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Effects of Nozzle Trailing Edges on Acoustic Field of Supersonic Rectangular Jet

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Acoustic measurements of a Mach 2, rectangular nozzle with modified trailing edges were carried out using three microphones, placed 90 deg apart azimuthally in a plane normal to the jet axis. The measurements were obtained at three streamwise locations, with microphone angles of 90, 60, and 30 deg with respect to the jet centerline. The trailing-edge modified nozzles substantially reduced the turbulent mixing and broadband shock associated noise radiation by up to 12 dB for the underexpanded flow regime and up to 7 dB for the overexpanded condition. However, in some symmetric modifications, the very-high-frequency noise was increased for the overexpanded condition. Screech tones in the overexpanded flow condition were either reduced or eliminated for asymmetric modifications, but amplified for symmetric modifications. The trailing-edge modifications were found to not significantly alter the noise field for the ideally expanded flow condition.

Nomenclature

D_{eq}	=	equivalent diameter, $(4h \times w/\pi)^{1/2}$
f_{actual}	=	frequency of the scaled nozzle
$f_{experimetnal}$	=	frequency of the test nozzle
f_f	=	primary screech tone frequency
h	=	nozzle exit height
L_{SS}	=	shock cell spacing
M_j	=	Mach number if the jet was isentropically expanded to the ambient pressure
N	=	total perceived noise
n	=	perceived noise
n_{max}	=	maximum perceived noise
W	=	nozzle exit width

Introduction

THE jet noise of aircraft has detrimental effects on the environment, causing economic hardships to those living in and around airports, and, in the case of nonideally expanded screeching jets, damage to the structure of the aircraft.[1] Proven methods for reducing jet noise do exist, but at great expense to the aircraft's overall performance, increasing the weight and drag of the vehicle. Researchers have been developing various noise-reduction techniques, which work on the premise that by increasing the mixing of the jet flow with a bypass flow, and thereby reducing the velocity, noise will be reduced.[2,3] Other methods for increasing the mixing of jet flows with the ambient air, which have demonstrated the ability to decrease the overall radiated noise in both subsonic and supersonic jet flows, include tabs or vortex generators,[4–14] nonaxially symmetric nozzles,[15–20] and simple shaping of the nozzle trailing edge.[18,20–26]

The main effect of a tab, which is similar in both subsonic and supersonic flows, is to generate a pair of strong streamwise vortices. These vortices entrain ambient air into the jet and substantially enhance gross mixing of the jet with the ambient fluid. The tabs have been shown to eliminate or reduce screech noise, to reduce substantially mixing and shock-associated noise in lower frequencies, but to increase it in higher frequencies.[4,5,8] Thrust penalties have been demonstrated for the tabbed nozzles, due to the partial blocking of the nozzle exit area.[8,12,13]

Trailing-edge modified nozzles have recently been examined for their ability to increase mixing and to decrease the far-field noise.[23,24,26] In underexpanded supersonic jet flows, streamwise vortices, generated by a spanwise pressure gradient over the modified trailing edges, caused a substantial increase in the mixing and a decrease in noise. An adverse pressure gradient within the nozzle for the overexpanded flow regime caused flow separation within the nozzle with minimal mixing enhancements and did not affect the mixing noise; however, the screech tones were substantially reduced. The ideally expanded flow regime exhibited no mixing increases or altered noise fields when the modifications to the trailing edges were either on the splitter plate in half nozzles or on the extension plates of a full nozzle.[23,24] Trailing-edge modifications have also been shown to not affect the thrust because they do not block the nozzle exit area.[24] The recent work on the noise field of supersonic rectangular jets with modified trailing edges was preliminary and qualitative because the facility was not anechoic.[23] The objective of the current study was twofold: first, to design and build a modular anechoic chamber that could be used for simultaneous flow and acoustic measurements and second, to use it to examine the far-field noise effects of nozzle trailing-edge modifications on an aspect ratio 3, Mach 2 nozzle in various flow regimes.

