

COVER PAGE

Document downloaded by @DAEL

Thu Nov 26 20:27:09 2026
For personal use

When automatic English translation is provided, only the original document is authentic.
The EAA cannot be held responsible of any translation error

Bibliographical reference

Turbulent Mixing Noise from Underexpanded Non-circular Slot Jets, T. J. S. Jothi and K. Srinivasan, Acta Acustica **vol. 99** (Number 4), 2013, pp. 514-523

DOI
https://doi.org/10.3813/AAA.918631

ACTA ACUSTICA UNITED WITH ACUSTICA
Vol. 99 (2013) 514 – 523
DOI 10.3813/AAA.918631

Turbulent Mixing Noise from Underexpanded Non-circular Slot Jets

T. J. S. Jothi[1)], K. Srinivasan[2)]
[1)] Department of Mechanical Engineering, National Institute of Technology Calicut, 673601 India
[2)] Department of Mechanical Engineering, Indian Institute of Technology Madras, Chennai 600036 India.
ksri@iitm.ac.in

Summary
This paper experimentally investigates the far-field turbulent mixing noise from underexpanded triangular and square jets. The investigations are focused on the noise from vertices and edges of these non-circular jets, and in some cases the results are compared with those of circular jets. The jet pressure ratio is varied in the range of 2 to 6, and the acoustic measurements are carried out along the jet axial plane from 37° to 135° (measured from jet exit axis). The experimental results indicate that turbulent mixing noise levels vary linearly with emission angle, notably with two different gradient values along upstream and downstream. These results are ascribed to the two different turbulent scales, viz.; large scales and fine scales, in the jet flow. The turbulent mixing noise from screeching circular jets are found to be higher compared to triangular and square jets. However at higher pressure ratios, as the screech ceases, the turbulent mixing noise from all the jets (circular and other non-circular jets) becomes similar.

PACS no. 43.28.-g

1. Introduction

Noise emissions from air breathing engines are becoming a worrisome problem to design engineers and fluid mechanics researchers, since stern norms are being laid on reduction of such emissions. Despite the active research in this field, reductions in noise levels are not substantial. Noise from jet flows is a major source of emission in comparison with other sources. Further, jet flows offer excellent opportunities to understand the physics of turbulence, mixing mechanisms, compressibility effects and noise emission phenomena. Lighthill [1] extracted the noise components analytically from the modified Navier-Stokes equation. There on, many researchers started working on noise related problems in fluid mechanics, thus expanding the new field of research. Jet noise emissions may be broadly classified as turbulent mixing noise, shock associated noise and Mach wave radiation. Turbulent mixing noise is due to the interactions of turbulent structures in the jet flow. Shock associated noise is due to the interactions of the convecting flow structures with shocks in the jet flow field. A component of shock associated jet noise namely screech can have a drastic effect on nozzle/aircraft structures if its frequency matches with the natural frequency of structural components [2].

In this paper, the emphasis is laid on the turbulent mixing jet noise content from non-circular nozzles, restricted to square and triangular nozzles. Non-circular jets can enhance flow characteristics desirable for practical applications, such as mixing required for combustion [3]. In the recent past, non- circular nozzles are also considered as effective passive mechanisms for noise reduction. Hence the turbulent mixing noise contents from such non-circular jets are interesting to investigate and understand how the nozzle topology alters the jet flow and noise. The following section discusses the past literature on flow and noise from non-circular jets.

Received 1 June 2012,
accepted 21 April 2013.

2. Background

2.1. Flow studies from non-circular jets

Research on flow characteristics from non-circulars jets have been carried out in plenty. It is observed from the literature that non-circular jets could demonstrate excellent performance characteristics such as mixing enhancement compared to the circular ones. In addition, the presence of corners and edges in non-circular nozzles tend to emanate varied vortex flow structures that helps in large and small scale mixing [4]. In general, the spanwise vortices (large vortices) generated from edges of nozzle are responsible for relatively lower frequencies, and the streamwise vortices (small vortices) generated from the corners/vertex are responsible for higher frequency emissions [5]. It can be observed that the number of corners/vertices present in the nozzle affects the jet flow anatomy drastically. Due to the reason mentioned above, the square jets exhibit faster

© S. Hirzel Verlag · EAA

mixing rate compared to the triangular ones. Interesting features of non-circular nozzles such as "*axis switching*" are discussed by Koshigoe *et al.* [6]. Numerous other papers discuss the flow and mixing properties of non-circular jets [7, 8, 9, 10, 11], including a review article by Gutmark and Grinstein [3]. The following section summarizes the literature on noise emission from non-circular jets.

2.2. Screech studies in non-circular jets

The present paper investigates the turbulent mixing noise from two specific non-circular jets, namely, square and triangular jets. In this regard, this section briefly reviews the existing literature on noise emission from non-circulars jets. Among the noise sources, turbulent mixing noise happens to occur in both subsonic as well as in supersonic flows. However the shock associated noise is imputed to the presence of shock structures in the jet flow. The shock associated noise can be further classified into screech tones and broadband shock associated noise (BSAN). Screech is due to the lock-on mechanism of the downstream propagating hydrodynamic wave and upstream propagating acoustic wave. This phenomenon tends to generate a high frequency, high amplitude tone. The broadband shock associated noise component is believed to be due to the scattering of coherent structures formed in the shear layer while interacting with the shock cell structures. A brief account of screech studies on non-circular jets follows.

Umeda and Ishii [12] showed that triangular nozzle produces screech tones for pressure ratios (R) ranging from 2 to 6, while the same was weakly observed in case of orifice jets [13]. Brassard *et al.* [14] investigated the mode-switching mechanism happening in underexpanded square jets. They noted that the screech modes shifted from toroidal mode to helical mode at fully expanded Mach number of 1.48. Raman and Rice [15] experimentally demonstrated the hydrodynamic modal evolution due to screech in an imperfectly expanded jet from convergent-divergent rectangular nozzle. Further interesting studies on rectangular bevelled nozzles were performed by Tam *et al.* [16] and Raman [17]. The noise generation from screeching phenomenon in non-circular jets has been abundantly discussed in the literature, including a detailed review article on screech by Raman [18]. Besides polygonal shapes, acoustic studies have also been carried out using elliptic non-circular nozzles [19, 20, 21].

