JOURNAL OF PROPULSION AND POWER
Vol. 17, No. 1, January–February 2001

Flow and Acoustic Properties of Underexpanded Elliptic-Slot Jets

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An experimental program was conducted to investigate the effect of aspect ratio on the flow and acoustic properties of unheated jets issuing from elliptic slots. The aspect ratios investigated ranged from low (2:1) to moderate values (3:1 and 4:1). Further, passive control or the mixing and noise characteristics is demonstrated. The experimental conditions chosen ranged from fully expanded ($M_j = 1.0$) to underexpanded jets with an equivalent Mach number of 2.0. The mean flow study reveals that in moderate aspect-ratio jet the azimuthal deformations take longer to evolve than in low aspect-ratio jet, resulting in lower bulk mixing. Notches, as passive control devices, enhance mixing in each aspect ratio. The acoustic properties of underexpanded jets show great variation with aspect ratio. Minor-axis sides of 3:1 and 4:1 plain jets radiate shock noise levels that are 4 and 10 dB, respectively, higher than those by 2:1 plain jet. The presence of notches alters the azimuthal emission characteristics of these jets. For a 2:1 jet notches bring down the noise levels along the major-axis plane by 5 dB, whereas for 3:1 and 4:1 jets notches effect the noise intensity along minor-axis sides and show a reduction of 3.5 and 7 dB, respectively, with a repeatability of 2%.

Nomenclature

b_n	=	local unit vector in the direction of the binormal
D_e	=	equivalent diameter of noncircular slot
L_a	=	equivalent semimajor axis length of plain elliptic slot
L_{avg}	=	average shock-cell length
M	=	local flow Mach number
M_j	=	Mach number obtained by correctly expanding an underexpanded jet
P_a	=	atmospheric pressure
P_e	=	pressure at slot exit
P_t	=	pitot pressure at subsonic flow conditions
P_{t2}	=	stagnation pressure behind the standing bow shock in front of the pitot tube
P_0	=	settling chamber pressure
U	=	local flow velocity
U_c	=	local centerline velocity
u	=	self-induced velocity of a vortex filament
X	=	coordinate perpendicular to exit plane
Y	=	transverse coordinate parallel to minor-axis plane of elliptic slot (Fig. 2)
Z	=	coordinate parallel to the major-axis plane of elliptic slot (Fig. 2)
θ	=	observer angle in the radial direction
κ	=	strength of the vortex filament
ρ	=	radius of curvature of the vortex filament
σ	=	core radius of the vortex filament
ϕ	=	observer angle in the azimuthal direction

Introduction

THE study of jet acoustic properties has gained paramount importance, especially since the proposal for the second-generation supersonic plane has been finalized. Furthermore, at high altitudes the jet is necessarily underexpanded unless it is exiting from a variable nozzle. It has been recognized for many years now that the noise radiated from an underexpanded jet (shock-containing) displays features that are different from that of a shock-free jet. The underlying cause being the presence of a stationary shock-cell pattern, which results in a shock shear-layer interaction and, hence, an additional noise known as the shock-associated noise.

The shock-associated noise consists of a discrete frequency component called *screech* and a second component known as *broadband shock noise*. The observation has been made that in the far-field the measured frequency of screech tone is the same regardless of the direction of observation.[1] This is in contrast to the strong directional dependence of the broadband shock-associated noise. Jets exiting from noncircular geometries, caused by a nonuniform azimuthal curvature, spread differently in different planes. As such, at underexpansion, they possess a nonsymmetric shock pattern, which results in a variation of radiated shock-noise levels along the azimuth. As such, they exhibit acoustic properties far different than those by conventional exit geometries. Furthermore, the shock noise depends on the jet Mach number and shape of the nozzle exit geometry that greatly influences the nature of the downstream development of shocks. Aspect ratio, defined as the ratio of the major-axis length to minor-axis length, is also an important parameter that alters the jet behavior at different regions along the azimuth and, hence, the shock-cell geometry, which eventually affects the jet noise characteristics.[2]

In the literature mean- and turbulent-flow investigations have been independently carried out for 2:1 (Ref. 3), 3:1 (Refs. 4 and 5), and 5:1 (Ref. 6) aspect-ratio (major axis/minor axis) elliptic jets. Previously Hussain and Hussain[7] carried out a comparative study of aspect-ratio effect in the range 2:1 and 8:1. They observed that for a given equivalent diameter the aspect ratio is an important parameter controlling the deformation and topological changes, i.e., bifurcation of large-scale vortical structures in elliptic jets, and the dynamics of low-aspect-ratio elliptic jets are basically different from that of jets of moderate to high aspect ratios. In low-aspect-ratio jets the deformation as well as the self-induced inward and outward displacements of parts of elliptic structures are small,[7] and as such there is a dominance of large-scale activity.[8] In high-aspect-ratio jets the azimuthal deformations take a longer time to evolve in the streamwise direction than in low-aspect-ratio jets.[8] When the distortions become appreciable, the vorticity is already very diffused, and hence, the entrained fluid induced by these diffused vortices would be much less.[3] As such there is a dominance of small-scale activity in high-aspect-ratio jets. And because entrainment of mass flow is primarily caused by large-scale activity, a low-aspect-ratio jet shows higher bulk mixing.[3,5] In addition, the axis-switching location was found to be a linear function of aspect ratio in elliptic[7] and rectangular[8] jets for the entire range of aspect ratios studied.

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However, the jet aspect ratios in the study of Bagdanoff et al.[8] were quite high, from 5 to 16. In this range of aspect ratios the jet behaves more or less like a two-dimensional jet.[3,8,9] Keeping this important aspect in mind, the selection of aspect ratios for the present study has been made.

When a jet is used for mixing purposes or for thrust augmentation, a large mass entrainment, especially near the nozzle, is desired. Winant and Browand[10] showed that in two-dimensional flows entrainment is dominated by vortex merging alone. However, in three-dimensional elliptic jets entrainment is caused by vortex merging and azimuthal deformation of vortices at the same time.[3] Also, it was observed by Wlezien and Kibens[11] that nozzles with intermediate origins generated noncircular vortices resulting in large entrainment. Thus, the asymmetry of these vortical structures is a technique or a means, active or passive, to enhance entrainment.