Anechoic Chamber and Jet Flow Facility

To test quantitatively the trailing-edge modified nozzles for their acoustic qualities, an anechoic test facility[27,28] was designed and employed. It is located at the Gas Dynamics and Turbulence Laboratory of The Ohio State University. A unique ability of this chamber is a result of its modular design, where, with very little modification to the structure itself, that is, removing a block of wedges for camera access, simultaneous flow and acoustic measurements can be taken without sacrificing the acoustic qualities.[29,30] The floor is removable for simplified camera setup inside the chamber and also for extending its capabilities to allow hemi-anechoic acoustic testing conditions. The chamber has a cutoff frequency of 250 Hz, provided by the acoustic wedges from Eckel Industries, and was tested for compliance to the American National Standards Institute (ANSI) Standard S12.35 for the decay of sound pressure levels in an anechoic room. Eight microphone paths, extending radially from a sound source in the center of the room to various corners and walls of the chamber, were employed to evaluate the attenuation capabilities of the anechoic wedges. Figure 1 displays the comparison of the measured sound pressure level (SPL) at increasing distances from the white noise source to that of the inverse radius squared law[31] for a path perpendicular to one of the chamber walls. Notice in Fig. 1 that there was excellent comparison, within 1.0–1.5 dB, of the theoretical curve as required by the ANSI standard. This result is similar to

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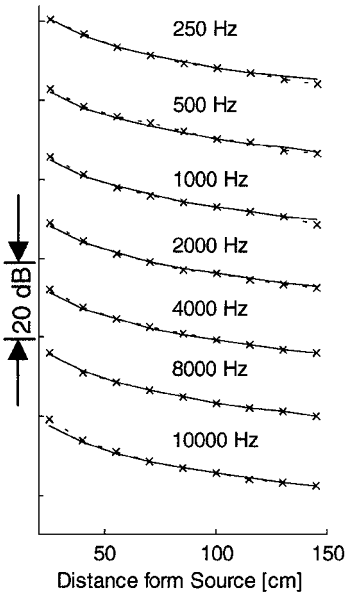
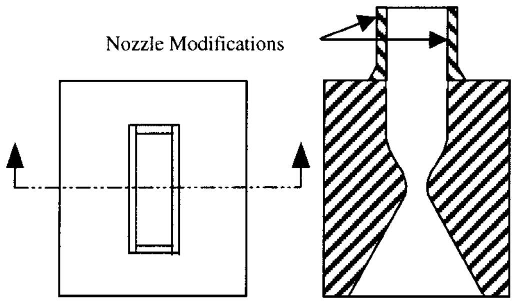
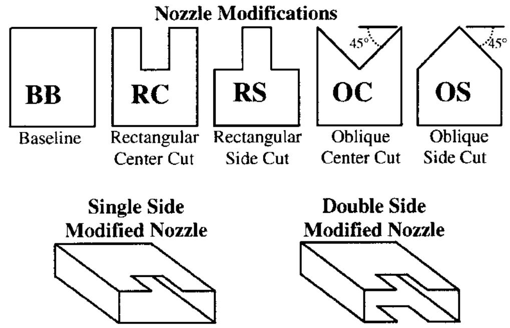


Fig. 1 One of the eight microphone paths in the chamber showing the decay of SPL measured (×) compared to that of theoretical curve (-) at various frequencies.



a) Nozzle block; notice location of nozzle modifications (not to scale)



b) Nozzle modifications; notice abbreviations in each diagram and single-side (asymmetric) and double-side modified (symmetric) cases (not to scale)

Fig. 2 Nozzle modifications used in the study.

those in the other seven paths.[28] Two four-stage compressors supply the air for the jet facility. The air is filtered, dried, and stored in two cylindrical tanks with a total capacity of 42.5 m^3 at 16.5 MPa. The air is delivered to the laboratory through a 10.2-cm- (4-in.-) diam main line, with a 5.1-cm- (2-in.-) diam line providing air to the jet. This line passes through a pressure regulator, which is controlled by the user, who sets a specified pressure in the stagnation chamber. The air is expanded through a transition cone from the supply line to a 24.1-cm-diam pipe that is 91.4 cm long for flow conditioning. The air passes through a perforated plate (37% porosity), two mesh screens, and finally converges through a transition cone to a 6.0-cm pipe that is 40.6 cm long. After passing through this pipe, it enters an aspect ratio 3 rectangular nozzle, which is positioned so that the major axis is vertical. The nozzle is attached to the pipe by an adapter, which takes the circular pipe cross section smoothly down to the nozzle shape.