2.3. Turbulent mixing noise studies in non-circular jets

It was Lighthill [1] who initially proposed that the acoustic power from subsonic jet flows is directly proportional to eighth power of the velocity. This noise indeed referred to the turbulent mixing noise from subsonic jet flows. Presently it is well understood that the turbulent mixing noise is due to the large scale and fine scales turbulent structures in jet flows. Unlike screech tones that are dominant in the upstream direction, turbulent mixing noise is dominant in the downstream side. It is observed that the turbulent mixing noise is directive at around 45–60 degrees measured from the jet flow direction (see the review article by Tam [22]), while being flat in the upstream angles. Turbulent mixing noise was extensively studied by Tanna [23] for various range of jet temperature and pressure ratios for fully expanded jets, and compared with the free convecting quadrupole theory. Seiner *et al.* [24] reported that turbulent mixing noise occurs in a broadband band and Strouhal number of the band peak varies from 0.1 to 0.25 depending upon the jet conditions like temperature and Mach number. Similar observation is demonstrated from an acoustic spectrum obtained from the present study (see Figure 1). Figure 1 shows a noise spectrum from a circular orifice jet at Mach number of 1.55 (pressure ratio, $R = 4$) and emission angle of 45°. The highlighted region in Figure 1 in the spectrum indicates the dominant region of turbulent mixing noise. The peak Strouhal number of the turbulent mixing noise band is ∼0.15 which is consistent with the values reported by Seiner *et al.* [24]. Moreover depending upon the type of nozzle, the peak and maximum Strouhal number tend to vary. Yu and Dosanjh [25] investigated noise from supersonic cold jets for two cases namely the correctly expanded jets where there are no shocks cells, and for underexpanded jets. They have shown that the noise sources for shock free jets are in between the laminar core tip and supersonic core tip. Most of the theoretical/analytical work on turbulent mixing noise prediction was carried by Tam and coworkers [26, 27, 28, 29, 30, 31]. For instance, the stochastic mathematical model to predict the turbulent mixing noise from jets was proposed by Tam and Chen [26]. They carried out this study by extending the theory proposed by Tam and Burton [27] which described the noise emissions from supersonically travelling instability waves. Tam *et al.* [28] investigated the turbulent mixing noise from supersonic jets and identified two components in them. One noise component is being generated due to the presence of large turbulent structures in the jet flow, and other from the fine scale turbulence. They also showed that the same follows for subsonic jet as well. Tam and Auriault [29] showed that the turbulent mixing noise

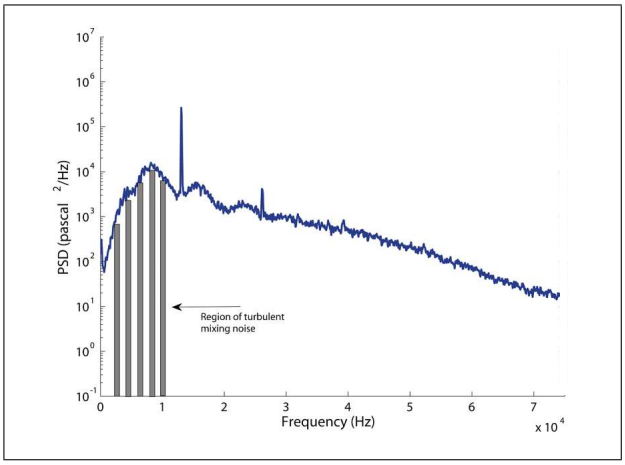


Figure 1. Spectrum indicating the region of turbulent mixing noise. This spectrum is obtained for a circular jet at Mach of 1.55 at emission angle of 45°.

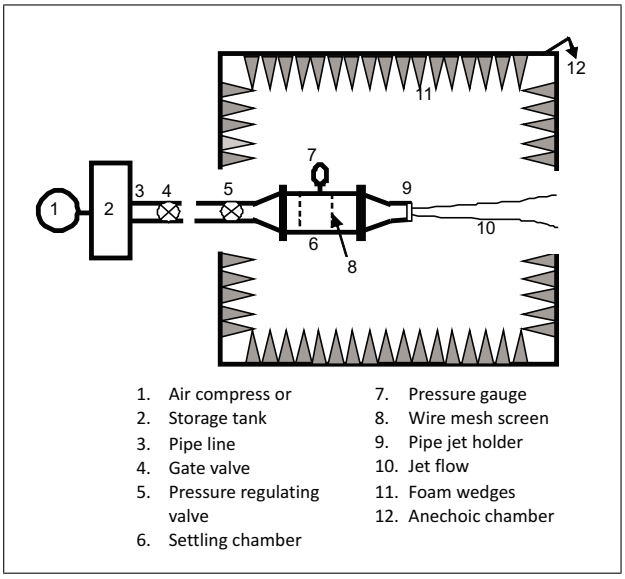


Figure 2. Schematic of the experimental setup.

emits from large scale as well as fine scale turbulent structures. The noise from large scale structures is found to be directive towards downstream, similar to those of Mach wave radiation. The fine scale turbulence noise seems to dominate in the sideline and upstream angles. They also proposed a semi-empirical formulation for predicting the spectra of turbulent mixing noise. Tam and Pastouchenko [30] also proposed a methodology for spectra prediction for noise from non-axisymmetric jets by extending their previous theory. Recently Tam *et al.* [31] investigated the sources of jet noise by various experimental methodologies, and proved the presence of large scale and fine scale turbulent mixing noise sources in jet flows. Viswanathan [32] performed independent studies to confirm the presence of two components of turbulent mixing noise.

3. Objectives and Motivation

The surveyed literature indicates that much of the studies on jets are devoted to understand the flow characteristics, screech and other noise sources mostly from circular jets. Thus, studies on turbulent mixing noise from non-circular jets are scarce in archival literature. Thus the lacuna in the literature on turbulent mixing noise component of non-circular jets motivated the present study on turbulent mixing noise emission from underexpanded triangular and square slot/orifice jets. The sound pressure levels and spectra are compared in the frequency range of 630 Hz to 10 kHz for various jets where the turbulent mixing noise is dominant. The minimum frequency is set based on the cut-off frequency of the anechoic chamber (discussed in section 4.2) and maximum frequency is considered as the limiting value for turbulent mixing noise beyond which screech tones start dominating. The above mentioned frequency range corresponds to the maximum Strouhal number range of 0.02 to 0.29 for jets having sonic velocity. Here the Strouhal number is defined as fD/U_j where f is the frequency of the turbulent mixing noise, D is the characteristics dimension which is considered as the nozzle diameter, and U_j is the fully expanded jet velocity. Thus at higher underexpansion pressure ratios, the fully expanded jet velocity takes higher value and thus the Strouhal number decreases. Further, the turbulent mixing noise along the vertices and edges of square and triangular jets are compared. The pressure ratio of the jet exiting from nozzles is varied in the underexpansion range of $2 \leq R \leq 6$ corresponding to fully expanded jet Mach numbers of $1.04 \leq M_j \leq 1.82$. The pressure ratio R is defined as the ratio of the stagnation pressure P_0 to the atmospheric pressure P_{amb}. The stagnation pressure is obtained from the pressure gauge connected to the settling chamber. Using the following isentropic relation fully expanded jet Mach number M_j can be estimated from the pressure ratio.

$$\frac{P_0}{P_{\text{amb}}} = \left(1 + \frac{\gamma-1}{2} M_j^2\right)^{\gamma/(\gamma-1)}$$

$$\Rightarrow \quad M_j = \sqrt{\frac{2}{\gamma-1}\left[\left(\frac{P_0}{P_{\text{amb}}}\right)^{(\gamma-1)/\gamma} - 1\right]}. \qquad (1)$$

In present study, jets evolving from orifices are considered rather than conventional convergent-divergent nozzles due to ease in fabrication of the former. Hence the present study can add value to the understanding of turbulent mixing noise from non-circular jets.

