JOURNAL OF PROPULSION AND POWER
Vol. 20, No. 3, May–June 2004

Acoustic Characteristics of Supersonic Jets from Grooved Nozzles

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The effect of internal grooves cut along the inner surface of the diverging portion of a Mach 1.8 converging-diverging nozzle on the characteristics of an axisymmetric jet was investigated experimentally. Decay, growth, and noise suppression characteristics of supersonic jets from plain nozzle, nozzle with two semicircular grooves, and nozzle with two square grooves are presented. The grooves act as effective passive controls, resulting in significant enhancement of jet mixing. The shock cell structure from grooved nozzle is weaker than that of plain nozzle. Acoustic measurement was taken in the nozzle exit plane and in the far field. In the grooved plane grooves show a definite advantage in terms of jet noise attenuation. However, in the plane normal to the grooved plane they are not effective in screech suppression. Further, the present results authenticate that nozzle pressure ratio plays an important role in the case where an adverse pressure gradient exists near the nozzle exit.

Nomenclature

M = nozzle-exit Mach number
P_a = ambient pressure
P_c = jet centerline pitot pressure
P_0 = stagnation pressure in the settling chamber
X = coordinate perpendicular to the nozzle-exit plane
Y = coordinate parallel to the grooved plane
Z = coordinate normal to the grooved plane

I. Introduction

THE passive control scheme investigated in this study is based on the modification of the boundary layer, growing along the nozzle inner walls achieved through partial notches. Streamwise vortices generated by the notches cut at the nozzle exit have been demonstrated to be effective in jet noise reduction.[1] These vortices provide the necessary secondary instabilities that aid the faster amplification of the primary instabilities and hence the growth of the coherent structures. In effect, the streamwise vortices bring in three-dimensionality to the otherwise, basically, two-dimensional spanwise organized vortical structures (coherent structures). Thus the evolution of the large-scale structures gets altered by the notches, which, in turn, alter the mixing and acoustic characteristics of the jet. In view of the effectiveness and simplicity of the notched axisymmetric nozzles, they were investigated in the present study. Similar studies have been conducted by many researchers.[1–3] Pannu and Johannesen[1] investigated underexpanded jets issuing from notched nozzles. The centerline pitot-pressure data indicated that the shock cell structure was modified and the jet decayed faster than the unnotched nozzle flow beyond the core region. They demonstrated that the dominant feature of the flow which determined the structure far downstream was the trailing vortices shed from the swept edges of the notches. They concluded that the notches were effective silencers, mainly because they caused the noise sources to be surrounded by a broad region of low-speed turbulent flow. Smith and Hughes[2] presented experimental results obtained for jets from notched nozzles in a coflowing freestream. The results showed that even at low jet velocities and with slowly tapering nozzles the notches produced quite distinct vortices that persisted well downstream. Also, it was observed that the introduction of a freestream had little effect on the development in the region of the vortices, although it reduced the rate of decay of the centerline velocity in the main part of the jet. Norum[3] tested a variety of asymmetric nozzles and had some success in alleviating the screech feedback loop. Varying lip thickness of the tube and introducing external tabs were found to decrease screech amplitude for certain modes. Long slots made on the tube yielded extensive suppression for all screech modes.

Wlezien and Kibens[4] studied the influence of nozzle asymmetry on supersonic jets. The asymmetric nozzles were constant-diameter tubes with various cutout exit shapes. They observed that the introduction of cutouts had a strong effect on the mixing and noise characteristics of the jet flowfield. Nozzles with multiple cutouts were found to release internal pressure before the jet reached the ends of the cutouts. The jet plume spread faster than the reference jet and had a lower core-flow Mach number. Miller and Seel[5] studied jets issuing from underexpanded nozzles fitted with castellations around their exit and compared them with those leaving plain nozzles. They observed significant improvement in jet entrainment rates in the case of nozzles with castellations. Krothapalli et al.[6] investigated the effect of slotting on the noise of an axisymmetric supersonic jet. They observed that the addition of fingers or slots to a converging axisymmetric nozzle contributed to significant noise reduction. They concluded that slots weakened the shock cell structure near the nozzle exit and thereby reduced the shock-associated noise. Wishart et al.[7] reported experimental results on supersonic jet control using point disturbances inside the nozzle instead of at the exit of the nozzle. They observed significant changes in shear layer development. Yu et al.[8] experimentally studied supersonic flow mixing and combustion using a supersonic nozzle that featured notches and ramps on its expansion side interior wall. The ramp nozzles were found to have a stronger effect on the supersonic flow mixing as compared to the notched ones. Verma and Rathakrishnan[9] carried out experimental investigation to study the effects of notches on the flow characteristics of elliptic-slot freejets. They observed that the angle of the sharp corner in the notch geometry plays a dominant role in the development of elliptic jets. They also reported that at underexpanded conditions the shock structure in the jet core is weakened considerably, close to the exit, as the angle of the sharp corner is increased from 60 to 90 deg, resulting in a significant reduction in far-field noise. The notched nozzles used for the preceding studies were made by completely removing the material from the wall of the nozzle at specific locations (in the form of V-shaped notches, in the form of fingers).[1,2] These notches can be effective in increasing the spread and reducing the noise of the jet, but they can also lead to considerable total pressure loss. Hence, a modified form of notch was thought of, which can prove effective while keeping the

Presented as Paper 2003-4402 at the AIAA/ASME/SAE/ASEE 39th Joint Propulsion Conference and Exhibit, Huntsville Alabama, 20 July 2003; received 11 August 2003; revision received 6 November 2003; accepted for publication 7 November 2003.

