Proceedings of the
International Conference on Mechanical Engineering 2003
(ICME2003) 26- 28 December 2003, Dhaka, Bangladesh

ICME03-FL-14

NOISE REDUCTION OF A SUPERSONIC JET BY REMOVING THE SHOCK STRUCTURE WITH A FORWARD SLANTED PERFORATED TUBE

M. T. I. Khan, K. Seto, Z. Xu and M. M. Alam
Department of Mechanical Engineering, Saga University, Saga 840-8502, Japan

ABSTRACT

The noise from an under-expanded supersonic jet was reduced by removing the shock structure of the jet with a forward slanted perforated tube. The perforated tube was attached to the exit of a convergent nozzle with a holding device and the jet was passed through the tube without any obstacle. Sound pressure level and thrust of the perforated tube were measured inside a semi-anechoic chamber. The shock-structure of the jet was visualized with a high-speed video camera along with the Schlieren apparatus. The aero-acoustic performance of the forward slanted perforated tube was compared with different types of perforated tubes (backward slanted and normal slanted tubes) and the tube with forward slanted perforation showed the best performance in all aspects. The removal of shock structure removed the jet screech as well as reduced the shock-associated broadband noise and finally reduced the overall sound pressure level of the jet. The elimination of inner sharp edges of the perforations also improved the noise suppression performance of the forward slanted oblique perforated tube.

Keywords: Under-expanded supersonic jet, overall sound pressure level, perforated tube.

1. INTRODUCTION

At high supercritical pressure ratios, the noise generating mechanisms of the major sources of the radiated noise from supersonic jet flows (e.g., the mixing and the shock associated noise components) are often coupled [1]. Normally, the intensity of the shock generated acoustic radiation is directly dependent upon the shock strength and the level and coherence of the flow fluctuations convected through the shock front [2, 3]. Therefore, to suppress aerodynamic noise components radiated by imperfectly expanded supersonic jet, the extent, the spacing, and the strength of the repetitive shock structure and the level and coherence of the jet flow fluctuations convected through the shock fronts need to be modified, such that the overall strength of the noise contributing sources and the effectiveness of their noise generating mechanisms are reduced.

Supersonic jet-noise suppression by relieving the pressure of an under-expanded jet through perforated tube has been reported by one of the present authors to inform the optimal length of the tube and the effects of the shroud on noise suppression [4, 5]. It has been demonstrated that the supersonic flow is produced by the addition of a perforated tube, and the flow at the exit of the perforated tube changes from under-expanded to correctly expanded or over-expanded jet as the length of the perforated tube is increased. In the present experimental study a comparison of different types of perforations of the tube has been performed and the forward slanted perforation is found most favorable in suppressing supersonic jet noise.

2. EXPERIMENTAL PROCEDURES

Nozzle, Perforated tube and Jet properties

A convergent nozzle was used in the present experiment to generate an under-expanded supersonic jet of interest. Preliminary experiments were carried out to obtain the reference data for the nozzle. The convergence angle, exit diameter (D), lip thickness, total length and the length of the converging parts of the nozzle were 30°, 10, 10, 110 and 26 mm respectively. Different types of perforated tube (B1-type, B2-type, N1-type, N2-type and O-type) and a base tube (solid tube) were used in the experiment and attached to the nozzle exit as shown in Fig. 1. The perforation angle (θ), diameter of perforation (ϕ) and the porosity of the perforated tubes were varied for different experiments. The thickness of the tube (t) was kept constant at 0.15D. The parameters of perforated tubes are shown in Table 1. It is shown in the table that B-type tubes have backward slanted oblique perforations, N-type tubes have vertical perforations and an O-type tube has forward slanted oblique perforations to the tube surface. The effective lengths (L) of the perforated tubes and the base tube were selected as 5D for the best performance [4]. The diameters of all tubes were same as that of the nozzle exit. The porosity of the perforated tube was calculated as the ratio of the total porous area to the total surface area of the tube. The cross-section of the porous area was used to calculate the total porous area of the tube. The air supply for the jet was taken from a reservoir of about 2 m^3 in volume and about 1 MPa in pressure. Air compressor, air cooling separator, air dryer, oil mist filter were used to maintain the dry unheated jet of air. The air was cooled in order to separate the water from the air before storage. The flow was controlled by manually operated sluice valve in conjunction with pressure reducing valves. Two lattices between which sound absorbent material was packed were placed in the 22.2D diameter settling chamber after the control valves in order to reduce the valve noise. The pressure and the temperature of the flow were measured after the chamber and just prior to the contraction at the nozzle exit, which was designed so as to avoid separation of the flow and produce a reasonably uniform velocity across the exit.