4. Experimental Procedure

4.1. Test facility

The cold air free jet test facility is supplied with compressed air from storage tanks having the total capacity of 20 m^3. The compressor pressurizes the air up to 8 bars absolute. The compressed air is brought to the settling chamber using 4-inch plumbing. The schematic of the test facility is shown in Figure 2. The air pressure in the settling chamber is regulated using a needle valve. The settling chamber has the dimensions of 380 mm internal diameter, and around 700 mm in length. The internal flow disturbances are eliminated by fine meshes provided inside the settling chamber. Since the present studies are carried out in the range of higher pressure ratios/Mach number, the initial turbulence levels are expected to be lower. Further, the structure-borne acoustic disturbances are reduced by lining the inner wall of the settling chamber with acoustic foam. The settling chamber is smoothly converged to 43.5 mm diameter where the required orifices are mounted using a disk holder which will be discussed in forthcoming sections. To minimize the acoustic reflections within the anechoic chamber, all exposed metallic surfaces are glued with acoustic foam. A brief discussion on the anechoic chamber is discussed in next section. The jet flow is exposed to the ambient where room temperature prevailed. Hence the jet temperature is considered to be at the room temperature (300 K).

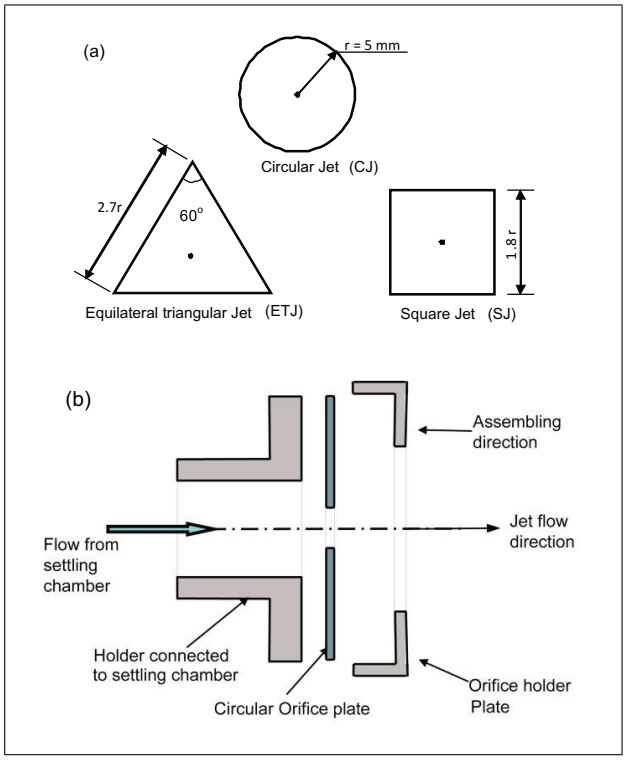


Figure 3. (a) Non-circular geometries considered for the study (b) schematic diagram of the orifice holder.

4.2. Anechoic chamber

The free air jet facility and other necessary equipments are enclosed in a semi-anechoic chamber of dimension 2.5 m × 2 m × 2 m (wedge tip-to-tip) in order to simulate a free-field environment. The schematic diagram showing the chamber with anechoic wedges at the interior is shown in Figure 2. Square pyramidal wedges are adhered to the walls of the chamber except the floor which is lined with carpet, and hence the chamber is semi-anechoic. The wedges are made of polyurethane foam material. The chamber is calibrated by verifying inverse square law along various linear paths inside the chamber. It is found that below the frequency value of 630 Hz the chamber is not anechoic, and thus taken as the cut-off frequency of the anechoic chamber. Thus this cut off frequency value is used as the minimum value for the estimation of turbulent mixing noise. The anechoic chamber has two sufficiently large inlet and outlet passages to allow free entrainment, and to avoid any recirculation zones inside the chamber.

4.3. Experimental models

The schematic of the square, triangular and circular nozzle slots are shown in Figure 3a. In the present work, jets exiting from slots are used instead of conventional nozzles. The usage of slots eliminates the azimuthally varying boundary layer effects [20] due to the negligible shear layer thickness in slots. Further, "expeditious manufacturing and ease of installation may necessitate the use of slots in preference to nozzles with contoured upstream shaping" as quoted by Quinn and Marsters [33] enables the researchers to use orifices rather than the conventional nozzles. The nozzle slots are fabricated using a mild steel plate of 73 mm diameter and 2 mm thickness. The required circular and non-circular shapes are cut-out at the center of this disk using Electro Discharge Machining (EDM)/wire cutting process. The non-circular geometries fabricated are equilateral triangular jet (ETJ), square jet (SJ), as shown in Figure 3a. All non-circular geometries are designed for a constant exit area of 78.5 mm^2, equivalent to the area of a circle of diameter 10 mm. Thus, the equivalent diameter of the square and triangular nozzles is 10 mm. The equivalent diameter (De) is a useful parameter introduced by Hussain and Husain [20] for elliptic jets, defined as $D_e = \sqrt{4 \times \text{area}/\pi}$. The slotted disks are mounted on a disk-holder as shown in Figure 3b. The periphery of the orifice plate is beaded with a thin rubber lining to ensure proper grip and to prevent air leakage. The disk holder is in turn, connected to the settling chamber.

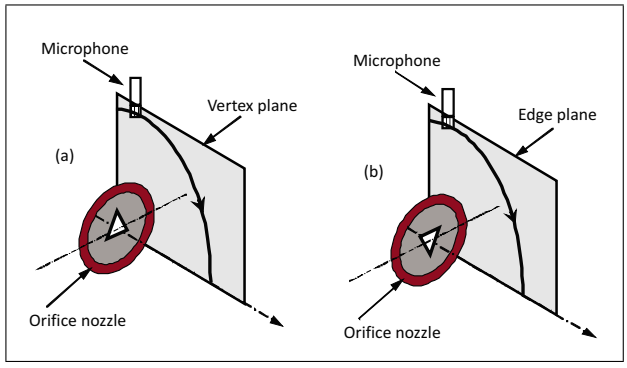


Figure 4. Measurement planes in non-circular jets along the (a) vertex and (b) edge.

4.4. Data acquisition

A quarter inch pre-polarized condenser microphones are used for acoustic measurements (PCB model no. 377A01, sensitivity of 4 mV/Pa at 250 Hz). The signals are low-pass filtered at 70 kHz using Krohn-Hite analog filter (model no. 3364) for anti-aliasing. The data are acquired at a sampling rate of 150 kHz. The automated angular traversing system is used for directivity studies. The distance between the center of the jet exit and the microphone is constant ($40D_e$). The microphone is directed in the range $37° \leq \phi \leq 135°$, along the edge and vertex side/plane of non-circular jets. The measurements made along vertices of non-circular jet are termed as vertex plane and when measured along edge is termed as an edge plane. The measurement planes along the vertex and edge side of non-circular jets are indicated in Figure 4. Further detailed descriptions of these facilities and measurement planes are discussed in Jothi and Srinivasan [13]. In blow down tests, the microphone is placed at $40D_e$ at an angle of 135°, and the stagnation pressure data is obtained continuously using a piezo-resistive pressure transducer (Endevco model no. 8510C-100) mounted inside the settling chamber.