The present investigation is aimed at studying the effect of aspect ratio in unheated jets issuing from elliptic slots. Turbulent jets issuing from slots are useful in the number of areas of interest to engineers, such as augmentation of thrust in V/STOL aircraft[12] and combustion in propulsion units.[5,12] Further, it has been shown by Gutmark and Schadow[5] that the slot jet has large- and small-scale mixing characteristics similar to jets with gradual contraction. This feature is important for engineering applications where the simplicity of slot design is advantageous,[5] which suggests that the overall mean flow characteristics of slot jets can be justifiably compared to jets issuing from nozzles.

The aspect ratios selected for the present study ranged from low (2:1) to moderate values (3:1 and 4:1). Further, a passive means of achieving mixing and noise control is demonstrated. Two square-shaped notches are placed symmetrically along the minor-axis side of the elliptic slot. Each notch conformed to 5% of the equivalent slot area. All of the slots, i.e., plain and modified, were of equal area, which was equal to the area of a circular slot of 10 mm diam, and thus the equivalent diameter of the plain/notched slots was 10 mm.

To the best of the authors' knowledge, there is no available literature in which can be found a systematic study of the effect of aspect ratio on the flow and acoustic properties of elliptic-slot jets. Such a study would be of paramount importance and of much relevance to practical situations like aircraft propulsive systems. All of the previous studies have been carried out for incompressible range.[7–9,13] In this paper we extend the study to fully expanded and underexpanded sonic free jets. Also, it has been reported in literature that the initial development of the jet is largely dependent on the conditions at the nozzle exit flow.[5,9,14,15] As such, instability in the form of notches are introduced along the minor-axis side. This has been done, in particular, to alter the initial shock development and hence significantly affect the noise field in these modified slot jets.

To study the effect of initial geometry alone on the jet development, jets issuing from slots were preferred. However, the effect of vena-contracta typical to sharp-edged slots was taken care of by smoothening the outer edges of the slot resulting in square-edged slots so that the jet expands as smoothly as it does from a contoured nozzle. This configuration was suggested by Hussain and Ramjee[16] and was found by them to be absent from the effects of vena-contracta. The slots thus formed were named by them as *disk nozzles*.

Experimental Setup and Procedure

The experiments were conducted using a high-speed jet facility that consists of a cylindrical settling chamber connected to high-pressure storage tanks. The desired slot geometry was carved on circular aluminum plates of 1.3 mm thickness. An O-ring was used between the settling chamber nipple and slot after which the slot was secured to the end of the settling chamber by tightly screwing the slot holder so as to ensure no leakage even at very high chamber pressure. The compressed air was ducted into the settling chamber where it was brought to an equilibrium stagnation condition. To minimize the disturbance level and fluctuations at the slot inlet, the air was passed through three fine-mesh screens in the settling chamber placed 3 cm apart, as shown in Fig. 1. The area ratio between the settling chamber end plate and slot was 100. The settling chamber pressure P_0, which was the controlling parameter in our investigation, was regulated using a pressure regulating valve. All of the pressure measurements were made using long U-tube mercury manometers.

Figure 2 shows a schematic diagram of the slot mounting attachments and the models used. Mean flow study was carried out only at full expansion $M_j = 1.0$. In addition to the mean flow characteristics, far-field shock associated noise, with its directivity both in azimuthal and radial plane (in aft quadrant) and average shock-cell length analysis are made. For acoustic study the test conditions ranged from correctly expanded sonic jets $M_j = 1.0$ to underexpanded sonic jets at P_0/P_a of 7.82, $M_j = 2.0$, corresponding to the level of underexpansion of 4.14. The Reynolds number based on the equivalent diameter and the equivalent exit velocity (based on M_j, which is defined as the Mach number obtained by correctly expanding the underexpanded jet) for the two conditions ranged from 2.36×10^5 to 4.72×10^5. The noise measurements were carried out in an jet acoustic chamber ($3 \times 2 \times 2$ m), which satisfied anechoic condition frequencies of 660 Hz and above. A Larsen and Davis 800B Model sound-level meter with 3.175 m microphone was used to obtain the overall sound pressure level (OASPL) measurements. The microphone was calibrated using a Larsen and Davis CA250 calibrator with corrections for day-to-day changes in atmospheric pressure. The accuracy, according to the manufacturers specifications, was within ±0.3 dB in the range of 20–20 kHz. Figure 3 shows the various measurement planes and microphone location for the present investigation.

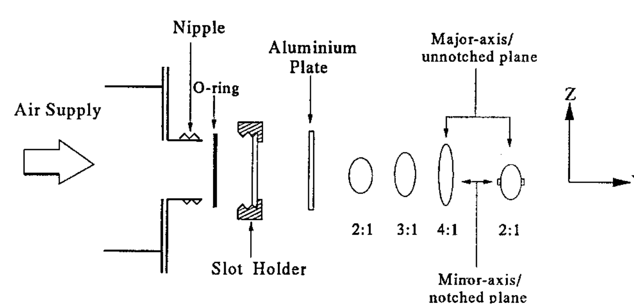


Fig. 2 Schematic diagram of nipple and mounting attachments for slot jets.

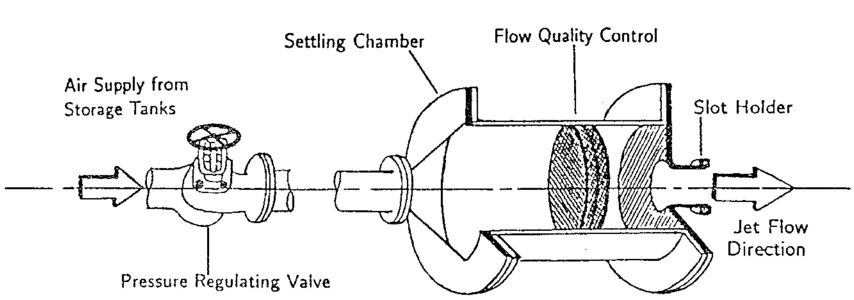


Fig. 1 Schematic diagram of the jet test facility.