Nozzle and Modifications

The aspect ratio 3, Mach 2 rectangular nozzle used in the present experiments was the same nozzle used in the previous studies,[24,26] having a Reynolds number on the order of 1.3×10^6. The nozzle dimensions are 0.95 cm high and 2.86 cm wide ($\frac{3}{8}$ by $1\frac{1}{8}$ in.). The equivalent diameter, the exit diameter of a circular nozzle with the same exit area D_{eq} for the nozzle was 18.6 mm (0.733 in.). The nozzle was designed for a nominal Mach number of 2.0, but the measured Mach number was 1.93. The modifications are made on the trailing-edge extensions, to allow the flow to reach full expansion before approaching the cutouts (Fig. 2a). In earlier results based on flow visualization and mixing and preliminary acoustic measurements,[23,24] four cutouts shown in Fig. 2b showed superior mixing and acoustic performance in comparison with other types of cutouts. In the current experiments, these four cutouts (total of eight modified nozzles) were tested against a baseline case at three flow conditions of ideally expanded ($M_j = 2.0$), overexpanded ($M_j = 1.75$), and underexpanded ($M_j = 2.5$). The nozzle-naming scheme will use the abbreviations introduced in Fig. 2. They include baseline nozzle (BB) and the modifications as rectangular center (RC) cutout, rectangular side (RS) cutout, oblique center (OC) cutout and oblique side (OS) cutout.

Acoustic Measurements

Microphone Placement

Far-field acoustic measurements were carried out, using three $\frac{1}{4}$-in. condenser microphones, B & K Type 4135, with a Type 2670 preamplifier, and two Type 5935 dual-microphone amplifying power sources. Two of the three microphones were positioned along the minor axis, with one located on the major axis of the nozzle, in a plane normal to the jet at downstream angles of 90, 60, and 30 deg, measured from the jet axis. The microphones were mounted from the wedges on the walls and floor of the chamber. Figure 3 displays the microphone setup and nozzle orientation. The microphones were placed in the far field, 40 equivalent jet diameters (74.5 cm) from the nozzle axis.

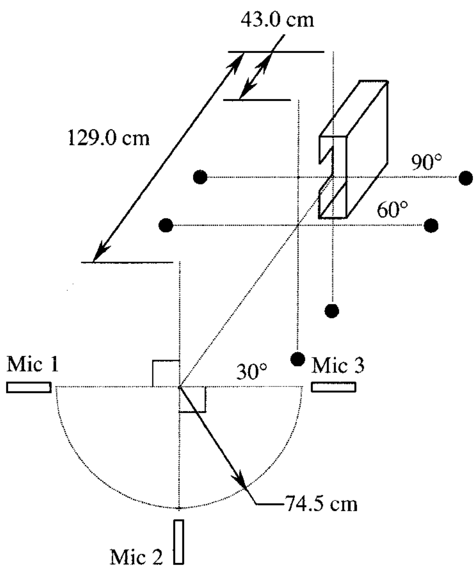


Fig. 3 Positions of microphones.

Data Acquisition

Acoustic data for the three microphones, at the three measurement angles, for the nine nozzles running at the three flow conditions, for a total of 81 data sets, were gathered using a National Instruments PC-416 A/D board, with a sampling rate of 190 kHz. The Labview data acquisition program sampled 100 blocks of 8192 points for each microphone, with a total sampling time of 4.31 s, and saved the data to the hard disk of a Pentium III personal computer. The frequency resolution or bandwidth is 23.2 Hz. The signals from the microphones were passed through a low-pass frequency filter, DL Instruments Model 4302, set to a cutoff frequency of 125 kHz. This was done to remove any high-frequency anomalies from the microphones and to eliminate any potential aliasing. Calibration of the equipment was completed using a B & K Type 4231 acoustical calibrator before each set of measurements, ensuring that the data being gathered were consistent with changes in temperature and humidity. During testing, a high-frequency (>50 kHz) anomalous signal was noticed. To remedy this, the protective microphone screens were removed.

Data Reduction

The acoustic data were averaged using an in-house fast Fourier transform program, based on the signal processing toolbox of MATLAB®, to obtain an averaged spectrum for each data set. The overall sound pressure level (OASPL) was then calculated by logarithmically adding the SPL for each frequency.