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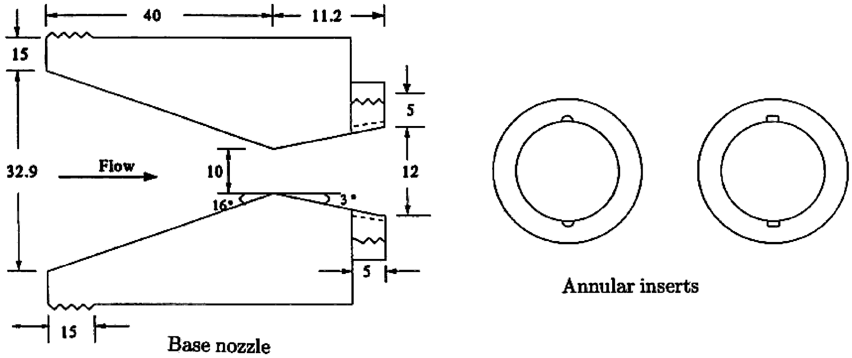

Fig. 1 Experimental model (all dimensions in mm).

pressure loss at a minimum. The notches in the present study were made by partial removal of material, that is, in the form of grooves as shown in Fig. 1. This can be expected to prevent the lateral dissipation of the pressure energy through the notches, thereby minimizing the loss of pressure. These nozzles are better described as nozzles with internally grooved exit.

Elangovan[10] and Elangovan and Rathakrishnan[11] evaluated the effect of vortex generators in the form of grooves on the penetration and spreading of jets from circular nozzles. In their experiments they found that the grooves weakened the shock cell structure of the underexpanded jets. The jet flowfield was found to be strongly influenced by the groove length. Navin Kumar Singh and Rathakrishnan[12] studied sonic jets from nozzles with tabs and demonstrated that passive control can be effective even when they project outside the boundary layer. Also, they have shown that the length of the tab is more effective in mixing promotion than the width for the same projected area of the tab. Sreejith and Rathakrishnan[13] refixed the limits for tab as the radius of the nozzle. Also, they demonstrated that in the limiting case, which is in the form of a cross wire along a diameter of the nozzle, the control is effective not only in mixing promotion, but they suppress the screech too, resulting in significant reduction of jet noise. The shock-associated noise was studied in detail by Seiner et al.[14] The problem of the response of an array of flexible aircraft-type panels exited by noise from a jet under near sonic conditions from a converging nozzle was studied by Charles et al.[15] They studied the effect of nozzle geometry on the radiated sound and jet instabilities. The results demonstrate a large disturbance in the vicinity of the converging nozzle, which acts as an additional source of sound.

From the preceding discussions, it is evident that there is a large amount of literature available on passive control of jets. Most of these passive controls rely on nozzle-exit geometry modification with projections or cutouts. But a projection or cutout at nozzle exit can cause considerable thrust loss. Therefore, in the present study passive controls were achieved by partial removal of material at the exit of the nozzle. The grooves are expected to control the jet mixing and noise without incurring significant thrust loss, as in the case of projections like tabs. Two different groove shapes, semicircular and square, were used in the present study. Jets from plain and grooved nozzles operated at correctly expanded, underexpanded, and overexpanded conditions were investigated to understand the effect of these grooves on the mixing and acoustic characteristics of Mach 1.8 jet in the presence of favorable, adverse, and no pressure gradient.

II. Experimental Detail

The experiments were conducted in the jet test facility at the high-speed aerodynamics laboratory of the Indian Institute of Technology Kanpur.[13] The models tested were Mach 1.8 convergent-divergent nozzles of exit diameter D 12 mm. Two grooves of semicircular and square cross sections were made at the nozzle exit at diametrically opposite locations. The details of the nozzle and grooves are shown in Fig. 1. The notches were in the form of grooves cut at the exit of the divergent portion and extended up to half the distance along the length. Because of the presence of the grooves, the nozzle-exit area increased by 10%.

Pitot-pressure variation along the jet axis X, and at different grid points in the jet field at different axial locations, and the jet noise and frequency at the nozzle-exit plane and at 100 times the nozzle-exit diameter were made for different nozzle pressure ratios (NPR) and geometries of the present study. A pitot probe of 0.4 mm ID and 0.6 mm OD in conjunction with a traverse and PSI 9010 model pressure transducer and a Larson and Davis sound level meter with $\frac{1}{8}$ in. (3.175 mm) microphone were used for the measurements. All of the noise measurements were made inside an anechoic chamber described in Ref. 16.

The acoustic measurements were made at two locations: in the nozzle-exit plane and far-field. For the far-field case acoustic data were acquired at a radial distance of $100D$ in the azimuthal plane, with the microphone at 30-deg orientation to the jet axis, as shown in Fig. 2. For both of the cases, acoustic data were acquired in two planes, namely, the grooved plane and normal to the grooved plane.

The pitot pressures measured were accurate within $\pm 2\%$. The noise measurements were with an accuracy of ± 0.3 dB, with the $\frac{1}{8}$ in. microphone having a flat response in the range of 10 to 50 Hz within ± 1 dB and 6.5 to 140 Hz ± 2 dB and the sound level meter of amplitude range -10 to 140 dB, in five suitable ranges of 60-dB dynamics range. The sound pressures measured were referred to 20 μPa.

III. Results and Discussion

A. Centerline Decay

The core length of a supersonic jet is a direct measure of the mixing and spreading characteristics of the jet. The core length is the axial extent up to which supersonic flow exists. In a supersonic flow, the measured pitot pressure corresponds to the total pressure behind the bow shock in front of the pitot probe. These results cannot be converted directly into velocity or Mach number because of the unknown entropy increase that has occurred. In a steady supersonic flow with a single normal shock wave ahead of the pitot tube, a large pitot pressure corresponds to low Mach number and vice versa.

Variation of pitot pressure P_c along the centerline of the jet for NPR 5.75 is shown in Fig. 3a. The absolute values of P_c are divided by the settling chamber pressure P_0 and plotted against the nondimensionalized axial distance X/D along the jet axis.