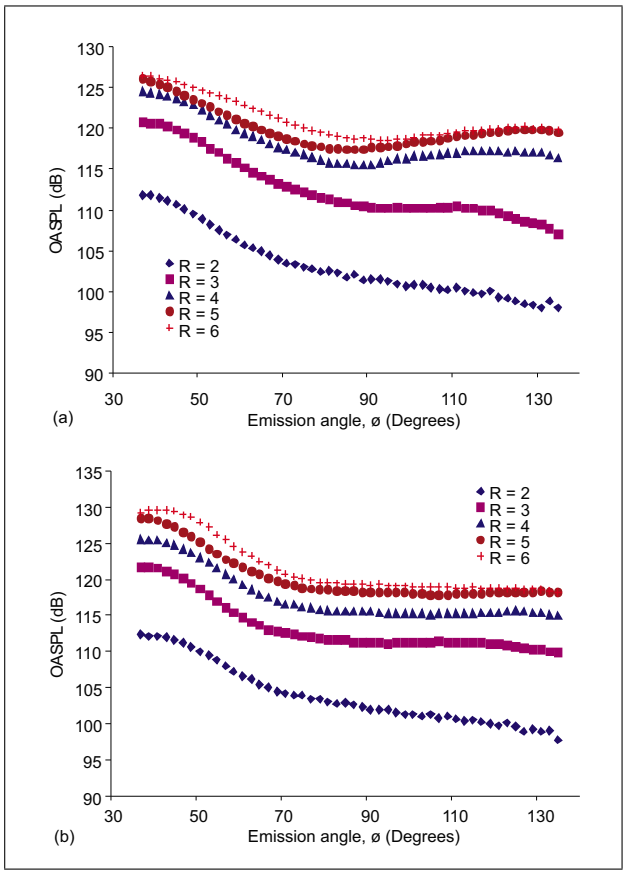


Figure 5. OASPL variations with emission angle along (a) edge and (b) vertex planes of triangular jet.

4.5. Uncertainty estimates

The equivalent diameters of the orifice nozzles vary are within the range of 10 ± 0.5 mm. The stagnation pressure in the settling chamber is maintained at an accuracy of $\pm 2\%$ of full scale. The repeatability tests showed that the frequencies and noise levels are repeatable within ± 73 Hz and ± 1 dB, respectively. The error in the microphone positioning is ± 1 mm. The piezo-resistive pressure transducer used for blow down studies has an uncertainty of $\pm 0.2\%$ of full scale. The temperature inside the anechoic room has a maximum variation of ± 1 °C.

5. Results and Discussion

In this section, initially the overall sound pressure levels (OASPL) of triangular and square jets are analyzed along the edge and vertex planes of non-circular orifices. This is followed by the turbulent mixing noise comparison of square and triangular jets with circular jet followed by the spectral and probability distribution studies.

5.1. OASPL analysis

OASPL variations with emission angles at various pressure ratios along the edge and vertex planes of triangular jet are depicted in Figure 5. OASPL is seen to be increasing gradually with pressure ratio along both the planes.

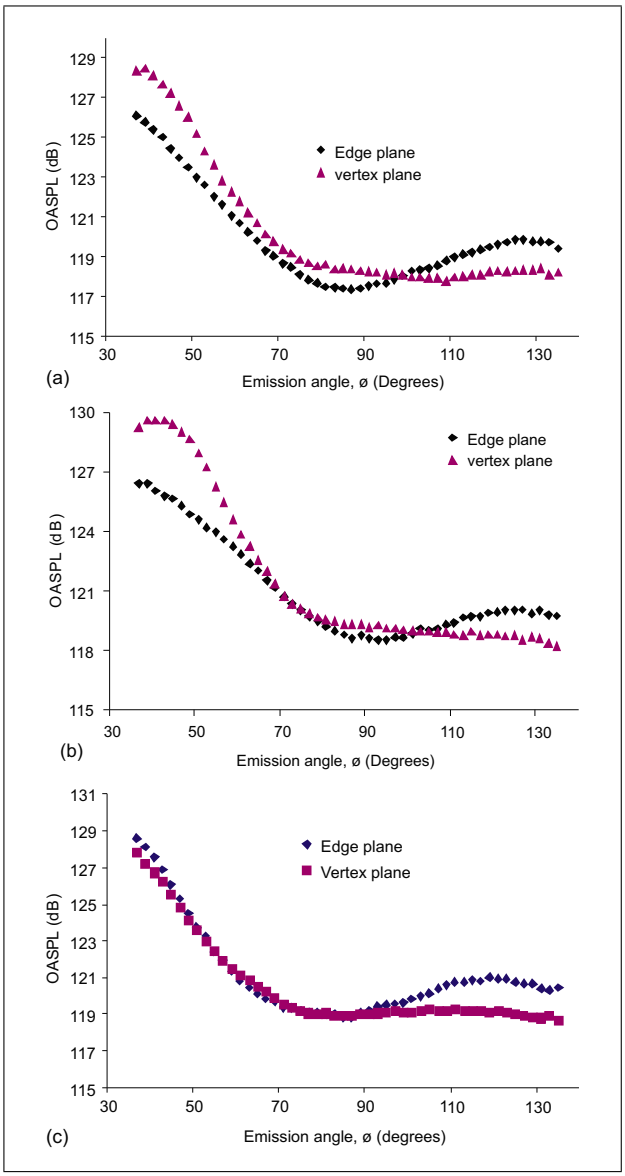


Figure 6. OASPL comparison along the edge and vertex planes of triangular jet at (a) $R = 5$ and (b) $R = 6$ and (c) square jet at $R = 5$.