The frequency data were also scaled to an actual-sized nozzle having an operating temperature of 800 K and a nozzle exit diameter of 0.3 m. This was accomplished by using the Strouhal number similarity, which shows that the ratio of the actual and experimental frequencies depend on the operating temperature of the jets and equivalent diameters of the nozzles.[28] The scaling factor was found as

$$f_{\text{actual}} = (0.1033) f_{\text{experimental}} \tag{1}$$

The operating temperature of the jet was taken to be 288 K. The scaled data were then converted to the third octave band, between the center frequencies of 50 and 8000 Hz, and the perceived noise level (PNL) was calculated.[1] The first step was to convert all decibel levels at every frequency to a noys decibel value, which corresponds to the annoyance weightings applied to certain decibel amplitudes at specific frequencies. Then, using[1]

$$N = 0.85 n_{\max} + 0.15 \sum_{i=1}^{23} n \tag{2}$$

$$\text{PNLdB} = 40 + \frac{10}{\log_{10} 2} \log_{10} N \tag{3}$$

where N is the total perceived noise, n is the perceived noise, and $n_{\max}$ is the maximum value of n, the PNL was in terms of PNLdB, or noys. The noys were then logarithmically added to obtain an overall value, much like the OASPL.

Experimental Results

The experimental results presented here are only a small fraction of the data detailed in Ref. 28. To understand the effects of the trailing edges on the noise, the effects of the modifications on the flowfield must first be examined. The mixing region of the jet at a cross section 1 equivalent jet diameter downstream of the nozzle exit is shown in Fig. 4 using condensed water particles, generated during the mixing process of the entrained moist and warmer ambient air with the cold and dry jet air.[24] These images illustrate the overall effects of the various trailing edges on the jet in different flow regimes. In the $M_j = 2.5$ case, the addition of the modifications to the nozzle generates a spanwise pressure gradient on the cutouts that induces streamwise vortices. The side cutout nozzles, OS and RS, induce kidney-type vortices that entrain ambient air into the jet as indicated by the arrows, and the center cutout nozzles, OC and RC, induce mushroom-type vortices that eject the jet fluid into the ambient. These vortices substantially increase the mixing in the shear layer.[24] For the overexpanded flow regime, $M_j = 1.75$, a slight mixing increase was noticed, but the formation of an adverse pressure gradient within the nozzle caused flow separation and prevented the formation of streamwise vortices. The ideally expanded case, $M_j = 2.0$, saw no induced vortices and, thus, no mixing increase. Details of the flowfield results and discussion can be found in Refs. 24 and 26.

Underexpanded Spectra

Figure 5 displays the spectra for the four modifications as compared to the BB case, showing that the far-field acoustic radiation was greatly reduced at 30 deg, over most of the spectrum, up to 12 dB. In Fig. 5, for ease of comparison, each spectrum is upshifted by 20 dB, the first with respect to the BB, and a smoothed (Butterworth filtered) BB spectrum is overlaid on each shifted modification spectrum. Notice that the nozzle modifications, OC, OS, and RC, have the greatest decrease in the noise over the entire range from 1.5 to 80 kHz, as does the RS nozzle modification, but with less of a drop in amplitude for the higher frequencies. Because the turbulent mixing noise due to large-scale structures is dominant at 30 deg (Refs. 32 and 33), the drop in noise could possibly be due the enhanced mixing from the streamwise vorticity and, thus, a reduction in the overall jet velocity.

Further investigation into the mixing processes of the nozzles could explain the behavior of RS in high-frequency range in

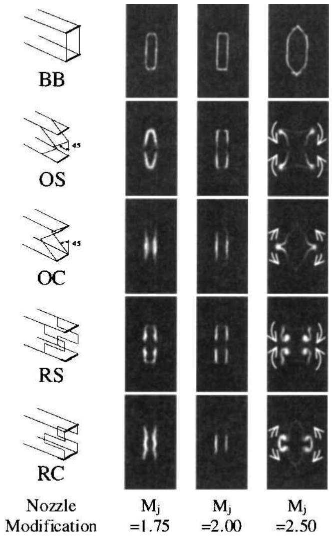


Fig. 4 Visualization of jet cross section at one equivalent jet diameter downstream of nozzle exit for over-, ideally, and underexpanded flow regimes with various nozzles.[24]