For the jet from the plain nozzle, near the nozzle exit, a sharp drop in the pitot pressure followed by a rise is observed, which signifies the presence of the normal shock wave commonly referred to as the Mach disc. For $X/D > 13$, the total pressure decays monotonically and has a variation similar to a subsonic jet. The oscillation in the plotted pitot-pressure data, Fig. 3a, for plain nozzle in the upstream regions ($X/D \approx 12$) are caused by the stationary shock structure in the jet. Because of probe interference with the shock structure, there is some measurement error, and the amplitude in the supersonic region should be considered only qualitative.[17] Figure 3a

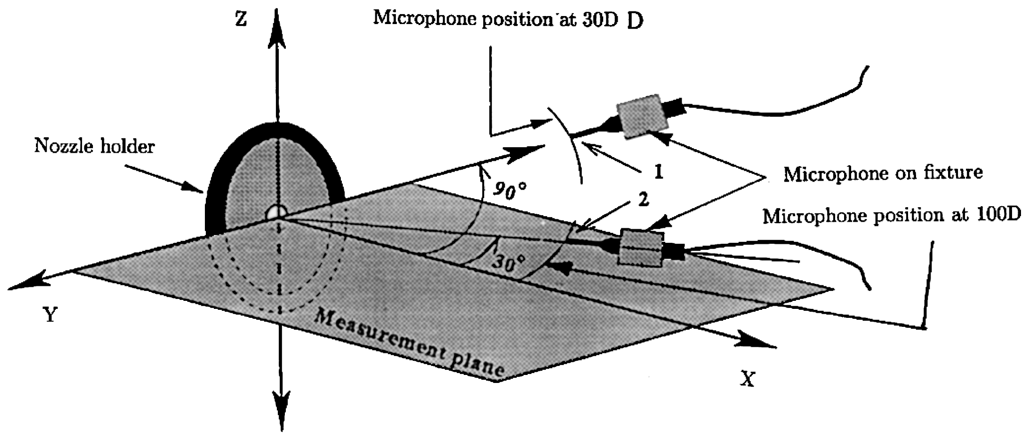

Fig. 2 Apparatus used for acoustic measurements and positions of the microphone. Measurement locations: 1, 90 deg to jet axis (nozzle-exit plane) and 2, 30 deg to jet axis.

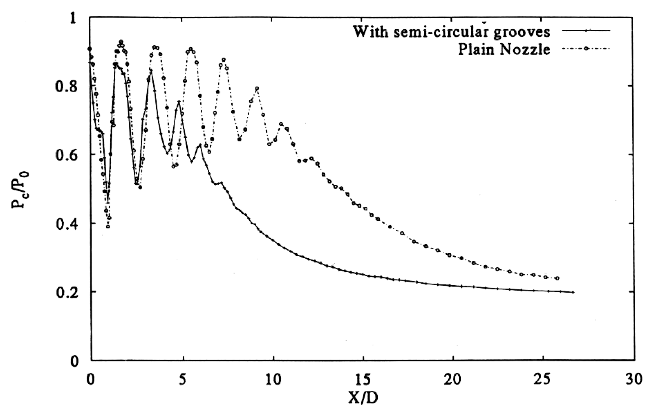

Fig. 3a Centerline pressure decay for $M = 1.8$ and NPR = 5.75.

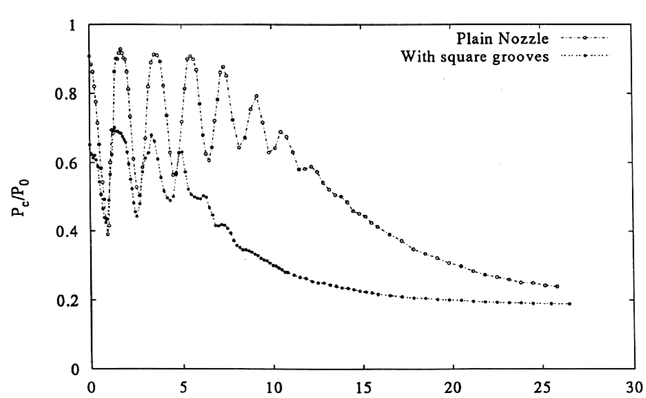

Fig. 3b Centerline pressure decay for $M = 1.8$ and NPR = 5.75.

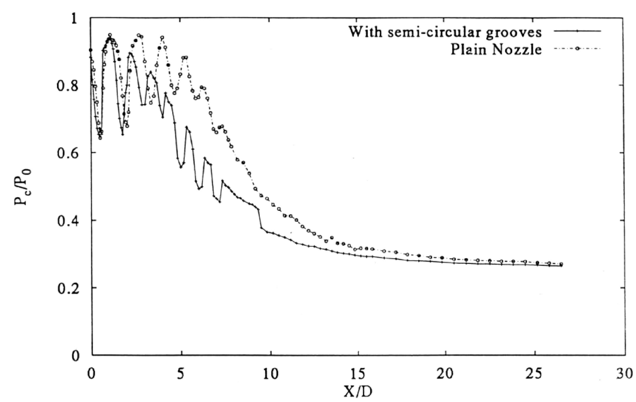

Fig. 3c Centerline pressure decay for $M = 1.8$ and NPR = 4.