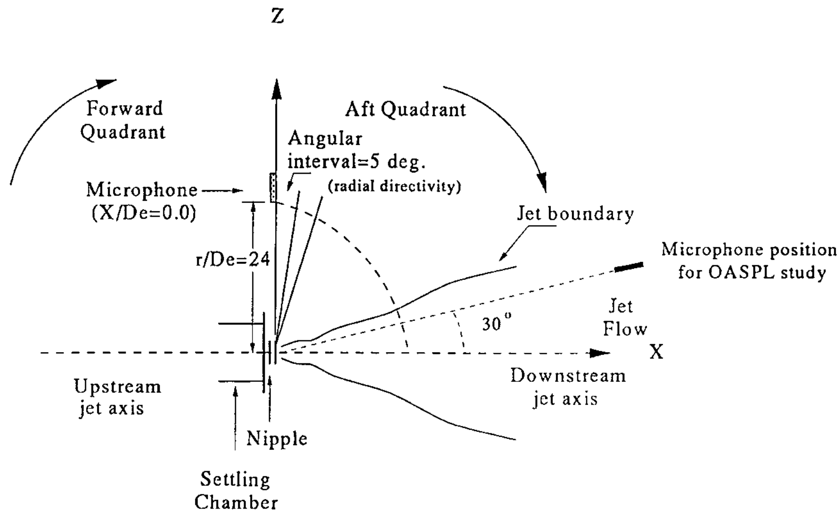


Fig. 3 Orientation sketch of microphone locations for sound measurements.

All of the tests were carried out at a room temperature of 30°C and 730 mm Hg of pressure averaged over the time taken for the completion of experiments. The variation in temperature was less than 0.1% and that for pressure about 2%.

Measurement Techniques

The sensing probe used for obtaining mean flow measurements of the flowfield for the present investigation was a pitot tube with an outer diameter of 0.55 mm. In addition to this, it was observed that close to the exit, i.e., for $X/D_e = 0.1$, the pressure is nearly constant for 80% of the slot diameter for all of the cases tested. The magnitudes of the pressures obtained with this probe size relative to the slot diameter were quite accurate. In all of the measurements, the sensing probe was oriented parallel to the jet X axis. The grid data were taken on one side (i.e., a quadrant) and extended to the whole flowfield assuming symmetry of flowfield about the Y and Z axis. Here the Y axis is taken along the notched/minor-axis plane and Z axis along the unnotched/major-axis plane of the elliptic slot as shown in Fig. 2.

Shock-cell length was measured by a simple nonintrusive technique. A sharp pointer attached to a traverse was positioned at the slot exit plane, but sufficiently away from the flowfield so as not to be of any disturbance to flow. The shadowgraph images of the underexpanded jets were captured on a screen along with the pointer. The angle made by the light source with the parallel beam reflected from the mirror was kept less than 5 deg, ensuring proper accuracy of the quantitative measurement of shock-cell length using shadowgraph images in conjunction with the pointer and the traverse arrangement. The pointer was moved parallel to the jet axis from the beginning of each shock cell to its end with the movement of the pointer being constantly monitored on the screen. The distance traveled by the pointer for each cell was measured by the movement of the traverse. Knowing the total length of the repetitive shock cells, up to four shock cells, the average of these is taken as the representative shock-cell length (L_{avg}).

Data Accuracy

The traverse is provided with a vernier scale with a resolution of 0.1 mm. Hence the accuracy of traverse movement along the X, Y, and Z directions was ±0.1 mm. The manometers had graduations of resolution 1 mm. All of the pressure measurements were accurate up to ±1 mm of the mercury column, and all of the measurements were found to be repeatable within ±3%. The noise measurements made were accurate, according to manufacturer's specifications, within ±0.3 dB in the range of 20 Hz–20 kHz. The shock-cell length measured was accurate up to ±2%. The repeatability of the noise and shock-cell measurements was within ±2 and ±3%, respectively.

Finally, although great care was taken in pitot-pressure measurements, the possibility of some inaccuracy in these measurements, in a highly turbulent and three-dimensional flowfield as in the present case, cannot be ruled out. But it may be presumed justifiably that this slight inaccuracy may not effect the results significantly as the results are primarily of a comparative nature.

Results and Discussions

Iso-Velocity Contours

To obtain a picture of the jet structure as it grows in the YZ plane at various axial locations, iso-velocity contours have been obtained from the grid study. Pitot (gauge) pressures are measured at various grid points in a quadrant of the flowfield and are reduced to local Mach numbers by using the isentropic relation

$$M = \sqrt{\left\{5\left[(P_s/P_t)^{-0.2857} - 1\right]\right\}} \tag{1}$$

In this equation P_s inside the jet is assumed to be the ambient pressure. P_t is the sum of $P_{t\mathrm{gauge}}$ and P_a. The local velocity U at any point in the flowfield is given by the product Ma_∞, where M is the local Mach number obtained by using Eq. (1) and a_∞ is the ambient speed of sound.

Figures 4a–4i show the iso-velocity contours for a plain ellipse with varying aspect ratio for the fully expanded case. As observed by Hussain and Hussain,[7] the plain ellipse grows slowly initially along its major-axis side with a simultaneous faster outward movement of the jet along the minor-axis side. As such, a pumping action[7] starts bringing in ambient fluid toward the jet centerline along the major-axis side and vice versa along the minor-axis side, and hence initiating the axis-switching phenomena typical to noncircular jets.

Hussain and Hussain[7] attribute the comparatively reduced growth of the jet along the major-axis plane to the deformation of noncircular vortical structures. The explanation given is that the extremely thin initial boundary layer in slot jets produces slender vortical structures with very thin cores (thus high vorticity) and with strong azimuthal variations in induced velocity. The self-induced velocity of a curved vortex filament[7] is

$$u = b_n(\kappa/4\pi\rho)\,\ln(\rho/\sigma) \tag{2}$$

This azimuthal variation of induced velocity results in the deformation of the convecting vortex structures and consequent axis switching.