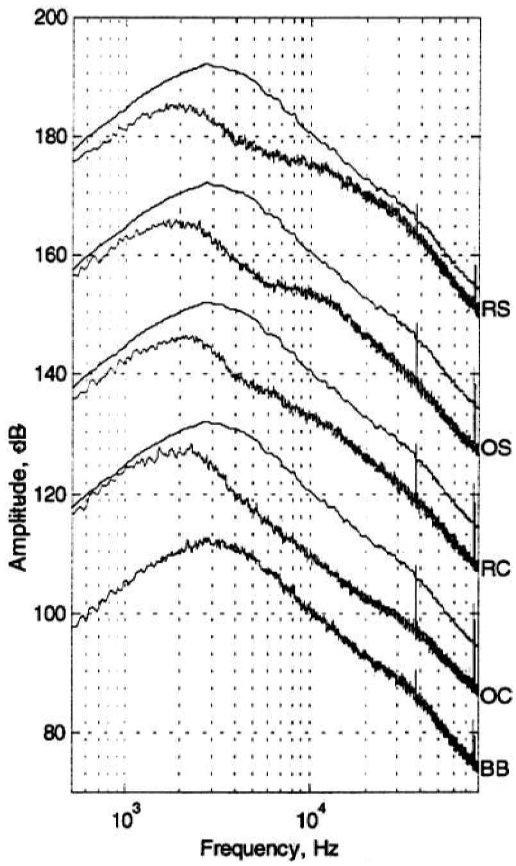


Fig. 5 Spectra from microphone 1 for double-side nozzle modifications as compared to baseline case for underexpanded flow condition measured at 30 deg; each spectrum has been upshifted by 20 dB.

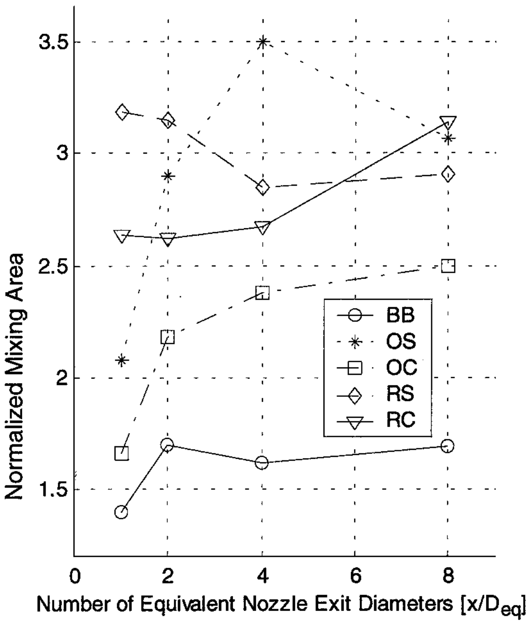


Fig. 6 Normalized-mixing area results for underexpanded flow of double-side modified nozzle configurations.[24]

comparison with other nozzles. Figure 6 displays the normalized mixing area, calculated from the flow visualization results, for four different downstream locations, x/D_{eq}, where D_{eq} is the equivalent nozzle diameter and x is the distance downstream from the nozzle exit.[24] Looking at Fig. 6, the RS nozzle modification, which entrains ambient air into the jet, is seen to have a strong early mixing, but to loose its strength farther downstream due to the destructive interactions that are taking place between the growing kidney-type vortices. OC, OS, and RC nozzle modifications are seen to have a low-to-mid early mixing area, which is gradually growing in the downstream direction. When Figs. 5 and 6 are compared, the interaction of the large-scale streamwise vortices in the RS case produces large-scale structures cascading to smaller-scale structures, much farther upstream, in comparison to the other cases. This produces high-frequency noise, which could cause the increase in the amplitude of the RS spectrum in Fig. 5 above 10 kHz.

For the 60-deg location, there was substantial noise reduction in frequencies above 10 kHz, for all cases except RS, and a slight increase in lower frequencies.[27,28] For the 90-deg location, there were some changes between 4 and 10 kHz, a slight decrease in amplitude and shift in frequency.[27,28]

Ideally Expanded and Overexpanded Spectra

Because of the lack of any measurable changes in the mixing for various nozzles in comparison with the BB nozzle in the ideally expanded flow regime (Fig. 4), there was also a lack of any change in the far-field radiated noise in any of the three angles investigated. Figure 7 displays a sample data set for the 30-deg location. The overexpanded case had a slight increase of mixing from the BB nozzle, as shown in Fig. 4, which accounts for some reduction in the low-frequency turbulent mixing noise for the 30-deg location, especially for OC and RC nozzles.[27,28] The screech tones were greatly affected by the nozzle modifications for the 90-deg location.