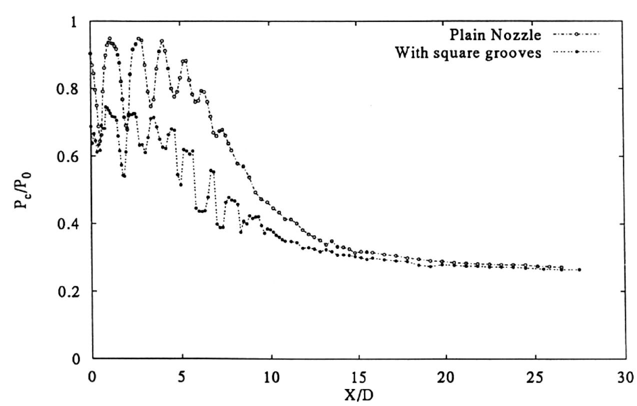

Fig. 3d Centerline pressure decay for $M = 1.8$ and NPR = 4.

indicates a drastic reduction of about 40% in the length of the jet core under the action of the grooves for the correctly expanded case. The variation of the total pressure along the centerline of the jet exiting from grooved nozzle suggests that the shock cell structure is significantly weakened by the presence of the grooves. This is seen from the significantly reduced amplitudes of the pressure data oscillations in the core region. The statement made by Krothapalli et al.[18] that the correctly expanded jets are wave free has to be looked into again because the jet from correctly expanded nozzle is also found to be wave prone, as seen from Fig. 3a. The only difference between correctly and underexpanded jets being that the expansion fan at the nozzle lip for the correct expansion is weaker than that for underexpansion. This is explicitly evident from the first Mach disc strength seen in Figs. 3a and 3e.

For the overexpanded condition the centerline decay is given in Figs. 3c and 3d. It is a general feeling among researchers working in the area of jet control that the passive control will not be effective when there is an adverse pressure gradient.[17] But Sreejith and Rathakrishnan[13] demonstrated that the control is effective even in the presence of adverse pressure gradient. Mach 1.8 jet at NPR 4 is with adverse pressure gradient, but it is seen that the grooves act as effective mixing promoters. With the semicircular grooves, the first two shock cells are behaving identically similar to those from plain nozzle. The second and third cells become very weak, but once again the shocks in the subsequent cells show increased strength. Also, the plain nozzle jets show only marginal decay upto fourth cell, even through the decay after the fourth cell is rapid. But, when the grooves are introduced the rapid decay in the supersonic zone begin from the second cell onwards. This might be caused by the

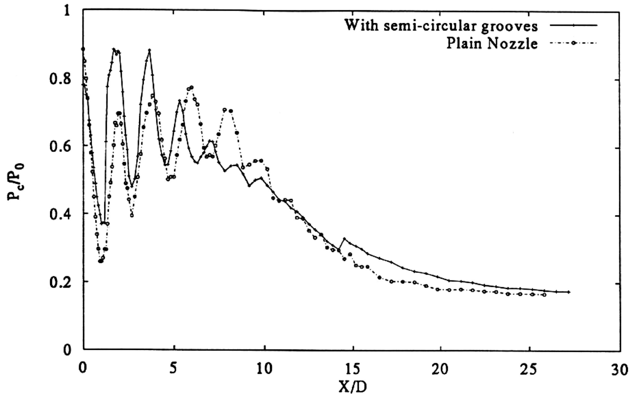

Fig. 3e Centerline pressure decay for $M = 1.8$ and NPR = 7.

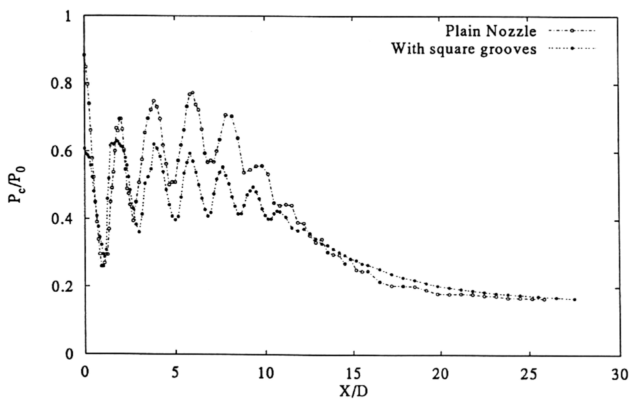

Fig. 3f Centerline pressure decay for $M = 1.8$ and NPR = 7.

penetration of the vortices introduced by the grooves toward the jet centerline. The process of this penetration is found to curtail the energy flow into the cells, as reflected from significantly reduced peaks after the shocks. Also, because of this enhanced mixing caused by the grooves the span of expansion fan activity is increased, especially for the shock cells beyond the second one, as evident from the spread out peaks.

The effect of square grooves on the centerline decay is shown in Fig. 3d. Unlike the semicircular groove, the square groove influences the mixing strongly right from the first cell. All of the shock cells have been weakened in the near field; however, the cells beyond the fourth one exhibit an increase in strength compared to the plain nozzle. A closer look into the vortex generation mechanism in these grooves will explain the reason behind the preceding results. The size of the vortex generated is proportional to the radius of curvature of the edge from which it is shed. Also, large size vortices are efficient entrainers of mass from the surrounding but are highly unstable and short lived. They easily get fragmented into smaller vortices and because of this are unable to travel long distances. Whereas small vortices are efficient mixing promoters, compared to large vortices they are highly stable. Therefore, they could be able to travel considerably long distances compared to their larger counterparts. For semicircular grooves the vortices generated are free from any corner effect and are of uniform size because of the absence of radius of curvature variation of the edge, and hence do not have any inner mixing mechanism in them. They come out of the groove as axial vortices and introduce mixing along the path of their propagation. In the process they promote mixing of the jet field, spend their energy, and get dissipated. This activity seems to be hectic around the third and fourth cells. Because the field is with an adverse pressure gradient, the expected long life of axial vortices gets reduced in overcoming the adverse pressure gradient. Hence, cells beyond the fourth one could able to gain energy from the surrounding high-speed fluid without being significantly inhibited by the axial vortices.