The OASPL rise is predominant at lower pressure ratios, while at higher pressure ratios of $R = 5$ and 6, OASPL values almost merge together (at $\phi = 135°$ and 37°). This indicates the fact that momentum addition beyond a particular pressure ratio to the jet flows does not effectively increase the intensity of the acoustic sources. Along the edge planes of triangular jets, the OASPL is seen to increase in the upstream ($\phi > 90°$), while it is almost constant along the vertex planes (Figure 5). This is more clearly showed in Figure 6, which makes the OASPL comparison along the edge and vertex planes of triangular and square jets at pressure ratios of $R = 5$ and 6. This comparison distinctly brings out the nature of noise emission along different planes of non-circular jets. In both the planes, the noise directivity is in downstream. However at downstream stations, the noise from vertex planes is higher by around 3 dB than along the edge plane. This is attributed to

turbulent mixing noise promoted by streamwise vortices generated at the vertices that propagate along the vertex plane. This effect is observed at almost at all the higher pressure ratios. In case of square jet, the OASPL values in the downstream along the vertex and edge planes are similar. The difference in noise emission is not much marked at normal direction to jet flow (around 90°). At upstream stations, noise emission is marginally higher for edge planes compared to vertex planes (Figure 6). The reason for this behavior is attributed to the upstream directive shock associated noise leading to such effect. Edge plane introduces spanwise vortices, which on interaction with shock cells generates acoustic waves having upstream directivity [13]. Further, blowdown tests are carried out to investigate the value of pressure ratio at which the OASPL starts dominating among the two planes. Acoustic measurements are taken along both the planes for the entire range of pressure ratios. For these tests, the microphones are placed at a distance of 35 mm from the vertex and edge side of non-circular geometries at an emission angle of 90°. The plots comparing the OASPL along the vertex and edge planes are shown in Figure 7 for triangular and square jets. In case of lower pressure ratios ($M_j < 1.3$), the noise emissions are identical along both planes for triangular jet (Figure 7a). This signifies the fact that at lower pressure ratios the interactions between coherent structures (generated along edge planes) and shocks are weak, thus leading to lower noise levels. Above the jet Mach number of 1.3, the noise along edge plane starts dominating since the above mentioned interaction becomes stronger. With further increase in Mach number the OASPL along the edge planes starts decreasing due dispersion of shock structures at higher underexpansion levels. This is similar to cessation of screech, wherein large jet width terminates the feedback loop [34]. In this case, the interaction of large scale vortices with the shock cells is interrupted by the widely expanded jet. The difference is not much marked in case of square jets where the noise levels from both the planes are almost similar (Figure 7b). The reason for this behavior is the proximity of streamwise vortices with spanwise vortices, mutually leveling out their effects.

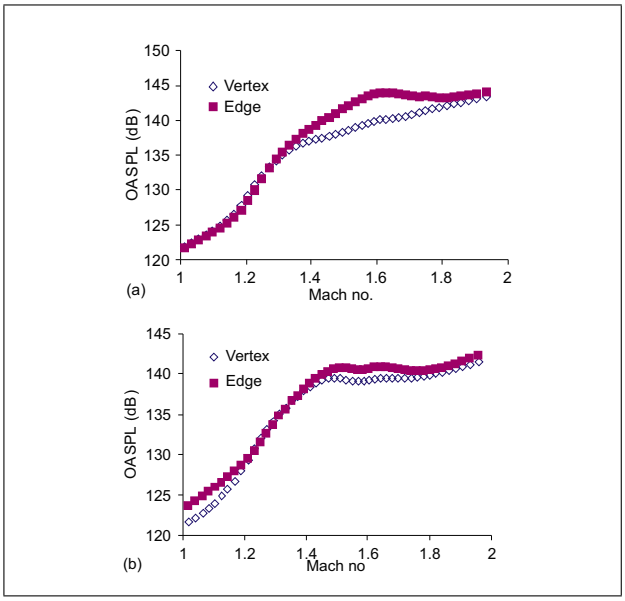


Figure 7. OASPL comparison along the edge and vertex planes of (a) triangular (b) and square jets.

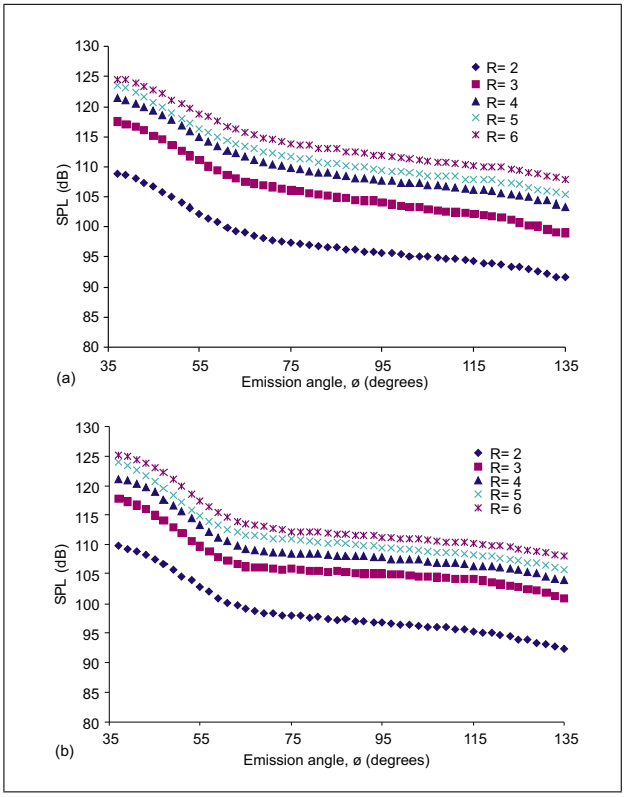


Figure 8. Turbulent mixing SPL variation with emission angle along the (a) edge and (b) vertex planes of triangular jet at various pressure ratios.

5.2. Turbulent mixing noise in non-circular jets

In present study, the sound pressure levels of turbulent mixing noise is calculated by integrating the spectrum amplitudes under the frequency range of 630 Hz to 10 kHz where this noise is dominant (see Figure 1). The variation of turbulent mixing SPL is shown in Figure 8 along the edge and vertex planes of triangular jet at various pressure ratios. The trend is observed to be almost similar along both the planes. In case of jet at nearly supersonic conditions of $R = 2$, the maximum noise level is around 110 dB. Soon after reaching the supersonic pressure condition ($R = 3$), the noise levels shows a sudden increase (around 117 dB). This is inferred to the shocks in the supersonic jets rendering to such effect which is observed in all cases of non-circular jets. It is also interesting to note that, gradual momentum addition to non-circular jets shows a smooth increasing trend in turbulent mixing noise levels.

The variation of turbulent mixing SPL with emission angle is observed to be linear. This is demonstrated in detail by splitting the noise variation shown in Figure 8 as two different noise regimes in Figure 9. Figure 9a shows