For the overexpanded flow condition, asymmetrically modified nozzles (Fig. 8), the screech is reduced in the RS case and practically eliminated in the OS, RC, and OC cases. This was caused by the breakup of the symmetry of the shock cells about the major axis of the nozzle, thus causing a diminished shock strength and acoustic feedback. The broadband shock-associated noise is also reduced for the RC and OC nozzle modifications, with only slight reductions for the other two cases. The mixing noise was also reduced up to 7 dB for all modifications in the 2–10-kHz range.

The symmetrically modified (double-side) nozzles for the overexpanded flow regime (Fig. 9) can be seen to have increased screech noise over the BB nozzle for the RS, RC, and OC cases, with still

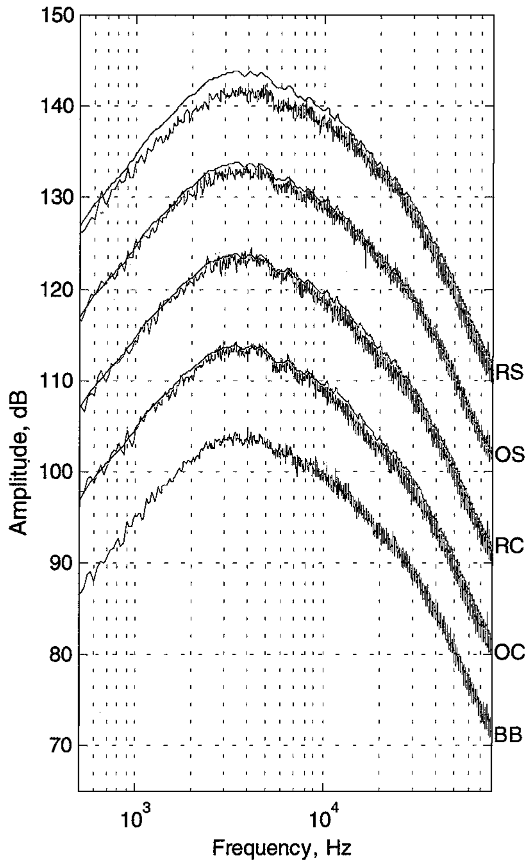


Fig. 7 Spectra from microphone 1 for single-side nozzle modifications as compared to baseline case for ideally expanded flow condition measured at 30 deg; each spectrum has been upshifted by 10 dB.

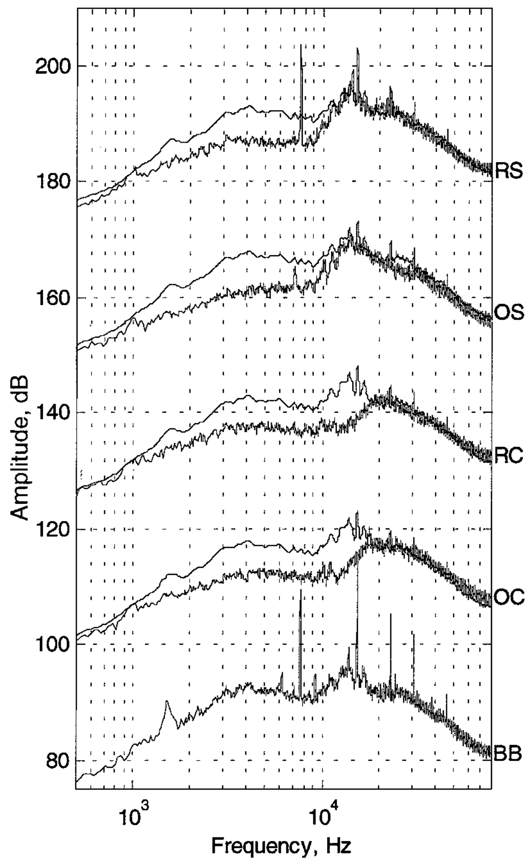


Fig. 8 Spectra from microphone 1 for single-side nozzle modifications as compared to baseline case for overexpanded flow condition measured at 90 deg; each spectrum has been upshifted by 25 dB.