A comparison of the iso-velocity contours at the same axial stations for the plain and square-notched jets very clearly indicates the effect introduced in the flowfield by the presence of notches in each aspect ratio (Figs. 4a–4i and 5a–5i). It is seen from the contour plots that the 2:1 square-notched jet switches axis earlier. Keeping in

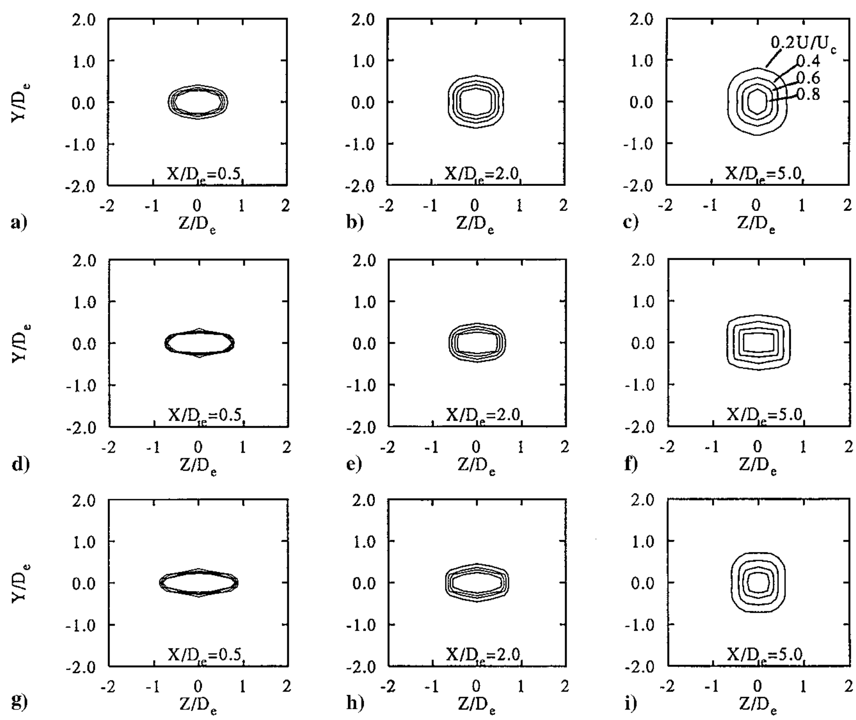


Fig. 4 Iso-velocity contours for plain elliptic-slot jets, M_j = 1.0: a)–c) 2:1, d)–f) 3:1, and g)–i) 4:1.

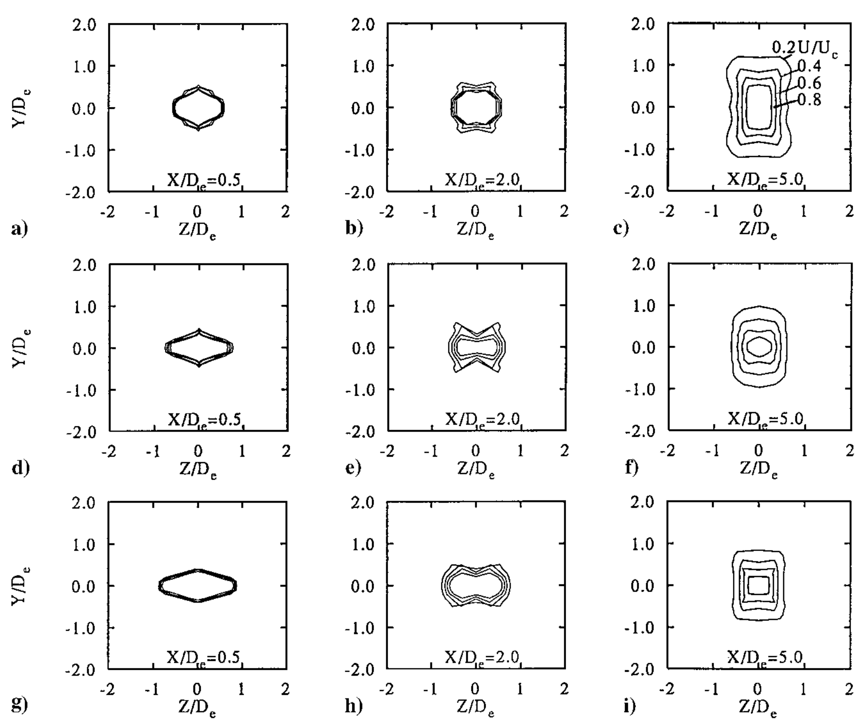


Fig. 5 Iso-velocity contours for square notched elliptic-slot jets, M_j = 1.0: a)–c) 2:1, d)–f) 3:1, and g)–i) 4:1.

mind that a smaller spacing between the velocity contours indicates lesser entrainment into the jet and vice versa, it is observed that, in the notched plane, as the jets grow in the downstream direction the spacing between the contours for the 2:1 case is higher than that for 3:1 and 4:1 jets, $X/D_e = 5.0$. Further, 3:1 and 4:1 jets do not seem to be significantly affected by notch presence.

From the preceding observations insight can be gained regarding the possible underlying process of jet growth as aspect ratio is increased. It is well known that in low-aspect-ratio jets there is a dominance of large-scale activity.[3,8] Because entrainment of mass flow is caused by large-scale activity, a low-aspect-ratio jet shows higher bulk mixing. Now a discontinuity introduced in the 2:1 jet in the form of a sharp-cornered notch is seen to provide low-velocity regions, which on interaction with the mean flow of the jet seem to alter greatly the uniform growth of vortices in that plane. This effect, however, is reduced as the aspect ratio is increased to the 3:1 jet and finally to the 4:1 jet where it is not seen at all (Figs. 4 and 5). This could be caused by the fact that in higher-aspect-ratio jets the deformations take a relatively longer time to evolve, and as such the effect of the notch does not seem to be as strong as in the 2:1 case. In addition to this, in higher aspect-ratio slots the distance between the major-axis ends and minor-axis ends is greater than that for the 2:1