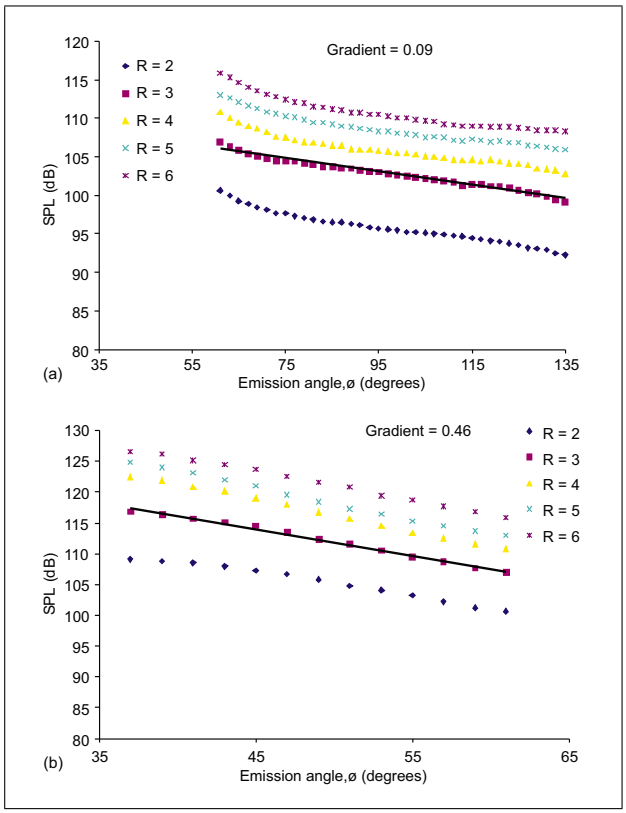


Figure 9. Turbulent mixing SPL variation with emission angles (a) $60° \leq \phi \leq 135°$, and (b) $37° \leq \phi \leq 60°$ along the edge plane of square jet at various pressure ratios.

the turbulent mixing SPL variation with emission angles in the range of $60° \leq \phi \leq 135°$ (upstream), and Figure 9b shows for $37° \leq \phi \leq 60°$ (downstream). Based on the plots in Figure 9, it is inferred that the noise emissions from turbulent structures can be physically divided in two regimes, and they independently show a linear variation with emission angles. In these two ranges of emission angles, although their turbulent noise levels are linear, their slope/gradient values are observed to be different, namely 0.46 and 0.09 for downstream and upstream respectively (Figure 9). Further interpretation shows that the turbulent mixing noise gradient at downstream is higher by around 5 times than that at upstream. The reason for the difference in gradient can be understood from the work of Tam and coworkers [26, 28, 31]. It is understood that along the downstream, the noise is dominant due to the large scale coherent structures moving at higher speeds thus emitting Mach wave radiation. While in upstream, the turbulent mixing noise levels are almost uniform thus indicating it as background noise generated by fine scale structures. Figure 10 depicts the pictorial illustration of the emission angles where turbulent mixing noise due to large scale and small scales are dominant.

5.3. Spectral studies

Figure 11 shows the spectral variation along vertex and edge planes of triangular jet at upstream and downstream emission angles of 135° (Figure 11a) and 55° (Figure 11b)

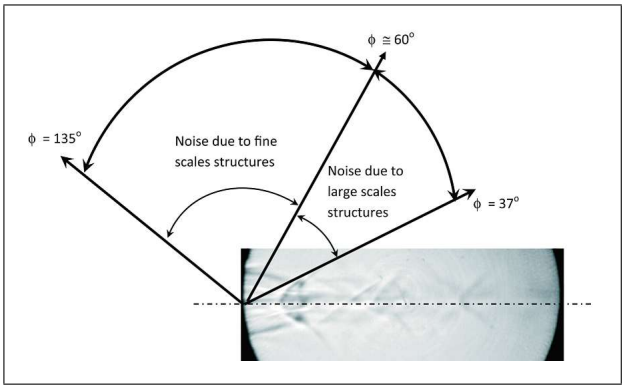


Figure 10. Regimes showing the turbulent mixing noise from various turbulent scales.

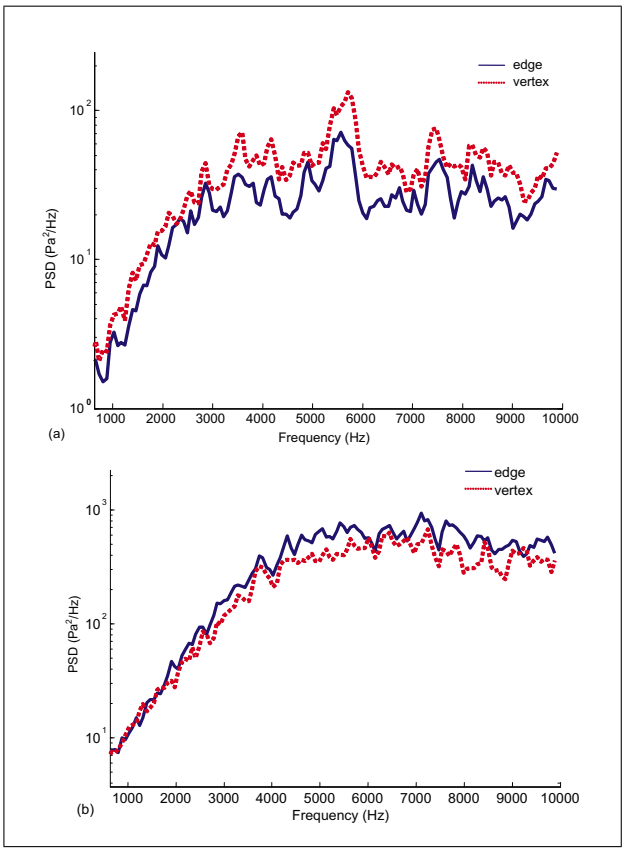


Figure 11. Spectral comparison of turbulent mixing noise along edge and vertex planes of triangular jet for $R = 3$ at emission angles of (a) 135° and (b) 55°.

respectively, at pressure ratio $R = 3$. The spectra are plotted in the range of frequencies where the turbulent mixing noise is dominant (630 Hz to 10 kHz). It can be observed from the spectra that the turbulent mixing noise amplitude in case of downstream angles is higher compared to that of upstream. As discussed in the earlier sections, the noise levels in the upstream are due to the fine scale turbulence, similar to background noise [22]. Hence such noise either from the vertex side or the edge side of the non-circular nozzle, their amplitude levels are expected to be same. For jets with higher pressure ratios it is observed that the

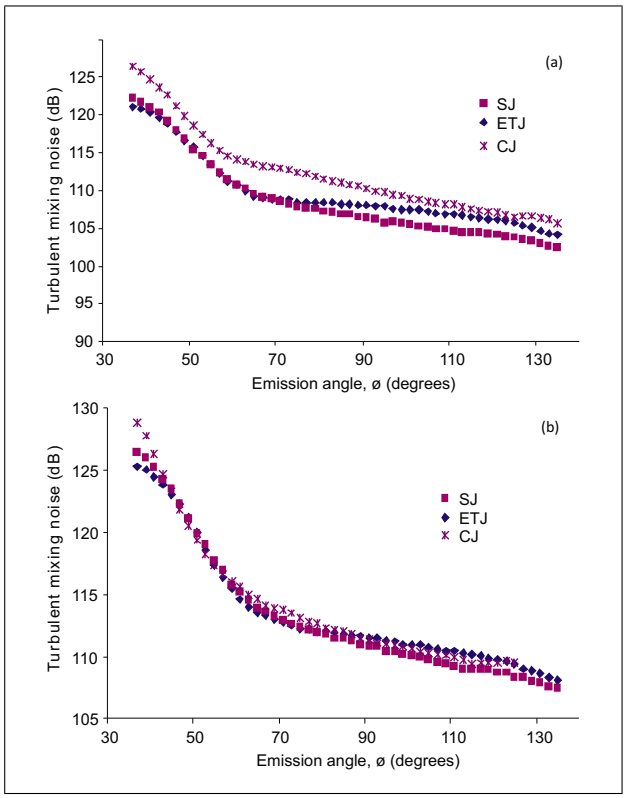


Figure 12. Comparison of turbulent mixing noise of non-circular jets with those of circular jet at (a) $R = 4$ and (b) $R = 6$.