For square grooves the vortices generated by the grooves experience an in-built mixing mechanism as a result of the sharp corners; therefore, they get fragmented when they come out from the grooves. This proves to be an advantage for mixing enhancement in the near field; however, because of the reduced strength compared to the vortices from the semicircular grooves, the decay achieved is not much in the near field. The preceding discussion can be quantified from the fact that, as seen from Figs. 3c and 3d, the rapid decay begins right from nearly $X/D = 2.5$ for the semicircular groove case, whereas for the square groove the rapid decay begins only from $X/D = 5$.

Whatever be the nature of the groove shape, the additional vortices introduced by the grooves will provide some shielding to the jet noise radiation at least in the plane of the grooves. This can be regarded as an advantage.

The centerline decay for underexpanded condition at NPR 7 is given in Figs. 3e and 3f. This is the field with favorable pressure gradient. Because of this, the groove effect is felt up to the end of the core. The semicircular groove is found to be effective in promoting the jet mixing. The shocks have become weaker compared to the plain nozzle case. Especially after the fourth cell the shocks have diffused significantly. However, for the square grooves, though the effect of groove is felt in the core, there is no significant reduction in the shock strength. This is because, as just discussed, a part of the vortex strength is consumed in overcoming the sharp corner effects, and hence they could influence the jet only marginally when a favorable pressure gradient is present.

B. Jet Flow Development

The jet from a nozzle, once it comes out, tries to expand as a free flow into the surrounding environment in the case of submerged jets. In the process the shear layer at the jet boundary interacts with the surrounding stagnant fluid. This action drags the surrounding fluid into the jet through the vortices formed as a result of jet interaction with the ambient fluid. This is termed as the well-known entrainment process. The vortices formed at the jet boundaries are large-scale turbulent structures and act as carriers of mass from the surroundings into the jet field. The entrained mass at low momentum tries to gain momentum from the high-speed fluid elements in the vicinity of the jet centerline. During this interaction, the large-scale structures get fragmented and carry the entrained mass towards the jet centerline. Therefore, it can be stated that in a jet field the large-scale structures act as mass carriers and the small-scale eddies act as distributors of the mass carried by the large-scale structures. Because of this, the jet velocity starts decreasing as the jet propagates downstream from the nozzle exit.

The velocity diffusion process initiated by the entrainment at the jet periphery propagates towards the centerline. When this process reaches the jet centerline, the potential core comes to an end. After this point on the jet axis, the decay becomes rapid and is termed as the characteristic decay in the literature. The jet propagation process just discussed is for subsonic jets. But when the nozzle-exit Mach number is supersonic, the jet field is dominated by shock waves and expansion fans for both correctly and incorrectly expanded jets. The entrainment is taking place at the jet periphery where there is a zone of subsonic flow. That is, supersonic zone in the jet central portion is submerged in the subsonic layer surrounding that. The axial extent of supersonic flow regime is termed as the core. Therefore, the aim in the case of supersonic jet control is two-fold; the control should result in core length reduction, and the shock in the core should be made weaker or eliminated. The former will result in aerodynamic advantage, namely, enhancement mixing, and the latter will result in acoustic advantage, namely, reduction in jet noise. Hence, the control effectiveness can be properly understood if the jet flow development structure is investigated. To achieve this goal, pressure surveys across the jet field were made, and the results were analyzed in the form of isobaric contours.

Comparison of isobars of plain nozzle and semicircular grooved nozzle revealed that the introduction of streamwise vortices by the semicircular grooves introduces mixing enhancement right at the nozzle exit. It was reflected as a large extent of the low-speed zone at the jet periphery. As the jet proceeds downstream, the mixing enhancement introduced by the axial vortices from the grooves results in faster decay of the jet compared to the plain nozzle. It is well-known that axis switching is a desirable phenomenon, capable of enhancing the mixing and improving the entrainment.[19–21] Further, the streamwise vortices weaken the shocks in the core and reduce the number of cells for semicircular grooves. This weakening of shocks and reduction of number of cells can be regarded as a definite advantage from the jet acoustic point of view because diffusion of shocks in the core will result in reduction of jet noise.

The isobaric contours for jet from plain nozzle and nozzle with square grooves at NPR 5.75 showed that the vortices from square grooves are better mixing promoters compared to semicircular grooves, but have relatively shorter life. This was clearly exhibited by the faster growth rate of the jet near the groove locations. The presence of weaker shocks in the controlled jet compared to the plain nozzle jet was evident from the isobars.

For the square grooves the axis switching was at about $X/D = 8$; therefore, it can be stated that the square grooves also make the jet behave like a noncircular jet. Also, it was seen that axis switching in this case is earlier compared to semicircular grooves. This clearly supports the argument given in the centerline decay discussion stating that the square grooves, because of the sharp corners, introduce faster mixing in the near field. In the case of both semicircular and square grooves, the vortices will provide a shielding effect on either side of the jet axis, and this shielding effect will result in noise reduction in that plane.

The isobars for NPR 4, which is an overexpanded condition for plain nozzle and the nozzle with semicircular grooves, were also studied. This flow is with adverse pressure gradient. Therefore, the control effectiveness will be less pronounced compared to the correct expansion case. It was found that the grooves promoted mixing through the generation of streamwise vortices right at $X/D = 0$, thereby rendering the jet to propagate like a noncircular jet. This resulted in an axis switching at about $X/D = 6$ for semicircular groove case.

Compared to the semicircular case, the mixing introduced by the square grooves is faster but confined to a smaller spatial extent. Also, the streamwise vortices lose their identity as early as $X/D = 4$, whereas for the semicircular grooves case it continues beyond $X/D = 4$. The axis switching in this case was at $X/D = 12$, which is much later than that for the semicircular case. This is because of the combined effect of weaker strength of vortices from square grooves and the adverse pressure gradient prevailing in the jet field.

