beveled nozzle is negligible. Narrowband data with a bandwidth of 23.4 Hz are acquired and synthesized to produce 1/3-octave spectra, up to a center band frequency of 80,000 Hz. For comparisons at model scale, the data are corrected to a common distance of 20 ft (6.096 m) from the center of the nozzle exit (coordinate system with origin at the center of the nozzle exit) and standard-day conditions: ambient temperature of 77°F (298°K) and relative humidity of 70%. The atmospheric attenuation coefficients are obtained from the method of Shields and Bass [13]. As verified by Viswanathan [14], the method provided by Shields and Bass is the most accurate for the higher frequencies of interest in model scale tests. The data have also been extrapolated to full-scale conditions of the jet engine considered. The measurements from the baseline and modified nozzles have been carried out at the appropriate engine cycle conditions and at realistic forward-flight velocity.

The baseline nozzle consists of convergent–divergent sections, with a centerbody (see Figs. 1 and 2 in [2] for details). A one-fifth-scale model, which represents a simplified version of the exhaust system of a typical fighter engine, was designed and built for the LSAF test. The jet engine based on which the model scale nozzle is

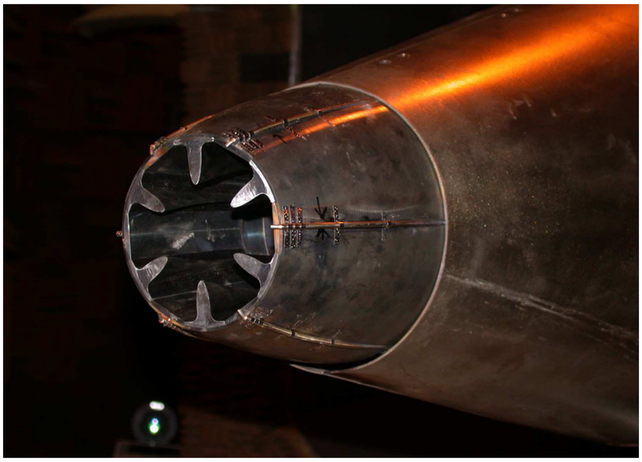
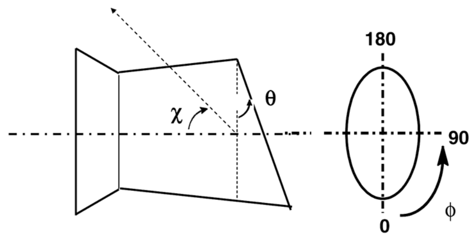
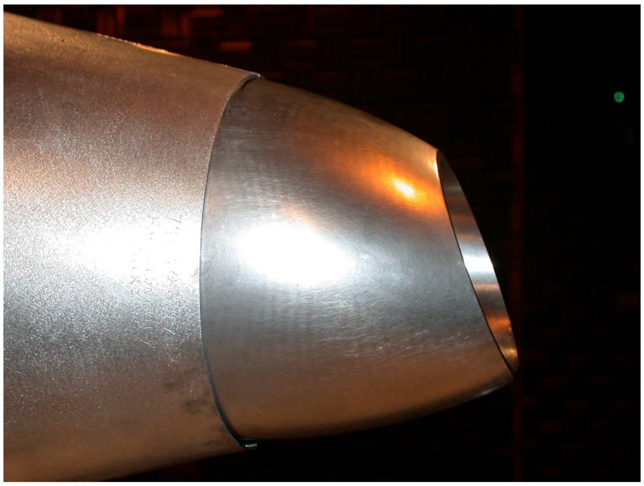


Fig. 3 Photograph of the corrugated nozzle with injection tubes.



a)



b)

Fig. 4 Beveled nozzle: a) conceptual sketch of a beveled nozzle and the measurement convention for the polar angle (χ), bevel angle (θ), and the azimuthal angle (ϕ) and b) photograph of evaluated nozzle.

built has a variable area nozzle; the nozzle throat area (A_8) and the nozzle exit area (A_9) vary as the engine is throttled, and the ratio (A_9/A_8) is a function of the fan rpm denoted by N1. Two representative N1s were selected; these corresponded to typical military takeoff (MIL) power (96% N1), which is used for aircraft takeoff and a reduced power (91% N1) that corresponds to cutback conditions. The ratio of the exit area to the throat area at 96% N1 is 1.398; the corresponding theoretical design Mach number for this area ratio is 1.76 [nozzle pressure ratio (NPR) = 5.41] for this nozzle; this geometry is referred to as nozzle system 1 here onwards. The ratio of the exit area to the throat area at 91% N1 is 1.224; the corresponding theoretical design Mach number for this area ratio is 1.56 (NPR= 4.0); this geometry is referred to as nozzle system 2. Two different sets of nozzle hardware, both baseline and modifications, were designed and fabricated to allow for the assessment of the noise reduction concepts.

Figure 2 shows the baseline nozzle: the inside surface is faceted and the external tubes provide a means for microjet injection. Both air and water were used, with the injection angle being 60° to the upstream jet axis. Six microjets, with uniform azimuthal spacing, were deployed. The injection tubes were spot-welded to the exterior surface of the nozzle, so as to restrain them in place when the wind tunnel was operated. Figure 3 shows the baseline corrugated nozzle, again with the injection tubes. As described in detail in [2,3], the inserts are designed to provide a smooth axial variation of the internal area that allows for the flow to develop without the formation of shocks in the external jet plume. There are six inserts, installed on alternate facets. The microjets were located on the center of the flat facets, without the inserts. The definitions of the various angles for the beveled nozzle are illustrated in Fig. 4a; Fig. 4b shows a photograph of a beveled nozzle, installed on the jet rig. Table 1 shows the various configurations evaluated at the two power settings in the test program. As seen, a comprehensive matrix of noise reduction concepts has been developed, so as to arrive at an optimum design for noise reduction. The aeroacoustic performance of the beveled nozzles has been examined in detail and is reported in a companion paper (see [15]). It is clearly established that there is substantial reduction of noise; secondly, there is an improvement in the static uninstalled thrust performance for most nozzles considered.

Table 1 Nozzle configurations evaluated at two different power settings

Configuration	Power setting
Bevel 20, 24, 28, 35	96% N1
Bevel 24, 32	91% N1
Corrugations	96% N1 and 91% N1
Microjet injection: air and water	96% N1 and 91% N1
Corrugations + air	96% N1 and 91% N1
Corrugations + water	96% N1 and 91% N1
Bevel 24 + microjet	96% N1
Bevel 24 + corrugation	96% N1
Bevel 24 + corrugation + microjet	96% N1

III. Results and Discussion

A. Thrust Performance

As already stated, one of the principal goals of this study is the development of nozzle concepts that do not incur a performance penalty or at most have a minor negative impact. Therefore, special care was taken in the thrust measurements. From a careful calibration exercise, it was established that the balance produced a linear response, with an error of ±0.13% (see Fig. 6 and associated discussion in [15]). The thrust measurements were obtained at the static conditions; the measurement of thrust for wind-on conditions poses several complications. First of all, the drag tare for the nozzle in the presence of the flight stream has to be quantified; the base drag of the nozzle is typically obtained by closing it off with a plate, on which several pressure transducers are installed. The pressure distribution on the base plate is then obtained for various wind-tunnel Mach numbers, and the various components of the measured drag are carefully bookkept. Such an undertaking is made more difficult by the presence of the injection tubes, and by the fact that the thrust produced by the injection (a small percentage) is not really metered. Therefore, the errors introduced were deemed to be of unknown magnitude, thereby bringing the measurements into question. It is well understood, though, that the assessment of the aerodynamic performance must include the external drag variations as well.