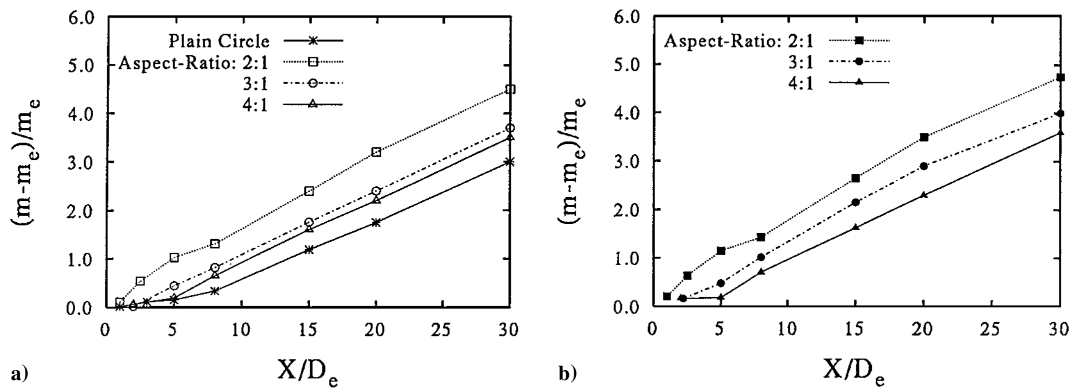


Fig. 6 Entrainment comparison with aspect ratio for a) plain elliptic-slot jets and b) square-notched elliptic-slot jets at M_j = 1.0.

case, as a result of which the disturbance introduced by the notch in 3:1 and 4:1 jets seems unable to influence the complete jet growth. Also in higher aspect-ratio slots the minor-axis ends being closer to the jet centerline, the disturbance introduced is unable to effect the overall jet development significantly (Figs. 5e and 5h). These effects delay the azimuthal deformations typical to relatively higher aspect-ratio jets.[7]

Figures 6a and 6b show a comparison of entrainment for each aspect ratio at full expansion. In these plots m is the local mass flux and m_e the mass flux at the slot exit. For the sake of comparison, entrainment for the plain circle is included, showing the advantage of using noncircular exit geometries for the purpose of enhanced mixing. It can be seen for the 3:1 and 4:1 cases that the azimuthal deformations take longer to evolve (Figs. 4b, 4e, and 4h), and as such these aspect-ratio jets entrain lesser ambient air and hence show relatively lesser jet cross-sectional growth than the 2:1 plain elliptic-slot jet. Further, it has been reported[3,9] that large entrainment is not observed in high-aspect-ratio jets and suggested that the optimum value is between 2:1 and 3:1.

As expected (Fig. 6a), the 2:1 plain elliptic-slot jet shows significantly higher entrainment values relative to the 3:1 and 4:1 plain jets. All of the elliptic cases show higher entrainment than plain circular jets. The decrease in entrainment with an increase in aspect ratio can be attributed to the fact that with increase in aspect ratio the azimuthal deformations take longer to evolve in the streamwise direction, and by the time they become appreciable the vorticity has already diffused.[8,9] The entrained fluid induced by these diffused vortices would be much less,[7] and hence a large mass entrainment was not observed relative to the 2:1 elliptic jet.

Figure 6b shows the plot when a square notch is introduced along the minor-axis sides of each aspect-ratio jet. The trend remains the same, with a 2:1 notched jet showing the maximum value followed by 3:1 and 4:1. Further, each notched jet shows higher entrainment relative to its plain counterpart.

Shock-Cell Length

According to Norum[17] and Wlezien and Kibens,[11] the shape of the nozzle exit geometry greatly influences the nature of downstream development of shocks. Further, introducing sharp corners in the exit geometry causes changes in the jet behavior at the different regions in its circumference and, hence, the shock-cell geometry, which eventually affects the jet noise characteristics.[18]

It is generally agreed, as has been found experimentally by several investigators, that the effective source is located at or downstream of the end of third shock cell.[19–24] The shock-cell length decreases with a distance downstream of nozzle caused by viscous and mixing effects, and its accurate measurement at the downstream location is sometimes very difficult. This is because that at these locations the jet is often very unstable. The shock cells are obscured by turbulence in the jet, and the shocks in the shear layer are too dispersed to form a clear image especially at their extremities.[25] Also, choked jet noise and, hence, the screech frequency are primarily dependent on the length of these shock cells and on the strength of these shocks in the shock-cell system.[17,26] Figure 7 shows the variation of L_{avg}/L_a vs M_j. Here, L_{avg} is the measured average shock-cell length(up to four cell spacings) and L_a the semimajor-axis length of the plain elliptic slot for each aspect ratio. This respective value of L_a is also used for nondimensionalizing the average shock-cell length of the notched ellipse of each aspect ratio and, hence, is referred to as the equivalent semimajor-axis length. For comparison Tam's theory[27] for 2:1, 3:1, and 4:1 elliptic jets is included. A fair amount of agreement between experiment and theory can be seen. However, the curves for the present case lie below the trend followed by Tam's theory.[27] Reduction in average shock-cell length is apparent for notched cases relevant to plain cases in each aspect-ratio range, as seen in Figs. 7a and 7b. This indicates a weaker shock-cell system in notched jets relative to their plain counterparts, which is necessary for overall jet noise reduction.

However, for better comparison Fig. 7c is plotted, which shows the effect of aspect ratio on shock-cell length reduction. For $M_j = 1.15$ the 2:1 plain jet shows a shorter L_{avg}. However, as the Mach number increases, notches begin to significantly alter the shock-cell development process so that L_{avg} for the 2:1 notched jet shows a considerable reduction that reaches a maximum at $M_j = 1.52$. The 3:1 plain jet shows approximately the same L_{avg} value as that of the notched case up to $M_j = 1.32$ after which the 3:1 notched jet starts to show a reduction. However, a 4:1 notched jet shows a considerable reduction in L_{avg} from $M_j = 1.15$ onwards up to the highest value of M_j. The reason for this being that for the 4:1 jet notches are closest to the jet centerline and, therefore, drastically affect the downstream shock formation.

Aeroacoustic Characteristics

Overall Sound Pressure Results

The variations related to azimuthal curvature of exit geometry change the jet behavior at different regions around its circumference and, hence, affect the flow instability characteristics[2,28] along different planes. Further, the variation in shear-layer thickness along the circumference affects the downstream shock development[15] and eventually the jet noise characteristics.[2,15,17,29–31] Because aspect-ratio variation drastically changes the local radius of the curvature of elliptic jets along major- and minor-axis planes, a difference in noise characteristics with aspect ratio in the two planes are expected.