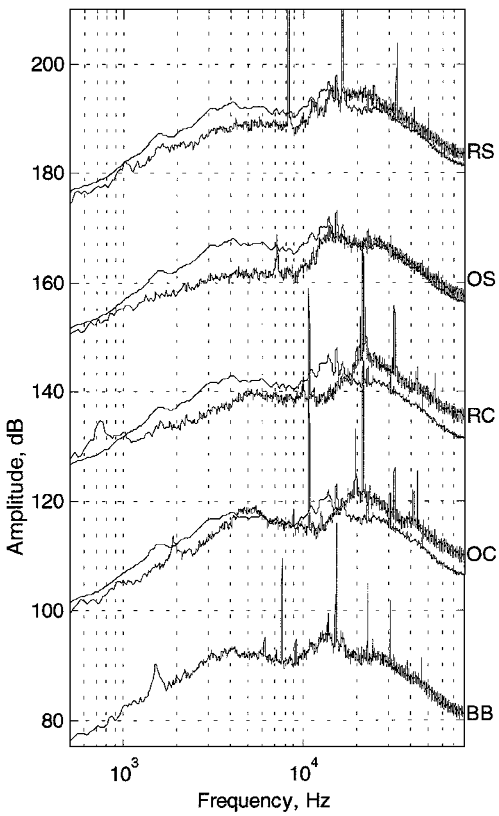


Fig. 9 Spectra from microphone 1 for double-side nozzle modifications as compared to baseline case for overexpanded flow condition measured at 90 deg; each spectrum has been upshifted by 25 dB.

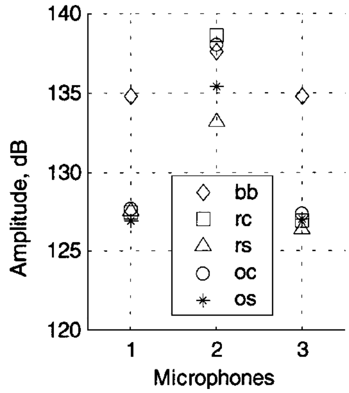


Fig. 10 OASPL as calculated for three microphones in underexpanded flow regime, double-side modified nozzle at 30 deg.

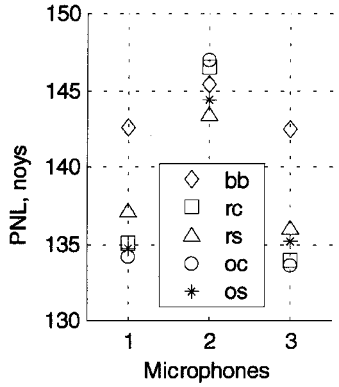


Fig. 11 PNL as calculated for three microphones in underexpanded flow regime, double-side modified nozzle at 30 deg.

diminished screech noise occurring in the OS nozzle. The return of the screech noise can be attributed to the symmetry of the nozzle. All of the nozzles except for OS exhibit an upshifted screech frequency. The broadband shock-associated noise, which saw a decrease for the RC and OC nozzle in Fig. 8, increased in Fig. 9 to over that of the BB nozzle, causing increased high-frequency noise, much like that seen in the tabbed nozzle cases. In this instance, the increase in the high-frequency noise appears to be caused by the increased screech noise in the nozzle. For the RS and OS modifications, there was negligible change in the broadband shock-associated noise.

The primary screech harmonic for the BB nozzle is 7600 Hz, with RS upshifting its primary harmonic to 8100 Hz, RC and OC upshifting to 11 kHz, and OS downshifting to 7100 Hz. The screech tone radiation frequency has been shown to depend on the spacing of the shock cells.[34] When the following equation[35] is applied:

$$L_{SS} = \frac{cM_c}{f_f(1 + M_c)} \tag{4}$$

where L_{SS} is the shock cell spacing, c is the speed of sound in the ambient, M_c is the convective Mach number, and f_f is the frequency of the primary screech harmonic, the effects of the modifications on the flow become clearer. For the BB nozzle, $L_{SS\,\text{at}\,7600} = 20.3$ mm; for RS, $L_{SS\,\text{at}\,8100} = 19.0$ mm; for RC and OC, $L_{SS\,\text{at}\,11000} = 14.0$; and for OS, $L_{SS\,\text{at}\,7100} = 21.7$ mm. The double-side modifications RS, RC, and OC cause the shock cells spacing to become reduced in size, creating a higher frequency of radiation than the BB nozzle and possibly creating a stronger shock cell structure. The OS modification for both single- and double-sided nozzles has an elongated shock cell structure, thus a lower frequency of radiation and possibly a weakened shock cell structure.