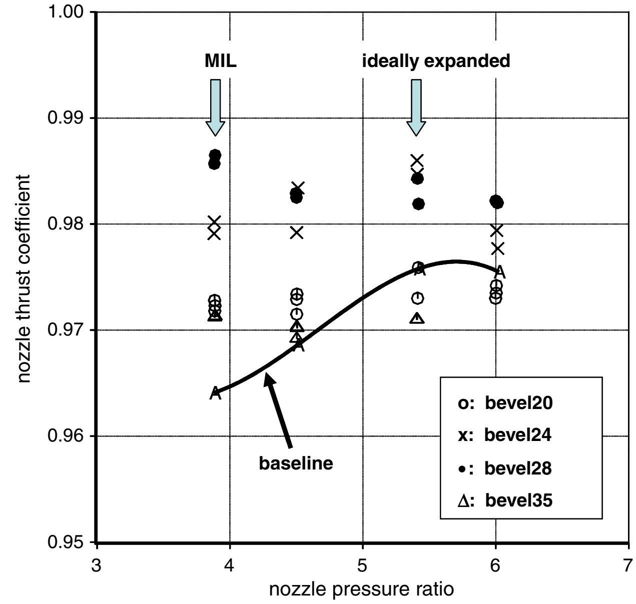


Fig. 5 Comparison of the thrust coefficients of the beveled and baseline nozzles. Nozzle system 1, 96% N1.

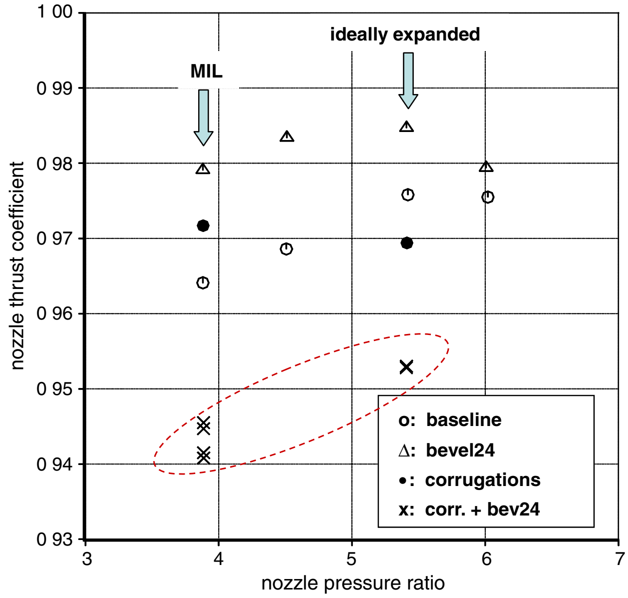


Fig. 6 Comparison of the thrust coefficients of the modified and baseline nozzles. Nozzle system 1, 96% N1.

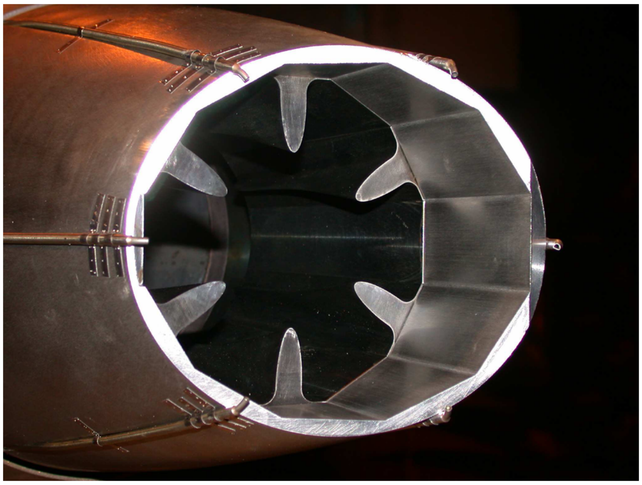


Fig. 7 Photograph of the nozzle with corrugations and bevel 24. Note that the corrugations extend to the nozzle exit plane at the left of the photograph. The short lip of the beveled nozzle is at the left.

Figure 5 shows a comparison of the static thrust performance of the baseline and beveled nozzles over a range of NPR. The NPRs that correspond to the MIL power and the ideally-expanded jet are also identified in this figure. The performance of the baseline nozzle, denoted by the letter A and a curve fit, follows the typical trend for a convergent–divergent nozzle: the thrust coefficient peaks close to the ideally-expanded NPR and drops off as the jet becomes progressively over- and underexpanded. Note that the polynomial fit seems to show a peak at a slightly higher NPR; this is an artifact of the curve fit, and measurements at closely-spaced NPR would be necessary to identify the exact design Mach number of the nozzle. It is also evident that all the beveled nozzles have a higher thrust coefficient at MIL power, when compared with the baseline nozzle. The increase in thrust coefficient ranges from ~0.75% for the bevel 35 to ~2% for bevel 28. Further, there is an increase in thrust coefficient at the higher NPRs for most of the test points shown; the reason for the improved thrust performance is examined and discussed in detail by Viswanathan and Czech [15]. The main observation is the following: the effective nozzle exit area for the beveled nozzle is lower than the geometric area because of the nonuniform pressure distribution at the nozzle exit plane. For overexpanded NPRs, this reduction in the exit area has a beneficial effect on the flow expansion, as the nozzle is operated closer to ideal expansion because of the lower (A_9/A_8). It is also established in [15] that the beveled nozzles produce at least the same absolute thrust as the baseline, thereby allaying any doubts about the aerodynamic performance of the beveled nozzles (see Sec. III.A in [15] for complete details).

Figure 6 shows a comparable plot for the corrugated nozzle and the combination of the corrugations and bevel 24. The microjet injection, with both air and water, provide a small increase in thrust coefficient. However, these thrust measurements are not included for the following reason: the tare due to the thrust of the microjets is not measured and therefore can not be properly bookkept in determining the true thrust coefficient. The following trends are observed in Fig. 6:

1) The corrugated inserts yield better thrust performance at MIL power, but produce a slightly reduced thrust coefficient at NPR= 5.41; the reason for these trends is straightforward: the corrugations result in the correct expansion at MIL power, thereby improving thrust performance, while the corrugations lead to shock formation at ideally-expanded conditions, thereby degrading thrust performance.

2) There is a striking reduction in thrust performance for the combination of corrugations and bevel 24; the reason for this reduction may be deduced through an examination of the final nozzle build in Fig. 7: the corrugations do not extend to the trailing edge of the beveled nozzle; rather, they terminate at the same axial location as for the baseline nozzle shown in Fig. 2.

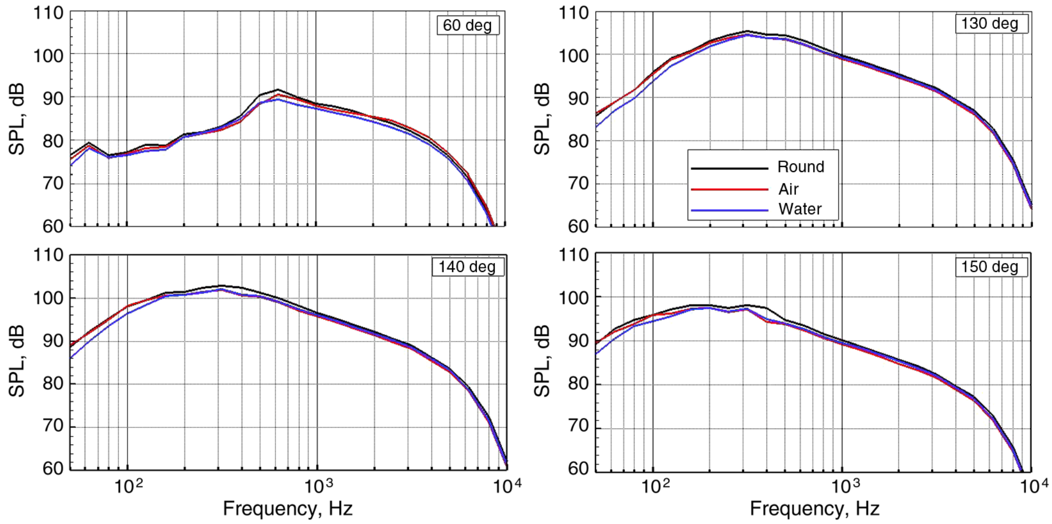


Fig. 8 Comparison of spectra at MIL power from nozzle system 1. $M_f = 0.0$.