The isobaric contours for NPR 7, which is an underexpanded condition, for plain nozzle and semicircular grooved nozzles revealed that, unlike the correct and overexpanded cases, streamwise vortices introduced at the nozzle exit are instantaneously convected to the jet periphery. This is because for an underexpanded jet a strong expansion fan is positioned at the nozzle lip and the flow coming out of the nozzle is powerfully turned away from the centerline. The combination of flow turning and increase in Mach number through expansion is responsible for the instantaneous convection of the streamwise vortices to the jet periphery. In the process, compared to the plain nozzle, for the grooved nozzles mixing activities were found to prevail over a large zone and were reflected as closely spaced isobaric contours.

As the jet propagates downstream, the mixing activity at the jet periphery tried to spread towards the jet axis. This results in reduction of shock strength in the core of grooved nozzle jet compared to the plain nozzle jet. For this case no axis switching was observed. This might be because the favorable pressure gradient prevailing in the field did not allow any lopsided growth of jet in mutually perpendicular axes. It is seen that all of the shocks in the core have become weaker even though the core length has not been influenced much by the streamwise vortices from the semicircular grooves.

The isobaric contours with square grooves for the case of NPR 7 were compared with the plain nozzle. It was seen that the mixing initiated by the streamwise vortices from the square grooves was more active than those from semicircular grooves. This is because the vortices from square grooves were relatively weaker and hence were unable to travel to the periphery, retaining their strength before getting mixed up with the mixing layer. Because of this, two distinct mixing zones were observed at $X/D = 0$ in the groove locations. Because of this weaker nature of these vortices, though the core gets influenced, the shocks are weakened only marginally. There is no tendency for axis switching in this case.

For the underexpanded case also these streamwise vortices, establishing two distinct zones of activities near the jet periphery, are expected to provide acoustic shielding resulting in some jet noise attenuation compared to the plain nozzle.

IV. Jet Noise

A. Frequency in the Grooved Plane

To understand the effect of acoustic shielding offered by the grooves on the jet noise acoustic measurements were carried out for the plain, semicircular, and square grooved nozzles at NPR 5, 4, and 3. To investigate the effect of grooves on the shock associated and mixing noise components, the measurements were made in the nozzle exit plane ($X/D = 0$), at radial distance of $30D$, placing the microphone in the grooved plane and normal to that. The frequency spectra for NPR 5 for the plain nozzle, semicircular grooved, and square grooved nozzles are shown in Fig. 4. It is seen that the plain nozzle shows a prominent screech at 10-kHz frequency and considerable shock associated noise, whereas the grooves were found to result in a screech of lower amplitude and higher frequency. Also, the mixing noise has come down considerably.

The spectra at $X/D = 0$ for all of the three nozzles of the present study at NPR 4 are given in Fig. 5. The plain nozzle exhibits

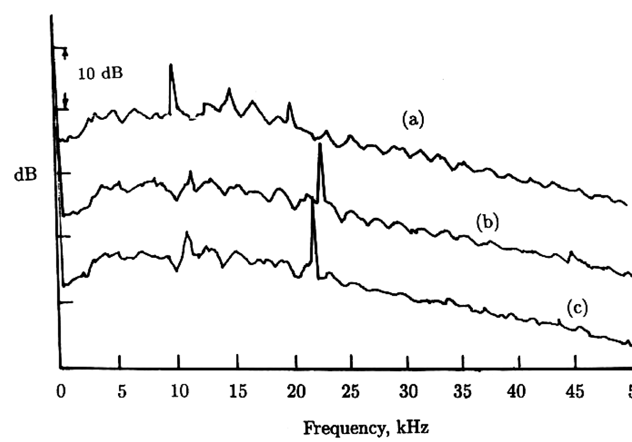

Fig. 4 Frequency spectrum for $M = 1.8$, NPR 5, $X/D = 0$, and $R/D = 30$: a) plain nozzle, b) semicircular grooves (in the grooved plane), and c) square grooves(in the grooved plane).

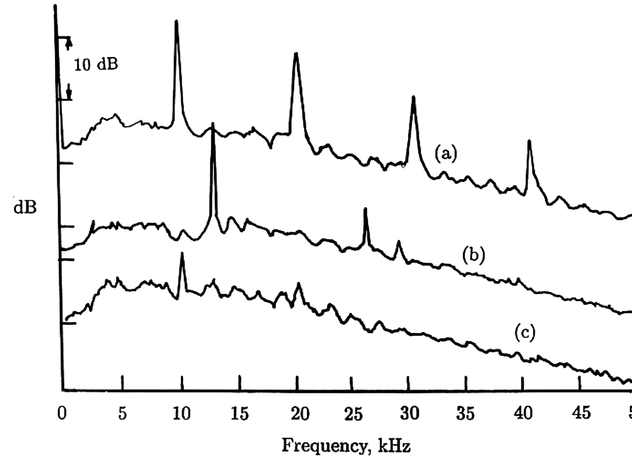

Fig. 5 Frequency spectrum for $M = 1.8$, NPR 4, $X/D = 0$, and $R/D = 30$: a) plain nozzle, b) semicircular grooves (in the grooved plane), and c) square grooves (in the grooved plane).

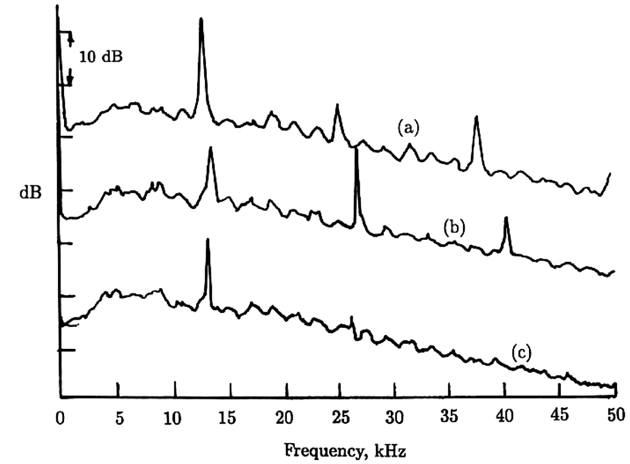

Fig. 6 Frequency spectrum for $M = 1.8$, NPR 3, $X/D = 0$, and $R/D = 30$: a) plain nozzle, b) semicircular grooves (in the grooved plane), and c) square grooves (in the grooved plane).