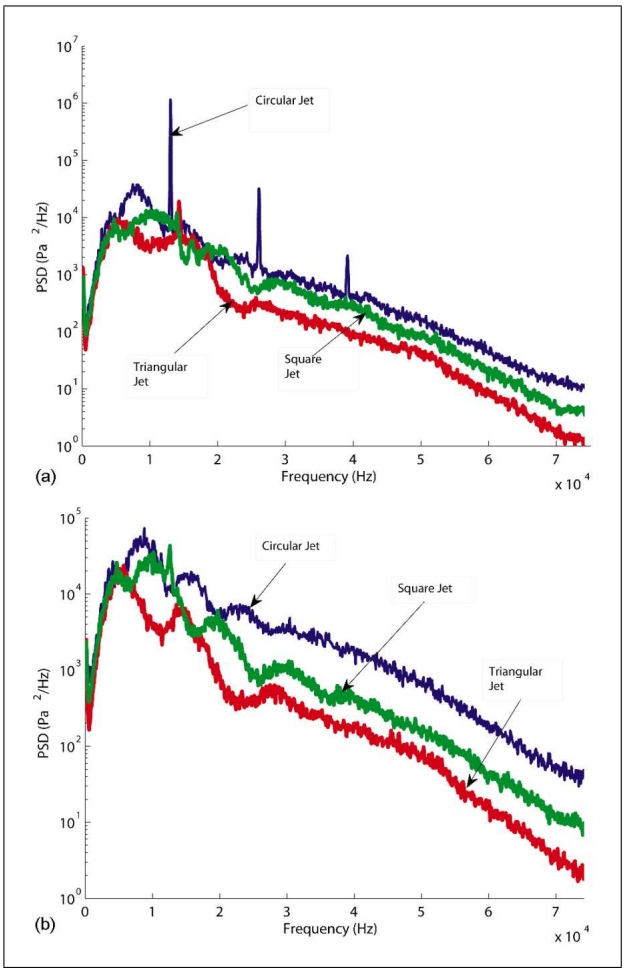


Figure 13. Spectra comparison of non-circular jets with those of circular jet at (a) $R = 4$ and (b) $R = 6$ at an emission angle of 37°.

spectra amplitude levels are similar in the upstream for jets along vertex and edge planes. However it is interesting to note that at lower pressure ratio jet ($R = 3$), the upstream amplitude of turbulent mixing noise along the vertex plane is higher compared to the edge plane. Moreover it is also observed that the upstream frequency events along the edge and vertex planes of triangular jet are almost similar (Figure 11a) and the dominant noise source is at around the frequency of 5.5 kHz. This may be due to the fact that at lower pressure ratios, the non-circular jets tend to become more unstable (akin to various instability modes in circular jets). And at higher pressure ratios such dominancy in acoustics sources are not observed. However in case of downstream emission angle, the spectra along the vertex and edge planes are not much similar (Figure 11b). Further as intuited, the amplitude of turbulent mixing noise along the edge plane is higher compared to the vertex plane. This may be because, the jets emerging from edge side tend to produce large scale structures leading to higher noise levels compared to vertex side that may generate streamwise vortices.

5.4. Turbulent mixing noise of non-circular and circular jets

Figure 12 compares the turbulent mixing noise from circular and non-circular jets at pressure ratios of 4 and 6. At pressure ratio of $R = 4$, the turbulent mixing noise of circular jet is the highest compared to the square and triangular jets (Figure 12a). It is explained from the fact that at this pressure ratio circular jet generates intense screech noise in addition to broadband noise (see the corresponding spectra in Figure 13a). Therefore the naturally excited screech tones help in augmentation of turbulent mixing in circular jets thus making its noise higher compared to the other jets [17]. In case of jets at higher pressure ratio of $R = 6$, it is observed that the turbulent mixing noise of the circular, triangular and square jets are almost similar as demonstrated in Figure 12b. The reason for this behavior can be emphasized from the fact that at higher pressure ratios, the circular jets ceases to generate screech tones (Figure 13b) and thus the turbulent mixing noise levels becomes similar for all these jets flows. The spectra in Figure 13 clearly reveals that the circular jets which are dominated by the screech tones at pressure ratio of $R = 4$ ceases to emit the screech tones at higher pressure ratio of $R = 6$. The screech cessation in supersonic jet flows is explained in detail by Raman [34]. Also it can be observed from the spectra (Figure 13a) that the turbulent mixing noise of circular jets at $R = 4$ is larger compared to the square and triangular jets.

To gain more insights about the nature of turbulent mixing noise emitted by various non-circular jets, the proba-

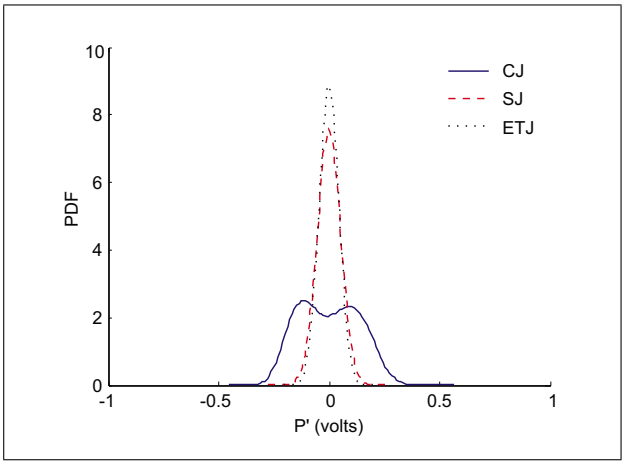


Figure 14. Comparison of probability density functions of non-circular jets with those of circular jet at $R = 4$ and $\phi = 130°$.

bility density functions (PDF) of time-series data are plotted. It is envisaged that PDF variations could demonstrate the differences between noise sources. These probability density functions values are obtained by a built in function in MATLAB software that estimates the PDF values from time series data in sets based on normal kernel function. The PDF plots of acoustic pressure signals from screeching circular jet and non-circular jets (square and triangular jets) are compared in Figure 14 for the conditions, $R = 4$ at an emission angle of 130° where the shock associated noise is dominant for circular jet. For a screeching circular jet, non-Gaussian (bi-modal) PDF is observed with higher variances. While the PDF of triangular and square jets show a perfect Gaussian with lower variance. This corroborates the fact that non-circular topology introduces more randomness to jet noise.