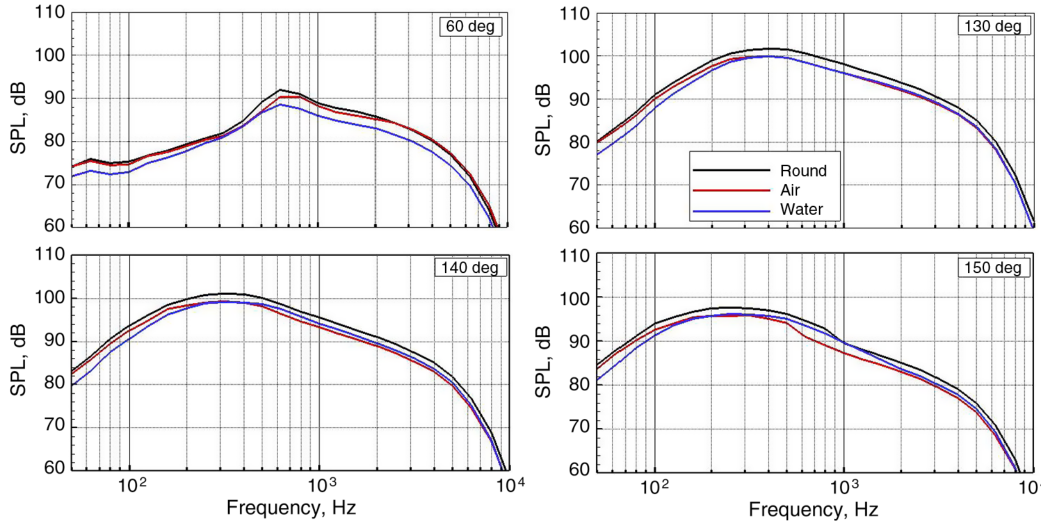


Fig. 9 Comparison of spectra at MIL power from nozzle system 1. $M_f = 0.233$.

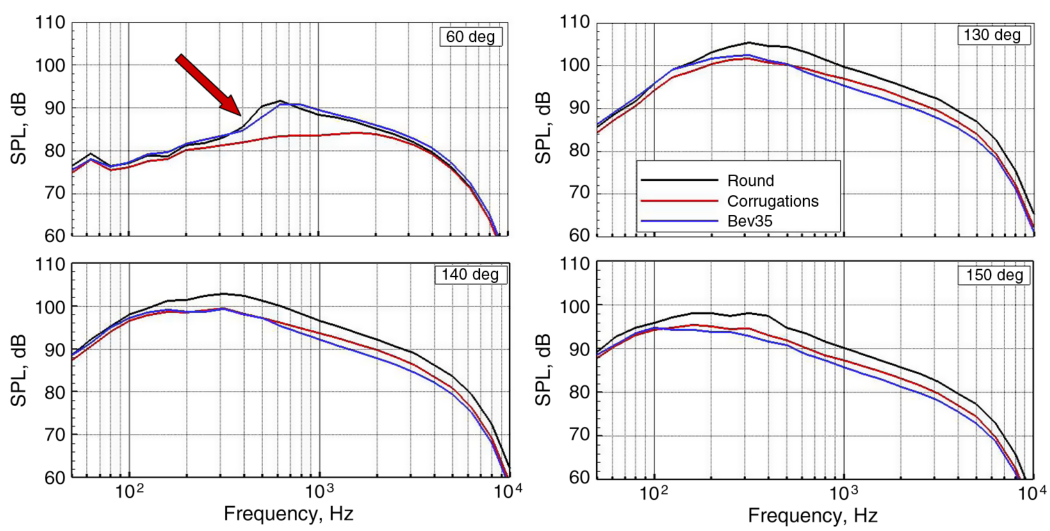


Fig. 10 Comparison of spectra at MIL power from nozzle system 1. $M_f = 0.0$.

Because of time constraints, only a new nacelle with a beveled trailing edge could be fabricated; a proper design in which the corrugations of different lengths would extend to the trailing edge was not completed. For the tested geometry, there are bluff base areas produced by the corrugations inside the nozzle. In addition to creating extra base drag, the flow quality is compromised. Instead of the elimination of the shocks through the proper adjustment of the flow area with the corrugations (see Fig. 2), shocks are reestablished

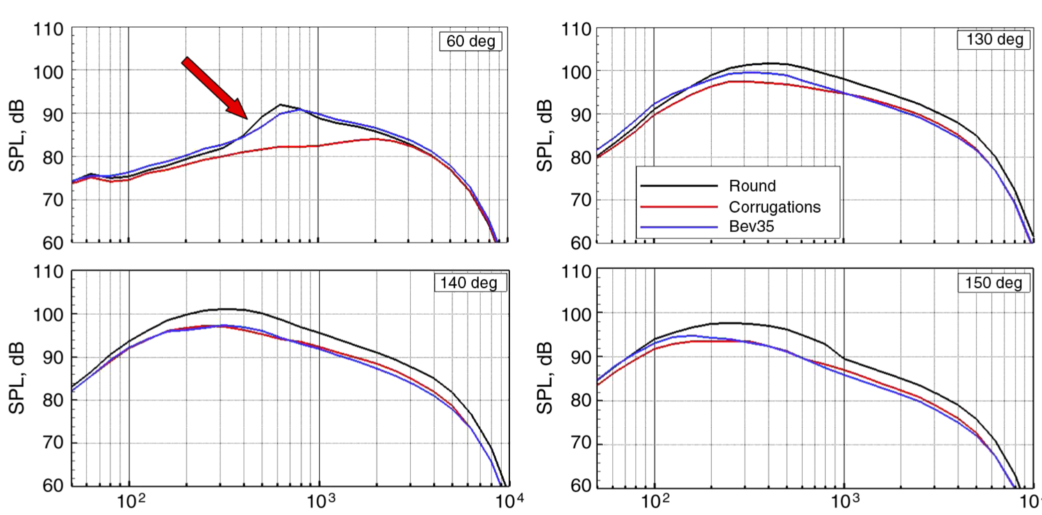


Fig. 11 Comparison of spectra at MIL power from nozzle system 1. $M_f = 0.233$.

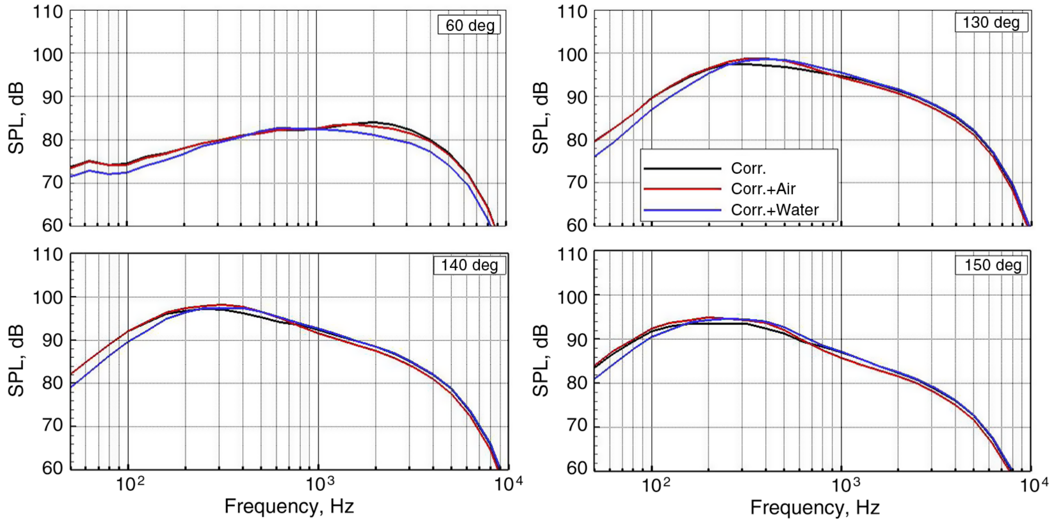


Fig. 12 Comparison of spectra at MIL power from nozzle system 1. $M_f = 0.233$.