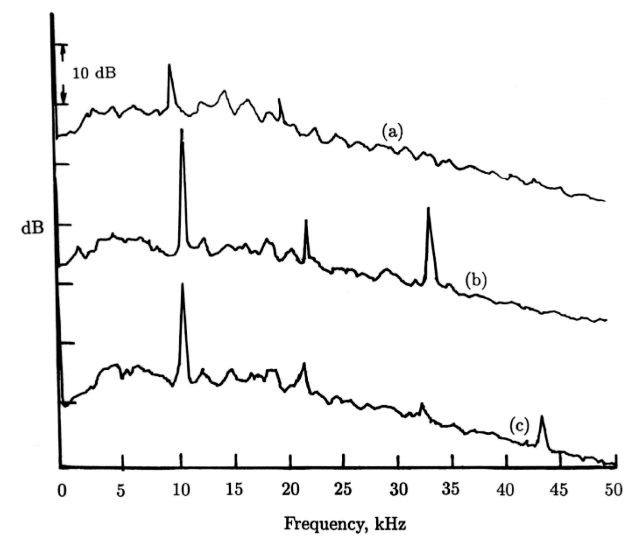

Fig. 7 Frequency spectrum for $M = 1.8$, NPR 5, $X/D = 0$, and $R/D = 30$: a) plain nozzle, b) 90 deg to the grooved plane (semicircular grooves), and c) 90 deg to the grooved plane (square grooves).

screech with four harmonics. The semicircular groove introduction suppressed the high-frequency harmonics of screech; only two screeches are present for this case. Also, the amplitude of the first and second screech is reduced significantly. The square grooves remove the last three screech harmonics and also reduce the first screech amplitude from 103 to 93 dB. For this NPR the suppression of the screech for square grooves case can result in an appreciable reduction in the shock associated noise.

For NPR 3, there are three screech harmonics seen for the plain nozzle as shown in Fig. 6a. When the semicircular grooves are introduced, the first screech amplitude is reduced from nearly 103 to 88 dB, but the second screech shows a marginal increase in its amplitude in the grooved plane as seen from Fig. 6b, whereas the square grooves, Fig. 6c, completely eliminate the second and third harmonics of the screech. Also, the first screech amplitude has been reduced significantly. Further, the mixing noise content has come down considerably in the grooved plane for both semicircular and square groove cases. These effects will result in reduction of the overall sound pressure level (OASPL).

B. Frequency in the Normal Plane

The frequency spectrum for the plain nozzle and the grooved nozzle in the plane normal to the grooved plane at $X/D = 0$ and NPR 5 are shown in Fig. 7. Compared to the grooved plane, there is a marked increase in the first screech amplitude for both the grooves. Also, the frequency of the first screech has been shifted from 10 kHz for the plain nozzle to about 11 kHz for the square grooves and slightly more than 11 kHz for semicircular grooves. This might be caused by the stronger and weaker natures of the streamwise vortices generated by the semicircular and square grooves, respectively. The mixing noise near the nozzle exit also has gone up in this plane for both the grooves. This can result in an increase of OASPL compared to the plain nozzle.

The frequency spectra for NPR 4 in the plane normal to the grooved plane showed a completely different nature compared to the grooved plane. For the semicircular grooves the amplitude of the first screech harmonic was reduced marginally, but the other three harmonics showed considerable increase in their amplitudes. For the square groove the first harmonic of the screech in the plain nozzle had been suppressed, but the second harmonic showed significant increase in its amplitude. The third and fourth harmonics were once again suppressed.

Similar results for NPR 3, in the direction normal to the grooves, showed that all of the three screech harmonics of the plain nozzle were getting augmented in this plane for both the grooves. A cross reference of the frequency spectra in the 90-deg plane for NPRs 5, 4, and 3 clearly established the decrease in groove effectiveness on screech suppression in the adverse pressure gradient.

The preceding results of the frequency spectra at $X/D = 0$ gave the qualitative nature of the control effectiveness in the grooved plane and in the plane normal to it. To quantify the groove effectiveness on the noise suppression, the jet noise (OASPL) and the corresponding frequency spectra were measured for plane and grooved nozzles at $100D$ and azimuthal plane ($R/D = 100$) and 30-deg orientation to the jet axis. This position and orientation is fixed in accordance with the study by Verma and Rathakrishnan.[9]

C. Far-Field Noise in Grooved Plane

Study of the frequency spectra for NPR 5, for all of the three nozzle configurations of the present study are shown in Fig. 8. It is seen that for the plain nozzle there are two screech harmonics. When the semicircular grooves are introduced, the amplitude of the first harmonic comes down from 105 dB, for the plain nozzle, to 100 dB and the second harmonic is completely suppressed. Also, the shock associated and mixing noise levels have come down significantly at all frequencies. This might be caused by the acoustic shielding offered by the streamwise vortices generated by the grooves. The OASPL has come down from 115.4 dB for the plain nozzle to 112.3 dB for the semicircular grooved nozzle. The square grooves are also effective in controlling the screech and in offering acoustic shielding. For this case the jet noise measured is 113 dB. Similar results for NPR 4 are shown in Fig. 9. Here again the grooves are