Figures 8a and 8b show the OASPL plots for plain aspect-ratio jets with the microphone placed at $\theta = 150$ deg to the upstream jet axis. In both of the planes, all aspect-ratio jets show approximately the same overall noise levels although the intensity is slightly higher in the major-axis plane relative to that along minor-axis plane. This difference in the noise levels along the two planes is related to the different jet modes predominant in each plane.[32] Schadow et al.[32] shaved that the flapping motion of the jet, which is responsible for higher spread and subsequent faster diffusion of cells, is prevalent along the minor-axis plane for $M_j > 1.15$, while the jet motion along major-axis plane is symmetrical with lower spread. At $\theta = 90$ deg, however, the 2:1 jet is observed (figures not shown)

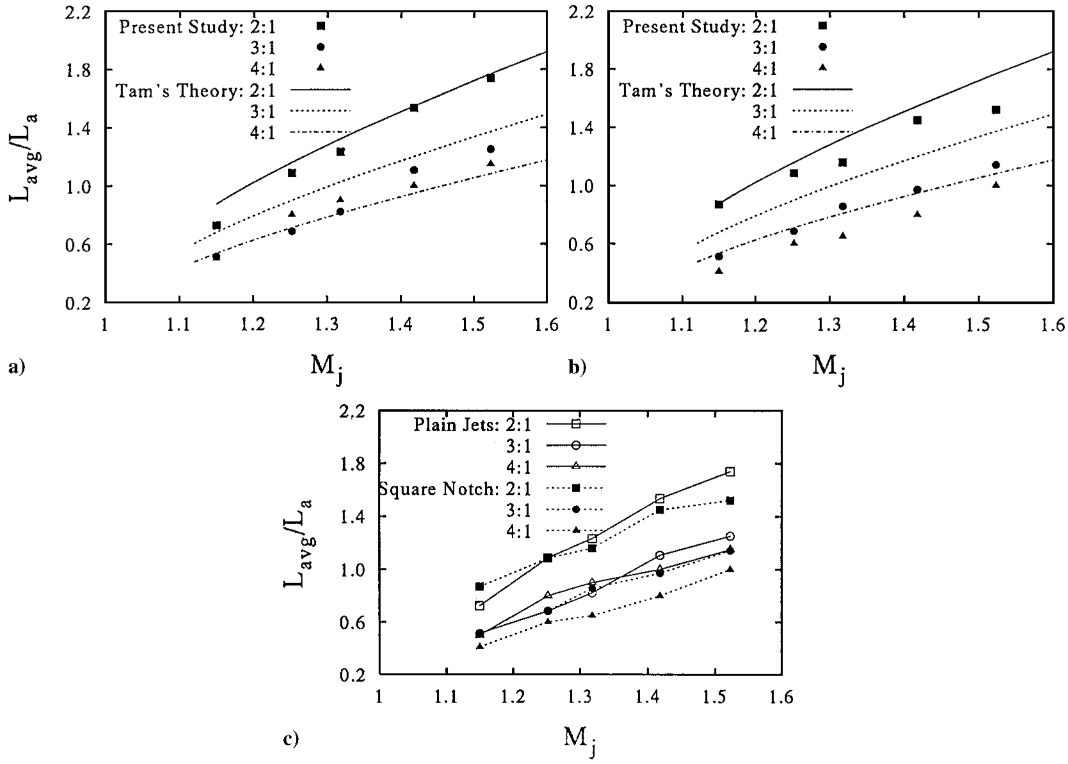


Fig. 7 Comparison of theoretical and experimental results of average shock-cell variation with M_j showing the effect of aspect ratio for a) plain elliptic jets, b) notched elliptic jets, and c) effect of aspect ratio on average shock-cell length variation for plain and notched jets.

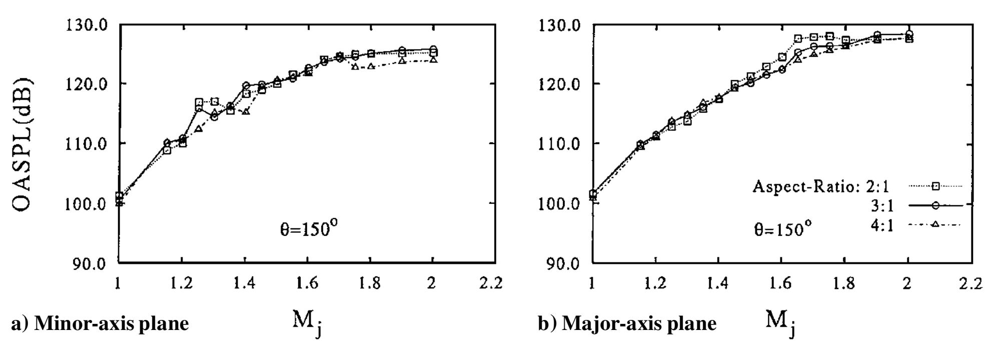


Fig. 8 Far-field OASPL variation with M_j showing the effect of aspect ratio for plain elliptic-slots jets, θ = 150 deg, R/D_e = 50.0 from slot exit.

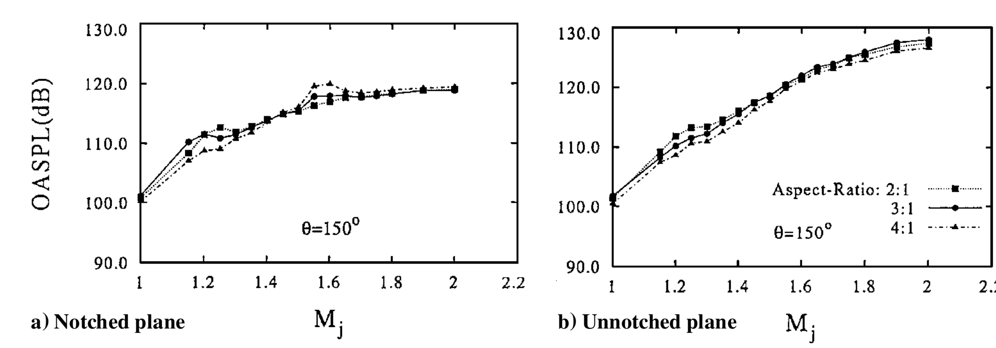


Fig. 9 Far-field OASPL variation with M_j showing the effect of aspect ratio for square-notched elliptic-slots jets, θ = 150 deg, R/D_e = 50.0 from slot exit.

to have higher noise levels relative to 3:1 and 4:1 cases in both the planes. The presence of the notch significantly affects the far-field noise characteristics of each aspect-ratio jet (Figs. 9a and 9b and for both angles).