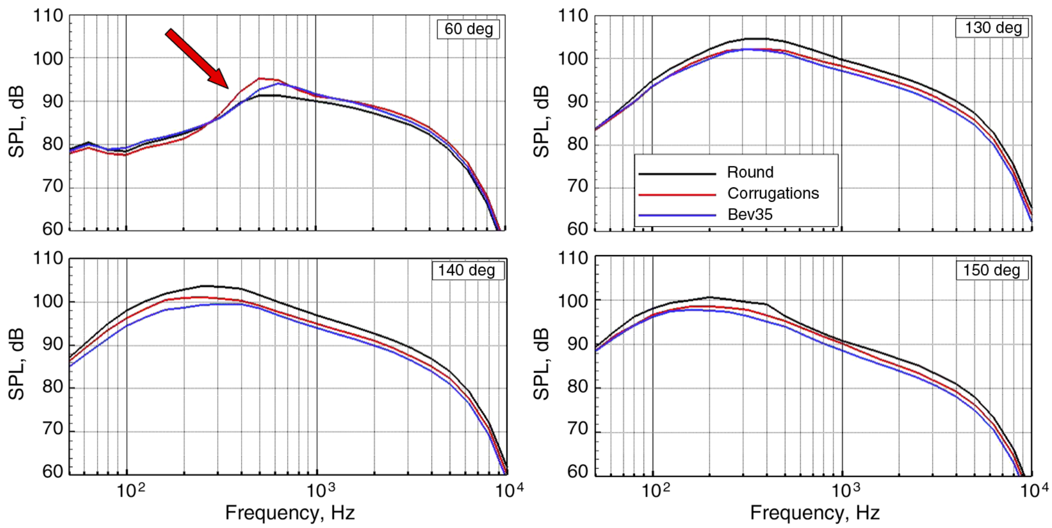


Fig. 13 Comparison of spectra at theoretical design Mach number (NPR = 5.41) from nozzle system 1. $M_f = 0.233$.

due to improper flow expansion with the geometry shown in Fig. 7. This conclusion is bolstered when the spectra are examined in Sec. III.B.

B. Acoustic Performance

Several noise metrics are used to characterize aircraft noise. The measured narrowband spectra are synthesized to produce one-third octave spectra. The one-third spectra are scaled to full scale, since the tests were carried out with models that were 20% of full scale. The aircraft is assumed to fly on a level trajectory at a fixed altitude of 1000 ft. Because data have been acquired up to 80 kHz, the maximum full-scale frequency is 16 kHz. Note that the integrated noise metrics cover the frequency range of 50 Hz to 10 kHz. The full-scale one-third octave spectra are then used to calculate the dBA and the effective perceived noise levels (EPNLs). The processing of the acoustic data obtained in the presence of a flight stream is more involved. The acoustic rays from the jet are subject to two effects: 1) convection in the downstream direction due to the freestream; and 2) refraction due to the tunnel shear layer. The changes in the spectral amplitude and the radiation angle due to the coflow have been calculated using the procedure developed by Amiet [16,17]. An interpolation of the resulting spectra at the true radiation angles to the radiation angles for the static case (fixed microphone angles) allows the direct comparison of the spectra obtained at various tunnel Mach numbers. For the jet with coflow, the appropriate propagation distances inside and outside the tunnel are calculated using Amiet's method together with the geometry of the jet and the wind tunnel. The proper values of the atmospheric attenuation coefficients inside and outside the tunnel flow are used.

Aeroacoustic measurements have been made at six different freestream Mach numbers of 0.0, 0.16, 0.20, 0.233, 0.28 and 0.32 for

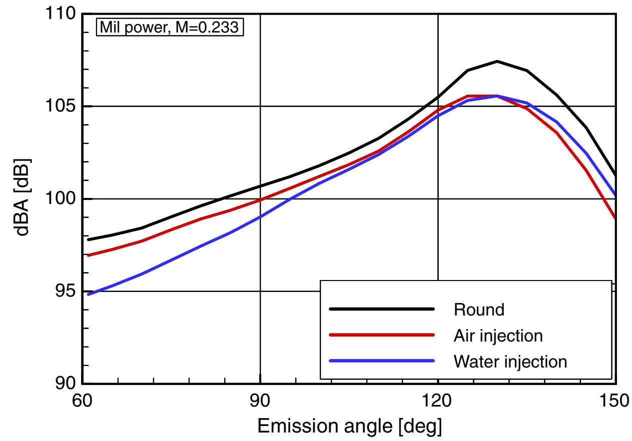


Fig. 14 Directivity of the dBA metric at MIL power from nozzle system 1. $M_f = 0.233$.

most of the geometric configurations described in Table 1. Only sample results are presented here. A discussion of the mechanisms responsible for noise reduction is deferred to the end of this section. First, spectral comparisons are presented at static conditions; four polar angles of 60, 130, 140, and 150° cover a wide range. Figure 8 shows full-scale spectra at MIL power for the baseline, and the baseline with air and water injections at static conditions. The injection pressure was maintained at 400 psi; the corresponding mass flow ratios (air/water mass divided by the engine mass flow rate) at MIL power are 3 and 33.5%, respectively, for air and water. These values increase at cutback power, due to reduced engine mass flow rate, to 3.47 and 39%, respectively. The addition of microjets produces spectral changes of only ~1 dB. A comparable plot with a flight-stream Mach number (M_f) of 0.233 is shown in Fig. 9. The introduction of a flight stream enhances the effect of the microjets and the spectral changes are larger. Figures 10 and 11 show the spectral variations due to the corrugations and bevel 35, with $M_f = 0.0$ and 0.233, respectively. First of all, the corrugations more or less eliminate the shock component at the lower radiation angle of 60°, for the static and wind-on cases. Such a reduction is also observed at all the angles in the forward quadrant (not shown) due to the proper expansion of the flow without shocks. In the peak radiation sector in the aft quadrant, both the nozzle modifications produce substantial reduction of ~4 dB across the spectrum from the turbulent mixing noise component. The beveled nozzle does not alter the spectra at the lower angles; this trend is consistent with those observed for beveled convergent nozzles. Figure 12 shows the effect of the addition of microjets in conjunction with the corrugations. The changes due to air injection are negligible, whereas the water injection produces a further noise benefit.

The performance of the corrugations and the bevel 35 nozzles at the theoretical ideally-expanded NPR of 5.41 is presented in Fig. 13; the flight-stream Mach number is 0.233. At this NPR, the area ratio (A_9/A_8) produced by the corrugation leads to incorrect expansion of the flow, resulting in increased spectral levels relative to the baseline in the shock component, at a polar angle of 60°. However, both the modified nozzles yield significant noise reductions of ~3 to ~4 dB across the spectrum in the aft radiation sector; of particular importance is the observation that the reduction is achieved at all the frequencies, without any increase at the higher frequencies.

The variations in the A-weighted noise metric are presented next. The noise directivity (in dBA) at MIL power and with $M_f = 0.233$ is depicted in Fig. 14. The peak level, dominated by the component of turbulent mixing noise, is higher than the levels at the lower radiation angles by ~10 dBA. This is so, even for the shock containing jet flows as in the current application. To achieve practical noise reduction, it is important to reduce the levels in the peak radiation sector. The changes in dBA due to the nozzle modifications, relative to the baseline, are presented now. Figure 15 shows such a plot for the air and water injections at MIL power and with $M_f = 0.233$: the air injection produces a ~0.6 dBA reduction at the lower angles and ~2 dBA reduction in the peak angles. The effect of the water injection is more pronounced on shock-associated noise, with a reduction of ~2.5 dBA at the lower polar angles. However, the noise benefit drops to ~1.3 dBA in the aft directions.