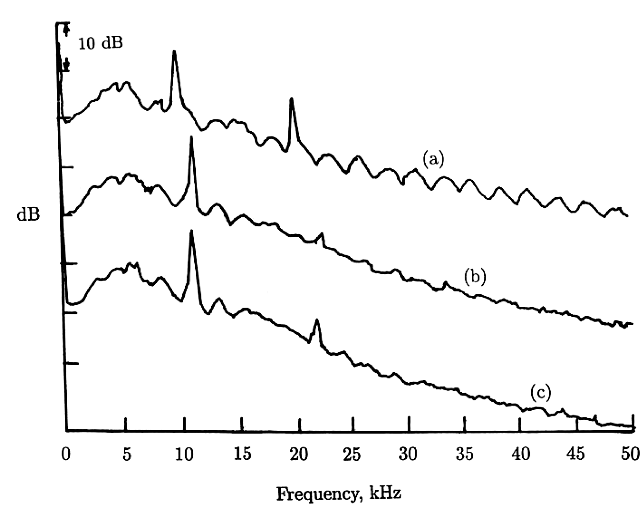

Fig. 8 Frequency spectrum for $M = 1.8$, NPR 5, $R/D = 100$, and $\theta = 30$ deg: a) plain nozzle, b) semicircular grooves (in the grooved plane), and c) square grooves (in the grooved plane).

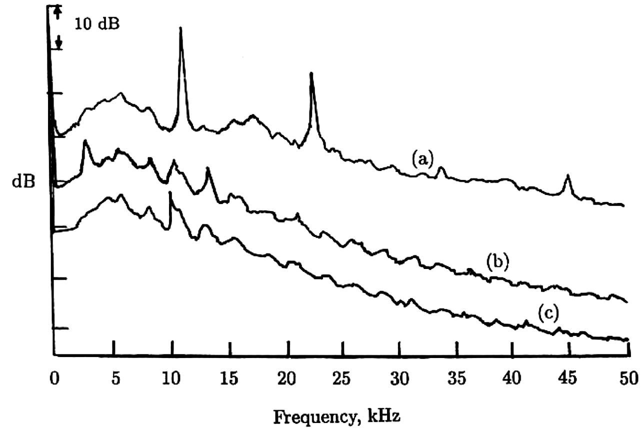

Fig. 9 Frequency spectrum for $M = 1.8$, NPR 4, $R/D = 100$, and $\theta = 30$ deg: a) plain nozzle, b) semicircular grooves (in the grooved plane), and c) square grooves (in the grooved plane).

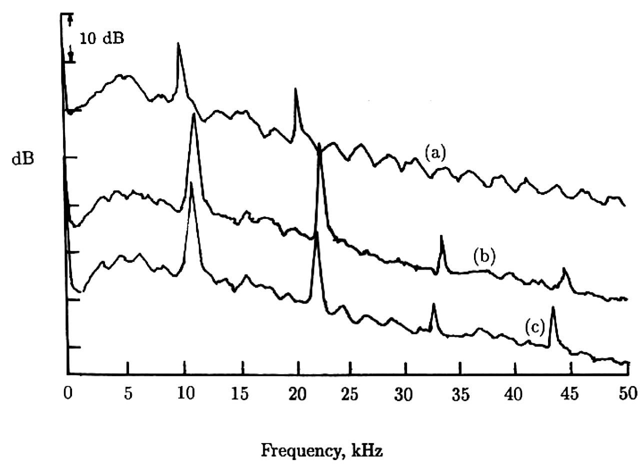

Fig. 10 Frequency spectrum for $M = 1.8$, NPR 5, $R/D = 100$, and $\theta = 30$ deg: a) plain nozzle, b) 90 deg to the grooved plane (semicircular grooves), and c) 90 deg to the grooved plane (square grooves).

effective in screech suppression, and this results in an OASPL reduction of 6.6 dB for semicircular grooves and 6.4 dB for square grooves.

The spectra for NPR 3 also showed that grooves were effective in acoustic control, resulting in jet noise reduction of 4.3 dB for semicircular grooves and 1.1 dB for square grooves.

D. Normal to the Grooved Plane

The frequency spectra for NPR 5 in the plane normal to the grooved plane given in Fig. 10 show that the advantage offered by the grooves is not experienced in this plane because the shielding effect offered by the streamwise vortices from the grooves is not present in this plane. Therefore, the screech tones are getting augmented when the grooves are introduced. It was reported by Krothapalli et al.[18] that although the screech tones and shock associated noise can be reduced by the introduction of streamwise vortices the increase in the turbulent mixing noise can result in an insignificant effect on the far-field noise for axisymmetric jets. The introduction of streamwise vortices can even lead to an increase in the jet noise. A similar effect is felt in the present study also. For NPR 5 there is an increase of 1.9 dB for semicircular grooves and 2.5 dB for square grooves. At NPR 3 the increase is 2.1 dB for semicircular grooves and 2 dB for square grooves, whereas for NPR 4 there is a reduction of 2.6 dB for semicircular grooves and 5 dB for square grooves even in the direction normal to the grooved plane. These results imply that the NPR plays an important role in the case of overexpanded jets.

V. Conclusions

The aerodynamic and acoustic characteristics of jets from nozzles with internal grooves were investigated. The grooved nozzles show better mixing characteristics than the plain nozzle, manifested by shorter core lengths and faster jet decay both in the near and far fields. The shock cell structure of jets from grooved nozzles is weaker than that of the plain nozzle.

The far-field noise characteristics of the grooved jets in the grooved plane show definite gain in noise reduction. However, such reduction, observed in the grooved plane, is not seen in the plane normal to the grooved plane. Any reduction in the mixing noise observed in the far field seems to be associated with the orientation of the grooves with respect to the measurement plane. This observation demonstrates the shielding effect offered by the streamwise vortices generated by the grooves. Also, for the overexpanded case of jet flow it was seen that the effectiveness of streamwise vortices on jet control is strongly influenced by the NPR.

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