If a comparison is made of the radiated shock-noise levels along the two planes for plain and notched jets, some interesting results are observed. Along the minor-axis/notched plane, at $M_j = 2.0$, notched jets show as much as 5–7 dB reduction in shock-noise intensity. However, the presence of the notch in the minor-axis plane has only a marginal effect on the overall noise radiated along the major-axis plane showing only a small reduction of 1 dB, relative to plain cases. The difference in shock-noise intensity in the notch jets between the two planes drifts apart by 9 dB at $M_j = 2.0$ relative to a 4-dB difference in plain jets.

The OASPL results suggest that changing the aspect ratio from 2:1 to 4:1 does not significantly alter the far-field overall noise characteristics. The presence of notch in each aspect ratio, however, affects the shock-associated noise characteristics relative to plain jets. Thus, notches seem to alter and weaken the downstream shock development and, hence, the acoustic characteristics significantly.

Azimuthal Directivity

The azimuthal variation of the far-field OASPL for plain and notched elliptic jets at $M_j = 1.5$ is shown in Figs. 10a and 10b with the microphone positioned at $\theta = 90$ deg, $X/D_e = 0.0$, $R/D_e = 25$. For plain jets (Fig. 10a) drastic variation in the noise radiated from the major- and minor-axis planes is discernible with aspect ratio. The 2:1 elliptic jet shows significant reduction in shock-noise levels in the minor-axis plane relative to major-axis plane. However, 3:1 and 4:1 jets show a reversal in the noise trend in the two planes. The 3:1 jet shows a higher shock-noise level in minor-axis plane relative to its major-axis plane. The noise intensity in the minor-axis plane further increases for a 4:1 case, while along the major-axis plane the shock-noise levels for the 4:1 jet falls below that of the 3:1 jet. The 4-dB increase in the radiated noise for the 3:1 jet along the minor-axis plane relative to major plane is observed, whereas this difference in the radiated shock noise in the two planes goes up to 10 dB for the 4:1 jet.

Such a reversal in radiated noise from the two planes of the 3:1 elliptic jet was also observed by Schadow et al.[32] with Mach-disk formation relative to the case with oblique shock interaction (absence of Mach disk). He further observed that, with the presence of a Mach disk, a strong noise source could be located near the Mach disk along minor-axis plane, whereas no source could be located on the major-axis plane. This suggests that the noise source mechanisms are greatly modified with aspect ratio and, hence, in the present study seem to be responsible for the reversal in radiated noise along the two planes as the aspect ratio is increased from small (2:1) to moderate (3:1 and 4:1) values.

Notches help reduce the difference in noise level between the two planes (Fig. 10b). For a 2:1 notched jet the noise levels in the major-axis plane are drastically brought down, by 5 dB, relative to the plain jet. For a 4:1 jet the presence of the notch does not alter the noise levels in the major plane relative to their plain jets, but significantly affects the noise levels along the notch plane. As much as a 7-dB noise reduction is observed for a 4:1 jet and 3.5 dB for a 3:1 jet.

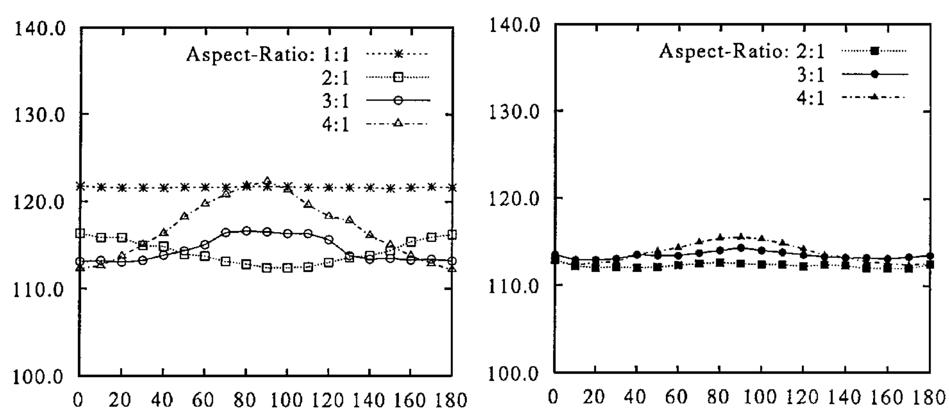
Thus, it is clear from the azimuthal directivity plots that instability characteristics vary significantly along the two planes with varying aspect ratio. In addition, the shock shear-layer interaction along the circumference and, hence, the noise emission characteristics vary with aspect ratio. The notch presence, further, alters the acoustic-source mechanism of these jets. However, for small aspect-ratio jets the presence of the notch significantly affects the noise intensity in both the minor- and major-axis planes, whereas for moderate aspect-ratio jets notch presence affects only the acoustic emission characteristics of the plane in which they are made. This may be caused by the greater distance between the minor and major axis end, which prevents the disturbance introduced in one plane from significantly altering the noise characteristics of other plane.

Radial Directivity in the Aft Quadrant

From the preceding discussion it is clear that the noise radiation mechanisms are greatly altered with aspect ratio. The present section discusses the effect of aspect ratio on angular directivity of radiated noise in the aft quadrant for both plain and notch elliptic-slot jets.