The effect of the freestream Mach number on the efficacy of the water injection and the corrugations is examined in Figs. 16 and 17, at $M_f = 0.16$ and 0.32, respectively. It appears that the benefit due to the water injection increases slightly in the forward quadrant and decreases slightly in the aft directions. Figure 18 shows the noise

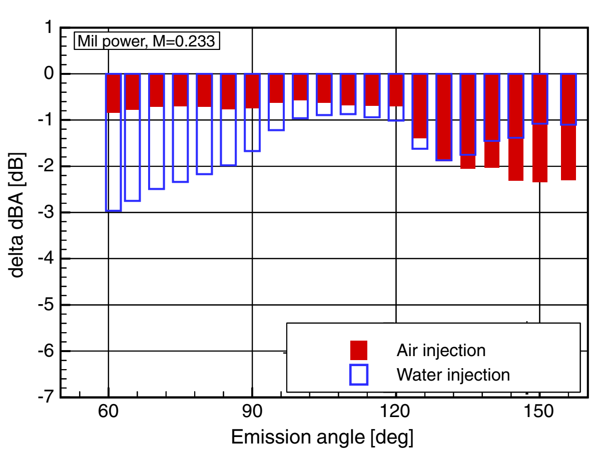


Fig. 15 Noise change relative to baseline at MIL power from nozzle system 1. $M_f = 0.233$.

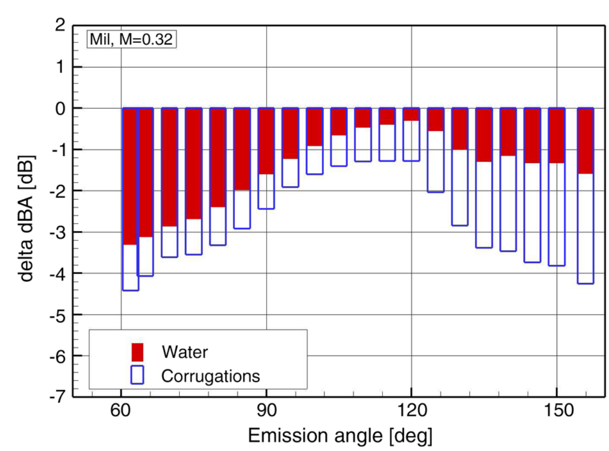


Fig. 17 Noise change relative to baseline at MIL power from nozzle system 1. $M_f = 0.32$.

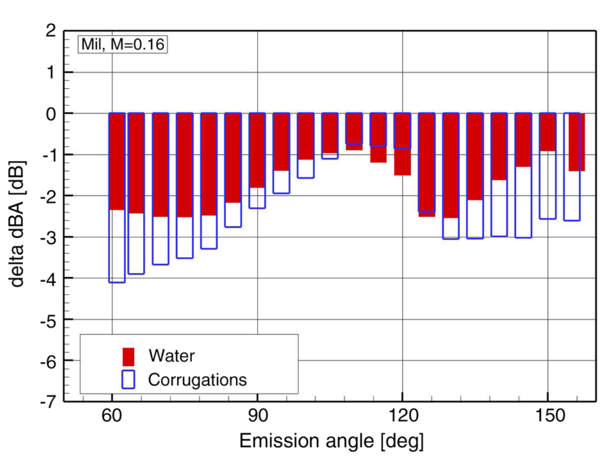


Fig. 16 Noise change relative to baseline at MIL power from nozzle system 1. $M_f = 0.16$.

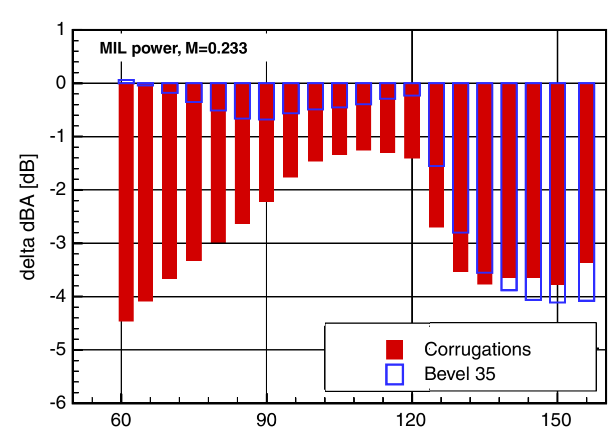


Fig. 18 Noise change relative to baseline at MIL power from nozzle system 1. $M_f = 0.233$.

benefit due to the corrugations and the bevel 35, again at MIL power and with $M_f = 0.233$. The corrugations produce large noise reductions due to the elimination of the shock-associated noise in the forward quadrant; the bevel 35 has only a small effect at these angles. In the peak radiation sector, the benefits are large: ~3.5 dBA for the corrugations and ~4 dBA for bevel 35. The effect of a lower freestream Mach number of 0.16, again at MIL power, for the corrugations and bevel 35 are examined in Fig. 19. The levels of noise benefit are comparable to those seen at $M_f = 0.233$ for both the corrugations and bevel 35, except for a slight erosion of ~0.5 dBA for the corrugations in the aft angles. An examination of Figs. 16–19 and other data (not included here) indicates that the noise reduction from the corrugations and bevel 35 is insensitive to the freestream Mach number at this power setting. It is important to keep in mind that the jet velocity at MIL power is ~2700 ft/s (825 m/s). The addition of a freestream with velocities of 180, 262, or 360 ft/s (at freestream Mach numbers of 0.16, 0.233 or 0.32) leads only to a slight reduction in shear between the jet and the ambient medium at rest. This is the reason for the observed insensitivity of the freestream Mach number on the effectiveness of the bevel and corrugations.

The effect of the addition of air and water injection to the corrugations, at MIL power and with $M_f = 0.233$, is shown in Fig. 20. The introduction of air has negligible effect, when we compare Figs. 18 and 20. An added benefit of ~1 dBA is realized in the forward quadrant, with a slight reduction of benefit in the peak sector for the addition of water injection. The effect of the addition of water is seen to be similar at a higher flight-stream Mach number of 0.32 in Fig. 21 (examine Figs. 17 and 21 together).

The performance of the combination of corrugations with bevel is investigated now. The optimum bevel angle that would produce the best noise benefit was not known before the test; several bevel angles were therefore considered. The design of the corrugations together with a beveled trailing edge presented several design and manufacturing challenges and necessitated the choice of a fixed bevel angle before any data were available. Based on past experience with the convergent beveled nozzles, and taking the effect of potential thrust loss due to beveling into consideration, the decision was made to proceed with a bevel angle of 24°. As it turned out, this was not the best choice. Figure 22 shows the relative performance of the bevel 24 and bevel 35 nozzles, at MIL power and with $M_f = 0.233$; the benefit of the bevel 24 is roughly half of what is seen with the bevel 35. The spectral variations due to the corrugations and the corrugations with bevel 24 are presented in Fig. 23. The most striking aspect is the reappearance of the shock-associated noise at a polar angle of 60°; this trend is seen at all the other lower polar angles as well (not shown). The spectral results are consistent with the degradation in the thrust performance of the combination, observed in Fig. 6 and discussed with the aid of the plot of the nozzle build in Fig. 7. A comparison of the change in dBA in Fig. 24 confirms the complete loss of the benefit for the shock-associated noise due to the corrugations alone, though there is a small augmentation of the benefit in the aft angles. The addition of water injection to the combination nozzle (Fig. 25) is seen to produce some benefit for shock-associated noise. However, the geometric features of the nozzle build (Fig. 7) have already vitiated the flow development and the hope of realizing the additive benefit of the combination of the corrugations with the bevel was not achieved.

A few sample results at cutback power with the nozzle system 2 are presented. The changes in dBA due to air and water injections are shown in Fig. 26; the flight Mach number is again 0.233. The effect of

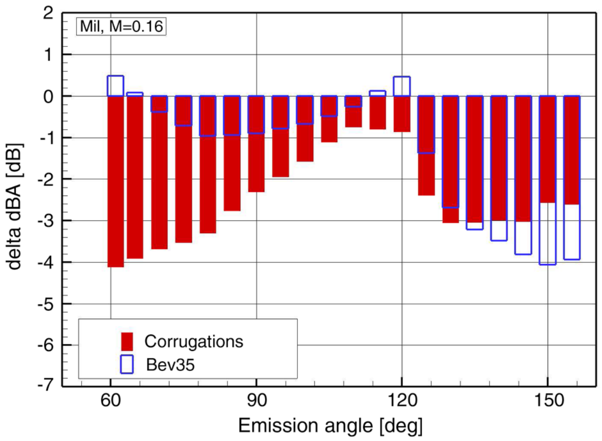


Fig. 19 Noise change relative to baseline at MIL power from nozzle system 1. $M_f = 0.16$.