6. Conclusions

This paper focuses on turbulent mixing noise from non-circular jets – specifically triangular and square jets, and how they compare with circular jets. Experiments are carried out at different underexpansion levels for turbulent mixing noise level measurements. The result outcomes of the experiments are as follows:

Experiments revealed that the turbulent mixing noise levels increased along the downstream. It was further observed that these noise levels vary linearly with emission angles at two different slope/gradient values. Along the downstream ($37° \leq \phi \leq 60°$) the variation in the turbulence mixing noise is steeper, while at upstream ($60° \leq \phi \leq 135°$) the observed slope is small. The linear fit curve indicates that the slope values for the former and latter are 0.46 and 0.09 respectively. It has been corroborated from the literature that this steeper slope variation of turbulent mixing noise in the downstream is due to the large scale coherent structures moving at higher speeds. Furthermore, the turbulent mixing noise in the upstream are due to the fine scale structures thus showing small variations in the slope. In addition, it is also noted that the screech tones in circular jet assists in promoting turbulent mixing noise. Thus screeching circular jets are seen to have higher turbulent mixing noise compared to triangular and square jets. The probability density function of non-circular jet noise data shows Gaussian behavior while non-Gaussian is observed for screeching circular jet substantiating the fact that noise data from square and triangular jets have almost random behavior.

References

[1] M. J. Lighthill: On sound generated aerodynamically: I. General theory. Proceedings of the Royal Society of London, Series A, Mathematical and Physical Sciences **211** (1952) 564–587.

[2] G. Raman: Supersonic jet screech: half-century from Powell to the present. Journal of Sound and Vibration **225** (1999) 543–571.

[3] E. J. Gutmark, F. F. Grinstein: Flow control with noncircular jets. Annual Review of Fluid Mechanics **31** (1999) 239–272.

[4] K. Srinivasan, E. Rathakrishnan: Studies on polygonal slot jets. AIAA Journal **38** (2000) 1985–1987.

[5] W. R. Quinn: Mean flow and turbulence measurements in a triangular turbulent free jet. International Journal of Heat and Fluid Flow **11** (1990) 220–224.

[6] S. Koshigoe, E. Gutmark, K. C. Schadow, A. Tubis: Initial development of non-circular jets leading to axis switching. AIAA J. **27** (1989) 411–419.

[7] F. F. Grinstein, E. Gutmark, T. Parr: Near field dynamics of subsonic free square jets: A computational and experimental study. Phys. Fluids **7** (1995) 1483–1497.

[8] K. C. Schadow, E. Gutmark, D. M. Parr, K. J. Wilson: Selective control of flow coherence in triangular jets. Exp. Fluids **6** (1988) 129–135.

[9] W. R. Quinn, J. Militzer: Experimental and numerical study of a turbulent free square jet. Physics of Fluids **31** (1988) 1017–1025.

[10] W. R. Quinn: Streamwise evolution of a square jet cross section. AIAA Journal **30** (1992) 2852–2857.

[11] K. C. Schadow, E. Gutmark, D. M. Parr, K. J. Wilson: Selective control of flow coherence in triangular jets. Experiments in Fluids **6** (1988) 129–135.

[12] Y. Umeda, R. Ishii: Oscillation modes of underexpanded jets issuing from square and equilateral triangular nozzles. Journal of the Acoustical Society of America **95** (1994) 1853–1857.

[13] T. J. S. Jothi, K. Srinivasan: Acoustic characteristics of non-circular slot jets. Acta Acustica united with Acustica **94** (2008) 229–242.

[14] M. Brassard, R. H. Chen, L. Chew: An experimental study of underexpanded square jet noise. Journal of Sound and Vibration **197** (1996) 255–261.

[15] G. Raman, E. J. Rice: Instability modes excited by natural screech tones in a supersonic rectangular jet. Physics of Fluids **6** (1994) 3999–4008.

[16] C. K. W. Tam, H. Shen, G. Raman: Screech tones of supersonic jets from beveled rectangular nozzles. AIAA Journal **35** (1997) 1119–1125.

[17] G. Raman: Screech tones from rectangular jets with spanwise oblique shock-cell structures. Journal of Fluid Mechanics **330** (1997) 141–168.

[18] G. Raman: Advances in understanding supersonic jet screech: Review and perspective. Progress in Aerospace Sciences **34** (1998) 45–106.

[19] E. Gutmark, C.-M. Ho: Near-field pressure fluctuations of an elliptic jet. AIAA Journal **23** (1985) 354–358.

[20] A. K. M. F. Hussain, H. S. Husain: Elliptic jets. Part 1: Characteristics of unexcited and excited jets. Journal of Fluid Mechanics **208** (1989) 257–320.

[21] K. W. Kinzie, D. K. McLaughlin: Aeroacoustics properties of supersonic elliptic jets. Journal of Fluid Mechanics **395** (1999) 1–28.

[22] C. K. W. Tam: Supersonic jet noise. Annual Review of Fluid Mechanics **27** (1995) 17–43.

[23] H. K. Tanna: An experimental study of jet noise. Part I: Turbulent mixing noise. Journal of Sound and Vibration **50** (1977) 405–428.

[24] J. M. Seiner, M. K. Ponton, B. J. Jansen, N. T. Lagen: The effects of temperature on supersonic jet noise emission. AIAA Paper 92-02-046, 1992.

[25] J. C. Yu, D. S. Dosanjh: Noise field of a supersonic Mach 1.5 cold model jet. Journal of the Acoustical Society of America **55** (1972) 1400–1410.

[26] C. K. W. Tam, P. Chen: Turbulent mixing noise from supersonic jets. AIAA Journal **32** (1994) 1774–1780.

[27] C. K. W. Tam, D. E. Burton: Sound generated by instability waves of supersonic flows. Part 1: Two dimensional mixing layers. Journal of Fluid Mechanics **138** (1984) 249–271.

[28] C. K. W. Tam, M. Golebiowski, J. M. Seiner: On the two components of turbulent mixing noise from supersonic jets. AIAA 96-1716, 2nd AIAA/CEAS Aeroacoustics Conference, State College, PA, May 6–8, 1996.

[29] C. K. W. Tam, L. Auriault: Jet mixing noise from fine scale turbulence. AIAA Journal **37** (1999) 145–153.

[30] C. K. W. Tam, N. N. Pastouchenko: Noise from fine-scale turbulence of nonaxisymmetric jets. AIAA Journal **40** (2002) 456–464.

[31] C. K. W. Tam, K. Viswanathan, K. K. Ahuja, J. Panda: The sources of jet noise: experimental evidence. Journal of Fluid Mechanics **615** (2008) 253–292.

[32] K. Viswanathan: Analysis of the two similarity components of turbulent mixing noise. AIAA Journal **40** (2002) 1735–1744.

[33] W. R. Quinn, G. F. Marsters: Upstream influence on turbulent jet from cruciform nozzles. Aeronautical Journal **89** (1985) 55–58.

[34] G. Raman: Cessation of screech in underexpanded jets. Journal of Fluid Mechanics **336** (1997) 69–90.