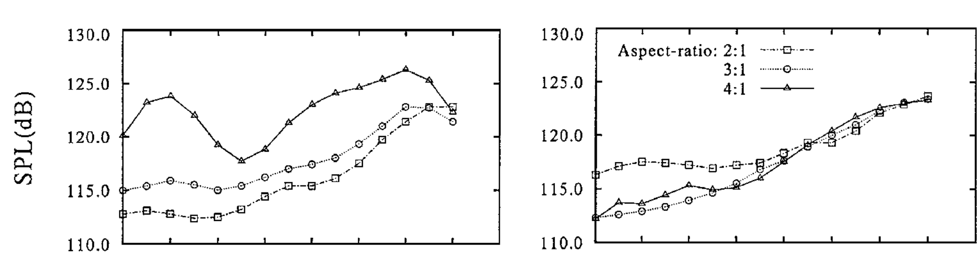
The effect of aspect ratio on the radial directivity of plain elliptic jets at $M_j = 1.5$ in both planes is illustrated in Figs. 11a and 11b. In the minor-axis plane (Fig. 11a) a 2:1 elliptic jet shows minimum noise levels, which increase significantly with the aspect ratio. However, in the major-axis plane a 2:1 jet shows the highest shock noise with 3:1 and 4:1 showing significantly lower noise levels (Fig. 11b), whereas the shock-noise intensity is observed to be the same for each aspect ratio at $\theta > 130$ deg.

Figures 12a and 12b show the radial directivity plots for different aspect-ratio jets with a notch introduction. In the minor-axis plane (Fig. 12a) a 4:1 jet shows the highest shock noise levels followed by 3:1 and 2:1 jets. Relative to their respective plain jets, it is discernible that along the minor-axis/notched plane a 4:1 notched jet shows significant noise reduction in the aft quadrant followed by a 3:1



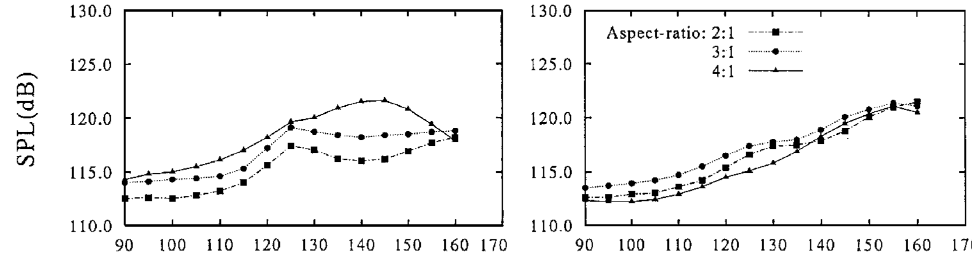
a) Plain jets ϕ b) Notched jets ϕ

Fig. 10 Effect of aspect ratio on the azimuthal directivity of plain and notched elliptic-slot jets at $M_j = 1.5$, $R/D_e = 25$.



a) Minor plane θ b) Major plane θ

Fig. 11 Effect of aspect ratio on the radial directivity of plain elliptic-slot jets, $M_j = 1.5$, $R/D_e = 25$.



a) Minor plane θ b) Major plane θ

Fig. 12 Effect of aspect ratio on the radial directivity of notched elliptic-slot jets, $M_j = 1.5$, $R/D_e = 25$.

case. At $\theta = 90$ deg a 4:1 jet shows about a 6-dB reduction. At $\theta = 160$ deg a 4:1 notch jet shows a 6-dB reduction followed by 3:1 with 3.5 dB and 2:1 with 5 dB. However, in the major-axis plane $\theta = 90$ deg the shock-noise levels do not show significant changes except for the 2:1 jet, which shows a 4-dB reduction. At $\theta = 160$ deg all jets show approximately a 2-dB reduction.

Thus, with the aspect-ratio increase the shock shear-layer interaction process seems to undergo drastic changes along the minor-axis planes, whereas only slight changes occur along the major-axis plane. Further, notch presence effects shock-noise levels both in the major- and minor-axis planes significantly. However, for the 3:1 and 4:1 notched jets a drastic reduction in noise is observed in the notched plane, whereas it is only slightly affected along the major-axis plane. As the distance between the minor- and major-axis ends increases with aspect ratio, any disturbance introduced because of the presence of the notch along the minor-axis plane is unable to significantly alter the noise characteristics of a major plane, although this is not so for small aspect-ratio elliptic jets.

Conclusions

Use of notches as a passive control for achieving mixing enhancement and noise reduction in small-to-moderate aspect-ratio slot jets has been demonstrated. The entrainment is observed to decrease with an increase in aspect ratio for plain elliptic-slot jets, which may be because as the aspect ratio increases the azimuthal deformations take longer to evolve in the streamwise direction and by the time they become appreciable the vorticity has already diffused.[8,9] The entrained fluid induced by these diffused vortices would be much less, and hence, a large mass entrainment was not observed[7] relative to a 2:1 elliptic jet. Notches affect the jet development of a 2:1 jet significantly, whereas they do not do so for 3:1 and 4:1 cases.

Notches significantly modify the shock development process and, hence, the noise characteristics in each case. At $\theta = 150$ deg all aspect-ratio plain jets show approximately the same overall jet noise levels although the intensity is higher along the major-axis plane by 2–3 dB relative to their minor-axis planes. The notches reduce the jet noise radiated along the minor-axis plane by approximately 6–7 dB.

Azimuthal directivity of noise is strongly influenced by slot aspect ratio. The 2:1 elliptic jet shows a significant reduction in shock-noise levels in the minor-axis plane relative to the major-axis plane. However, 3:1 and 4:1 jets show a reversal in the noise trend in the two planes. The 3:1 jet shows a higher shock-noise level in the minor-axis plane relative to its major-axis plane. The noise intensity in the minor-axis plane further increases for the 4:1 case, whereas along the major-axis plane the shock-noise levels for the 4:1 jet falls below that for the 3:1 jet. This reversal in noise radiation with aspect ratio can be caused by the change in initial shock-structure development. The presence of the notch alters the azimuthal emission characteristics of these jets. For small aspect-ratio jets the presence of the notch significantly affects the noise intensity in both the planes, whereas for moderate aspect-ratio jets the presence of the notch affects the acoustic emission characteristics only in the plane in which they are made. This may be caused by the greater distance between the minor and major end, which prevents the disturbance introduced in one plane to significantly alter the noise characteristics of the other plane. For plain elliptic jets the noise is minimum for aspect ratio 2:1 and increases with an increase of aspect ratio.

The intensity of shock-associated noise is strongly dependent on the aspect ratio. Further, aspect ratio seems to be a parameter strongly governing the initial conditions, azimuthal deformations, shear-layer development, downstream shock development, and, hence, alters the noise-producing mechanism.

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