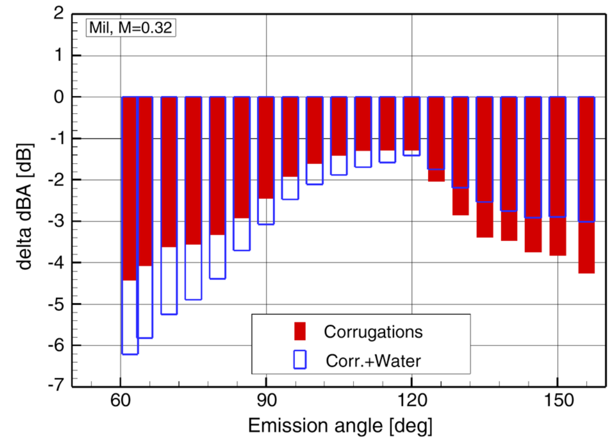


Fig. 21 Noise change relative to baseline at MIL power from nozzle system 1. $M_f = 0.32$.

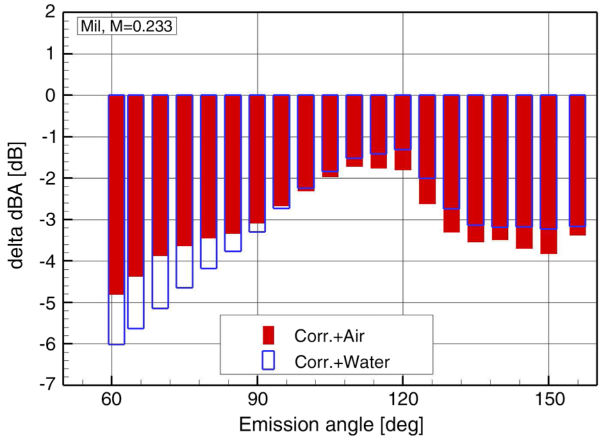


Fig. 20 Noise change relative to baseline at MIL power from nozzle system 1. $M_f = 0.233$.

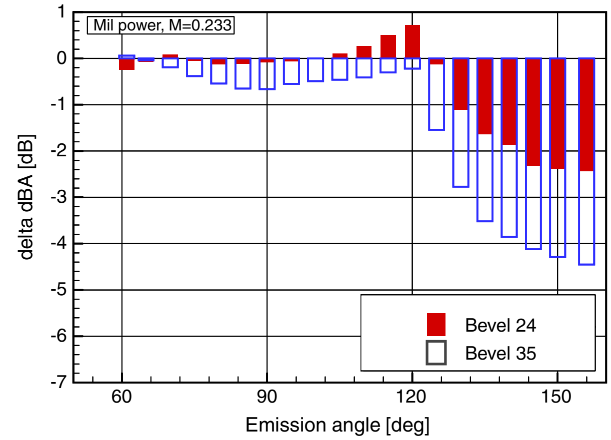


Fig. 22 Noise change relative to baseline at MIL power from nozzle system 1. $M_f = 0.233$.

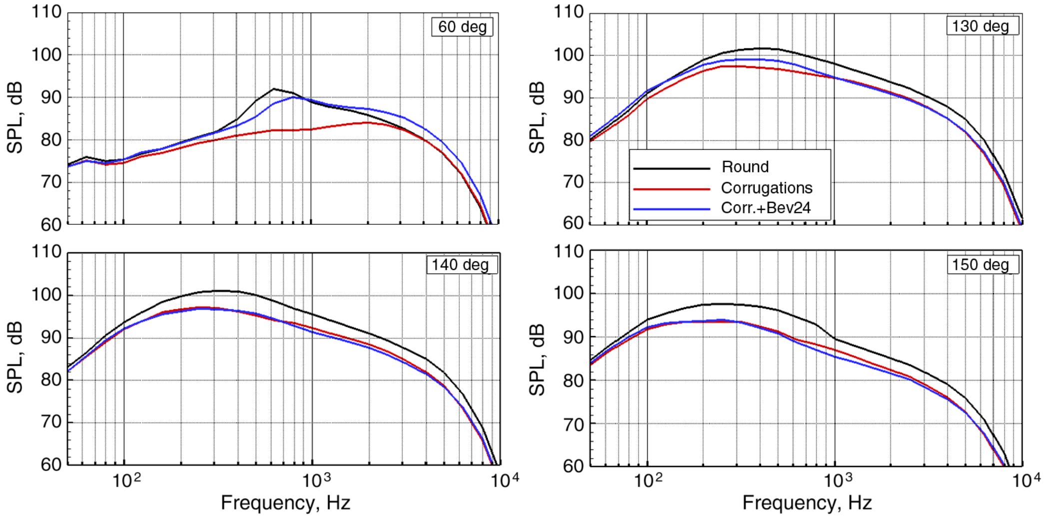


Fig. 23 Comparison of spectra at MIL power from nozzle system 1. $M_f = 0.233$.

the air injection at this lower power is similar to that seen at MIL power in Fig. 15. However, there is a dramatic increase in the benefit due to the water injection for the shock-associated noise in the forward quadrant, with negligible change in benefit at the aft angles (compare Fig. 26 with Fig. 15). A comparable plot for the performance of the corrugations and bevel 32 is shown in Fig. 27. Again, the benefit of the corrugations at the lower angles is greater than that seen at MIL power. The more surprising aspect is the large reduction due to bevel 32 in the forward angles. The reason for the observed trend is the following: when the nozzle trailing edge is beveled, there is a reduction in the effective flow area and it is lower than the geometric area (in the slanted plane that coincides with the beveled trailing edge). This effect was quantified for convergent beveled nozzles by Viswanathan [7,8] and examined in detail in [15]. The situation is somewhat different for the convergent–divergent beveled nozzles. At supercritical NPRs, the throat is choked and therefore the mass flow rates are not altered by the beveled trailing edge. This fact has been verified in Sec. III.A in [15]. The reduction in effective exit

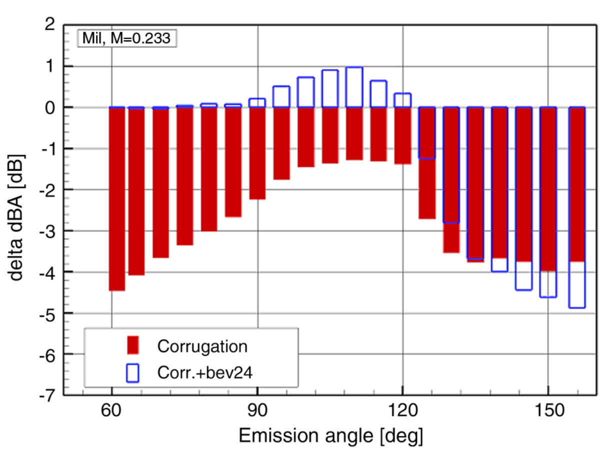


Fig. 24 Noise change relative to baseline at MIL power from nozzle system 1. $M_f = 0.233$.

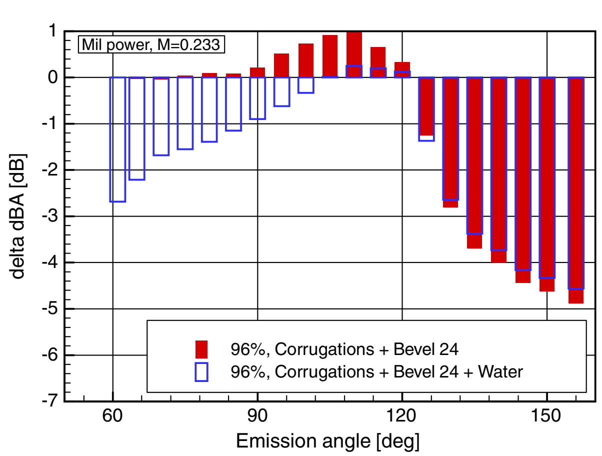


Fig. 25 Noise change relative to baseline at MIL power from nozzle system 1. $M_f = 0.233$.