OASPL

The overall sound pressure level (OASPL) displays the changes in the overall radiated noise due to the modifications. For the underexpanded flow regime, Fig. 10 displays the results for the OASPL calculated at the three microphone locations for spectra presented in Fig. 5. Notice that the noise has been greatly reduced for both sides of the nozzle and for all modifications. In the sideline microphone location (microphone 2) only the nozzles that entrain ambient air into the jet (RS and OS) and thus flatten the mixing layer on the sideline, as in Fig. 4, tend to decrease noise up to 5 dB. The OASPL changes at 60 and 90 deg were relatively small.[27,28]

The overexpanded OASPL results for the 90-deg microphone location are similar to the spectra, where the noise is being slightly reduced and increased in the asymmetrically and symmetrically modified nozzles, respectively. For the 30-deg microphone location, both types of nozzles showed reduction in the OASPL. The ideally expanded OASPL plots also have the same characteristics as the spectra, whereas there is no change from the BB nozzle.[28]

PNL

The perceived noise level (PNL) amplitude levels for the scaled nozzle were greater than that of the OASPL amplitude values, most likely due to the heavy weighting of the higher frequencies. Figure 11 displays the underexpanded case examined in this paper. Notice that the reductions seen from the creation of the streamwise vortices are still present and are of the same magnitude as the OASPL values. For the overexpanded cases, the PNL had smaller deviations from the BB nozzle than they did in the OASPL cases.[28] The ideally expanded case did not have any deviation, as would be expected.[28] Conclusions that could be drawn from the PNL are that the actual-sized nozzle could radiate at a higher decibel level than that of the test nozzle, with less reductions in the screech noise, but still major reductions in the downstream turbulent mixing noise.

Summary

The acoustic experiments for a Mach 2 rectangular jet with trailing-edge modifications have been carried out in the newly designed anechoic chamber to investigate the effects of modifications on the acoustic far field. Measurements were conducted in the 90-, 60-, and 30-deg directions from the jet axis to capture the effects on the screech and broadband shock-associated noise in their dominant radiation direction (upstream) and to measure the effects on the turbulent mixing noise and possible Mach wave radiation in their dominantly downstream radiation direction. Three microphones on a plane normal to the jet axis, two placed on the minor axis and one on the major axis of the nozzle, were used to measure the effects that the single- (asymmetric) and double-side (symmetric) trailing-edge modifications had on the far-field noise.

In the underexpanded flow regime, the greatest effects of the modifications are in creation of the streamwise vortices, which reduce the acoustic far-field radiation by up to 12 dB for both the single- and double-side modified nozzles. In the overexpanded flow regime, the screech tones were reduced or eliminated for the single-side modified nozzles. The cause was a disruption in the symmetry of the nozzle about the major axis and a weakened feedback loop. The OS modification also caused an elongation of the shock cell structure, dropping the screech frequency by 500 Hz. The double-side modified nozzle in the overexpanded flow regime had an increase in screech noise over the BB for all nozzles except the OS case. This was caused by the symmetry in the nozzle about the major axis and a strengthening of the shock structure by a compression of the cells, demonstrated by looking at the upshift in the screech frequency. OS still exhibited reduced screech noise and an elongation of the cell structure. The perfectly expanded case was not affected by the modifications.

The OASPL and the PNL were calculated for a test nozzle and a scaled nozzle, respectively. Both had similar reductions in the turbulent mixing noise for the 30-deg measurement location in comparison with the BB case. The ideally expanded case was also similar because there were no deviations from the BB. For the overexpanded flow regime, the OASPL had reduced screech noise evident in the single-side modified nozzle, with increased screech noise in the double-sided modified nozzle. The PNL results still exhibited these decreases, but in a reduced amount. There was also a 10-dB difference between the OASPL and the PNL results, possibly signifying that the overall noise for the larger nozzle would be greater; however, the reductions in the overall mixing noise would still be present in the underexpanded operating conditions

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