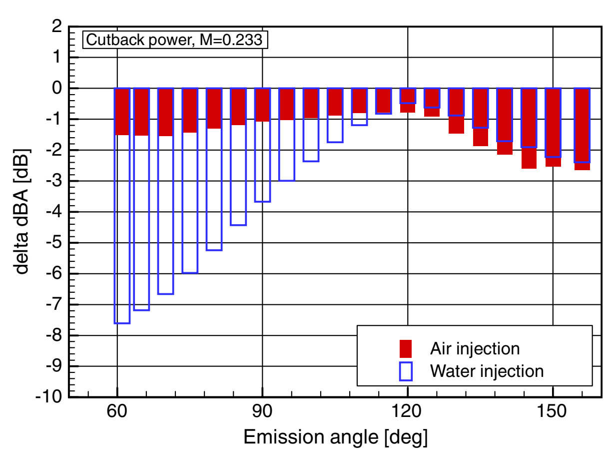


Fig. 26 Noise change relative to baseline at cutback power. Nozzle system 2, $M_f = 0.233$.

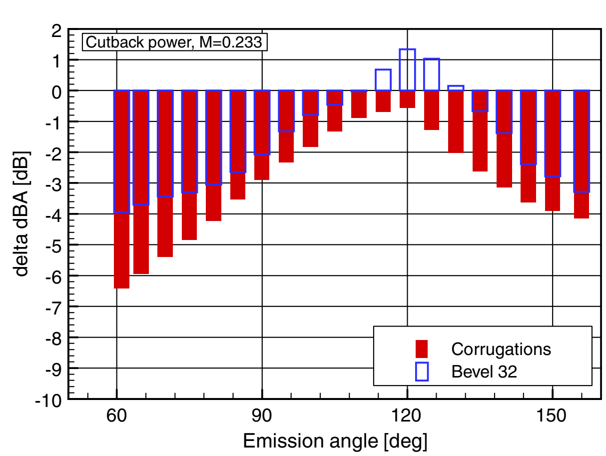


Fig. 27 Noise change relative to baseline at cutback power. Nozzle system 2, $M_f = 0.233$.

flow area, however, has two beneficial effects: 1) substantially improved thrust performance for severely overexpanded jets; and 2) better flow expansion with reduced shock strengths for overexpanded jets. Consequently, the component of shock-associated noise should have lower levels; this expectation is reflected in Fig. 27. The question that must be asked is the following: why is no benefit in shock noise seen with the bevel at MIL power, say in Fig. 22? The following argument is offered. The shock strength is usually characterized by the parameter $\sqrt{|M_j^2 - M_D^2|}$, raised to some exponent. The value of the exponent has been believed to be 4; recent measurements and analyses by Viswanathan et al. [18] indicated, however, that the exponent has a dependence on both the polar angle and the jet temperature ratio. Regardless, the value of the shock parameter is 0.69 at cutback power and 0.85 at MIL power. When we consider the facts that all the modified nozzles produce a larger benefit for the shock-associated noise at cutback power, we can infer that the beveled nozzles could be effective when the shock strength is not large.

The noise benefit of the water injection in conjunction with the corrugations is reported in Fig. 28; the flight-stream Mach number is 0.233. As seen at other conditions, there is an added benefit at the lower angles and a small erosion of benefit in the aft angles.

For the sake of completeness, the effect of the modified nozzles on the EPNL, effective perceived noise decibel (EPNdB) metric is shown in Fig. 29. Note that this metric is used for the certification of commercial aircraft, and as such, many researchers are familiar with this noise metric. The figure shows the benefit, relative to the baseline nozzle, for all the nozzles at MIL power. All the modified nozzles yield a benefit in the EPNL metric. The trends are consistent with the spectral variations. As expected, the corrugated nozzle provides the

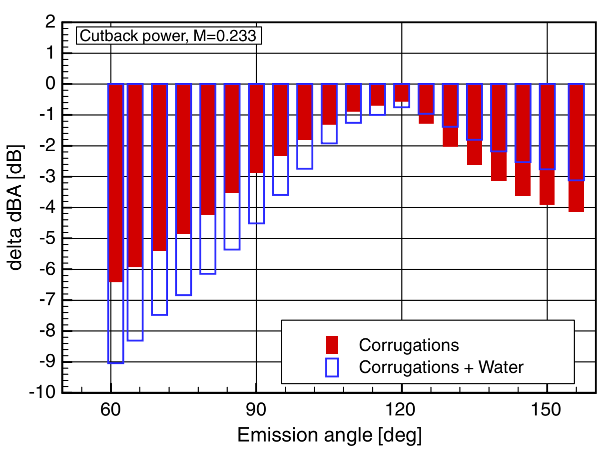


Fig. 28 Noise change relative to baseline at cutback power. Nozzle system 2, $M_f = 0.233$.

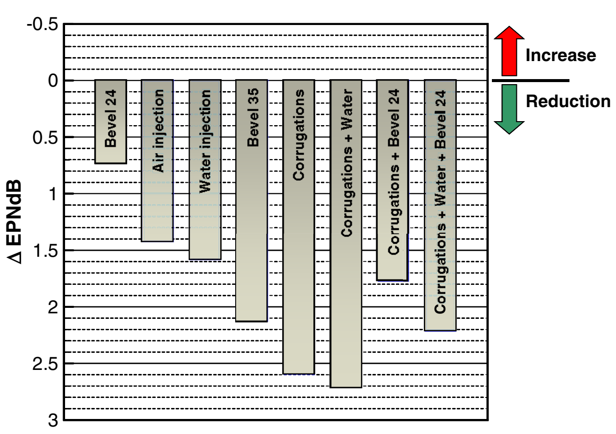


Fig. 29 Noise change relative to baseline at MIL power from nozzle system 1. $M_f = 0.233$.

largest benefit in stand-alone mode, ~2.6 EPNdB. The addition of water augments this benefit by 0.1 EPNdB. The bevel 35 yields a benefit of ~2.1 EPNdB; in rough terms, the benefit in shock noise reduction is worth ~0.5 EPNdB for the corrugations at MIL power.

The reasons for the noise reduction from the different nozzle modifications are now examined. The corrugations are specifically designed to produce optimally-expanded flow at MIL power; it should not be surprising then that the shock-associated noise is more or less eliminated at MIL power. However, the flow is incorrectly expanded at other NPRs and shocks are established once again, resulting in the generation and radiation of broadband shock-associated noise. Spectral reductions are observed at the aft angles for a wide range of NPR with the corrugations. The turbulent mixing noise is the dominant component in the peak radiation sector. The exit plane with the corrugations resembles a lobed mixer; such a nozzle design is known to reduce noise at the peak aft angles and has been investigated for more than four decades. Computed flowfields of the jet plume for the corrugated nozzle, as shown in Sec. IV.B in [2], indicate that the flow is highly nonuniform in the cross-sectional planes and is similar to that produced by the lobed mixer. The same mechanism for noise reduction presumably prevails for the corrugations as well.

Flowfield measurements using particle image velocimetry were carried out by Krothapalli et al. [5] for a normal jet and a jet with water injection. The water droplets in the plume modifies the turbulence structure significantly, resulting in reductions of 10 and 30%, respectively, in the root-mean-square turbulence velocity fluctuations in the axial and radial directions. In addition, an even larger reduction of 40% is observed for the turbulent shear stress relative to a normal jet. This reduction in turbulence levels is thought to provide the observed noise reduction. The injection of water interferes with the formation of shock cells and thereby reduces broadband shock-associated noise. As seen here in Figs. 17 and 26, this effect is more pronounced than the reduction in turbulent mixing noise in the peak angles. The minor spectral modifications due to air injection and a larger change due to water injection can be attributed to the large difference in the percentage of mass injection ratios, air vis-à-vis water.

The noise reduction mechanisms of convergent beveled nozzles have been examined in detail in Sec. IV.C of [6]. For round jets, the angular sector in which the noise generated by the large-scale turbulent structures/instability waves is dominant is confined to angles close to the jet axis. However, for a beveled nozzle, this component of noise is beamed to lower polar angles. Of greater significance is the fact that this noise is radiated towards the azimuthal direction with the shorter side of the beveled nozzle. Therefore, less acoustic energy is available for radiation to the aft directions and hence the observation of lower levels across the spectra for the beveled nozzle. This hypothesis was verified by Viswanathan [19] through the examination of far-field correlations for both round and beveled nozzles (see Sec. IV.B in [19] for complete details). Specifically, it was demonstrated in [19] that 1) high correlation levels are observed only at angles where the spectral shape has a sharp peak with rapid roll off away from the peak; 2) for round nozzles high correlation levels are observed only at large aft angles; and 3) for beveled nozzles in the azimuthal direction of the shorter lip, the angular sector in which highly correlated noise is observed is shifted to lower polar angles. Now, the jet velocities in the current test for fighter aircraft are much higher than those investigated in [6,19]. Consequently, the contribution of noise from the large-scale turbulent structures is more pronounced. As such, the preceding mechanism should yield a large noise benefit in the aft quadrant for the beveled nozzle. This expectation, before the test, has been validated by the test results. When combinations of these three ideas are evaluated, the different mechanisms play contributory roles in providing noise reduction.

Flow measurements for the nozzles tested in this program are not available. Computational simulations for individual concepts such as the bevel or the corrugations have been carried out. The flowfields offer some insight to the physics of the problem; detailed computational investigations are needed to glean further understanding. It is essential to carry out computational simulations of the corrugation/bevel concept so as to arrive at an optimum design, before another wind-tunnel test. The noise reduction observed in the peak radiation angles for a wide range of NPR with the bevel suggests that it might be possible to obtain larger noise reductions in combination with the corrugations. The reduction in the effective flow area for the bevel might be used to offset some of the issues associated with the corrugations at off-design conditions. A joint computational and experimental program that builds on the lessons learnt from the current test would be valuable. The noise of fighter aircraft continues to be a major problem for the United States Navy and low-impact nozzle designs are vital for noise mitigation.

IV. Conclusions

The aeroacoustic performance of three low-noise nozzle designs was evaluated experimentally, both statically and in the presence of forward flight, in the LSAF at The Boeing Company, with simultaneous measurement of thrust and noise. The main goals have been met, in the collaborative effort of the test program of 1) evaluating the noise reduction potential of various suppression concepts, individually and in combination thereof; and 2) creating a database that enhances our current understanding of high-speed jet noise. Two different physical models with appropriate area ratios to simulate the engine operating conditions at different power settings have been considered; these two correspond to 96% N1 (MIL power) and 91% N1 (cutback power). The different concepts considered are the following: microjet injection with air and water; corrugated nozzle inserts; and beveled nozzles with bevel angles of 20, 24, 28 and 35° at MIL power, and 24 and 32° at cutback power. Furthermore, the nozzles were operated over a wide range of NPRs and freestream Mach numbers in the range of 0.0 to 0.32, thereby generating a large database. Only a small portion of the results has been presented here.

The typical nozzles that power fighter aircraft are operated at overexpanded NPRs at MIL power and during low-altitude operations. Shocks are present, consequently generating shock-associated noise. However, the turbulent mixing noise which is dominant in the peak radiation sector is $\sim$10 dB higher than the noise radiated to lower polar angles where shock-associated noise is dominant. It has been established in [15] that the beveled nozzles produce at least the same absolute thrust as the baseline nozzle. The static thrust performance of all the modified nozzles is superior to that of the baseline nozzle in stand-alone mode. However, the performance of the combination of corrugations with bevel 24 produced degradation in thrust due to the final nozzle build, which was not as originally planned due to many constraints. The corrugations have been specifically tailored to eliminate/minimize shocks at a fixed power; the effect of beveling the nozzle trailing edge has the same salutary effect due to the reduction in the effective exit flow area, thereby leading to better flow expansion. The deflection of the plume due to the beveling is within $\pm 1.5°$, with a resultant minor loss in axial thrust. However, the beneficial effect of better flow expansion more than compensates for this small deflection.

The reasons for the noise reductions for the different concepts have been examined and discussed. Water injection reduces the turbulence fluctuation levels in the axial, radial and shear stress components, possibly providing noise reduction. The corrugated nozzle more or less eliminates shock at a particular design NPR, thereby minimizing broadband shock-associated noise at the lower polar angles. In addition, the corrugations produce a jet plume with a convoluted cross-sectional profile similar to that produced by a lobed mixer; this desirable flow feature leads to reduction in noise in the peak aft angles. For the beveled nozzle, the noise radiated to the peak aft angles by the large-scale turbulence structures is beamed to lower polar angles relative to the peak angle for the baseline nozzle. Of greater significance is the fact that this noise is radiated towards the azimuthal direction with the shorter side of the beveled nozzle. Therefore, less acoustic energy is available for radiation to the aft directions and hence the observation of lower levels across the spectra for the beveled nozzle. The salient results on the acoustic performance of the various concepts are enumerated next:

1) The air injection has only a minor effect on the spectra at various freestream Mach numbers. This observation is consistent with past measurements under static conditions.

2) At MIL power, the water injection produces a more pronounced benefit at the lower angles where the shock component is dominant; the magnitude of the benefit in the dBA metric varies from $\sim$2 to $\sim$3 dBA at a polar angle of 60° and drops to $\sim$1 dBA at 90°. The benefit at large aft angles is $\sim$1 dBA. These levels of benefit more or less hold for a range of freestream Mach numbers from 0.16 to 0.32.

3) At MIL power, the corrugations provide the largest benefit at the lower polar angles. The dBA benefit is $\sim$4 dBA for a range of freestream Mach numbers from 0.16 to 0.32. As for the water injection, the benefit drops to $\sim$1 dBA at 90°. At the aft angles, there is a benefit of $\sim$3 to $\sim$3.5 dBA, which again varies only slightly with freestream Mach number, at MIL power.

4) At MIL power, the beveled nozzles provide little modifications to the spectra at the lower polar angles. All of them provide a benefit in the dBA metric in the peak radiation sector: the magnitude of the benefit increases with the bevel angle and reaches a value of $\sim$4 dBA for bevel 35. The effect of freestream Mach number is again limited.

5) At MIL power, the addition of water in conjunction with the corrugations and the bevels (not shown) augments the noise benefit $\sim$1 dBA at the lower angles and reduces the benefit in the aft angles.

6) The combination of the corrugations with the bevel 24 did not produce the hoped-for benefit at MIL power. Because of the geometry of the final nozzle build, in which the corrugations did not extend to the beveled trailing edge but terminated inside the nozzle instead, shocks were established in the plume and there was no reduction to the shock component. The combination did produce the largest benefit in the aft radiation sector. Further investigation of this combination, with the proper geometry, is desirable.

7) The addition of water at MIL power to the combination of corrugations and bevel 24 did provide a benefit at the lower polar angles. However, the magnitude of the reduction was lower than that seen for the corrugations alone.

8) At MIL power, all the nozzles tested provide a benefit in the EPNL metric.

9) At cutback power, greater reductions in the dBA metric at the lower angles are seen for both the water injection and the corrugations.

10) The trends seen for the addition of water at cutback power in conjunction with the corrugations are the same as at MIL power: enhanced benefit at lower angles and slightly reduced benefit at aft angles.

11) At cutback power, the bevel 32 also provides a benefit at the lower polar angles. This benefit is thought to be due to the reduced shock strength.

The results presented here are promising. Further investigations are necessary to optimize the noise reduction potential, especially in the twin-podded mode prevalent in the engine installations of fighter aircraft.

Acknowledgments

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