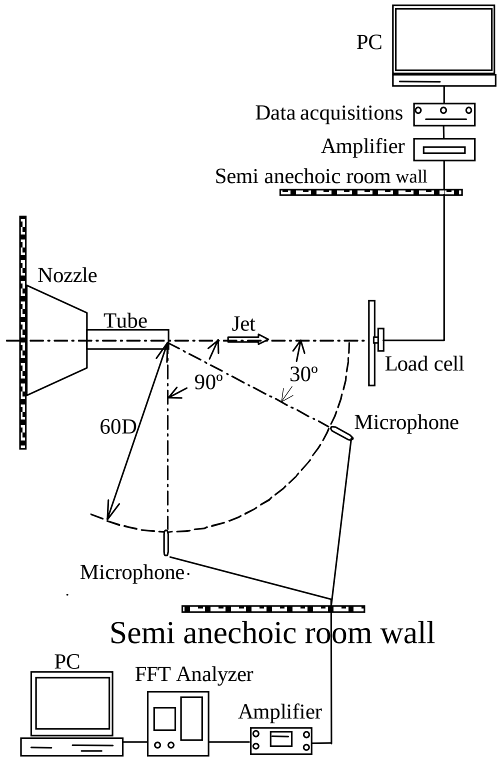


Fig. 1 Schematic view of Experimental apparatus

Acoustic Measurements

Measurements of sound generated from an under expanded supersonic cold jet were carried out in a semi-anechoic chamber of about 3.5 x 3 x 2m in volume. A condenser microphone of 6.35 mm (1/4 inch) (Bruel & Kjaer, Denmark) was used and traversed along a measuring path of 60D radial distance from the center of the nozzle (as well as perforated and base tubes) exit as shown in the figure. The microphone was placed in the same horizontal plane of the tubes making angles of 30 and 90 degrees with the jet axis. The angle was measured from the direction of jet flow. Acoustic signals were taken and analyzed with the help of a signal amplifier and a two channel FFT analyzer. Finally all data were processed by a personal computer. Pressure ratio (the ratio of the jet pressure to the ambient pressure) was changed from 2.2 to 4.0 at the step of 0.2. Moreover, the acoustical data were also taken at the pressure ratios of 4.4, 4.8, 5.0, 5.8, 6.2, 6.6 and 7.0.

Thrust Measurements

A steel disk of diameter 20D was installed vertically toward the way of the jet. A load cell measured the pressure that was pressed by the jet to the disk. The data of load cell was amplified and saved in the personal computer. For measuring the thrust of perforated tubes a data acquisition device (NR 350, Keyence, Japan) was used. The distance of the disk from the nozzle and the tube exit was maintained as 5D for the best fit to the theoretical analysis [6]. Thrust of nozzle as well as perforated tubes were measured for the pressure ratios of 2.0, 3.0, 4.0, 5.0 and 6.0.

Optical Measurements

For the observations of the shock containing jet, Schlieren visualization apparatus was used. A spark of magnesium electrodes provided the illumination, the effective duration being about two microseconds. Shock structures and the oscillations of shock cells were observed with a high-speed video camera (FASTCAM – ultima – UV3 / IR3, Photron, Japan) of segment film 9000 pps and the segment film size 256 x 256 dots. In the range of pressure ratios as mentioned above jet structures were optically observed for the base tube as well as for the perforated tubes.

3. EXPERIMENTAL RESUTLS AND DISCUSSION

Noise Suppression with Forward Slanted Perforated tube

Overall sound pressure level (OASPL) of a shock associated cold jet ejected from a nozzle with and without straight tube or perforated tube has been analyzed. Sound generated from the jet has been suppressed with a forward slanted oblique perforated tube (O-type) as shown in Fig. 2 and Fig. 3. In this case O-type perforated tube makes an acute angle with respect to the jet axis. Figure 2 shows the noise suppression by the O-type perforation when measurement was carried out at 90 degrees. Similarly Fig. 3 shows the measurement at 30 degrees. In both cases O-type tube suppresses a remarkable amount of OASPL. In the measurements of 90 degrees, this forward slanted perforated tube reduces 12 dB of OASPL with respect to the base tube and 15 dB compared to the convergent nozzle. However, it is seen in Fig. 2 that some discrete tones increase the OASPL

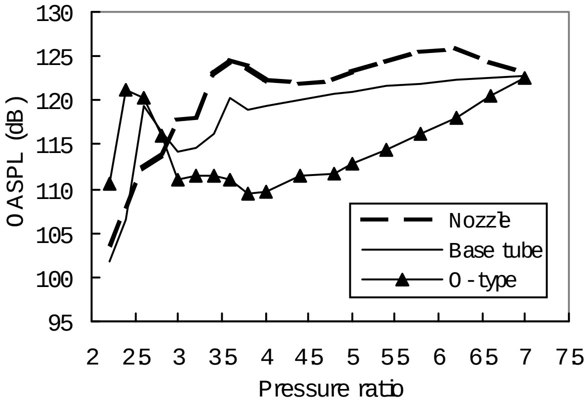


Fig. 2 Variation of OASPL with jet pressure ratio (measured at 90 degrees)

at lower pressure ratios. The discrete tones are considered as a kind of edge tone.

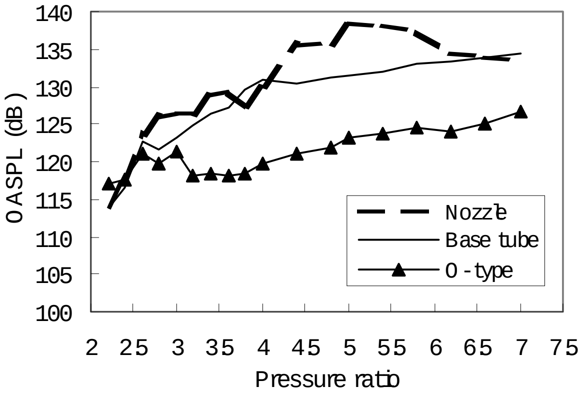
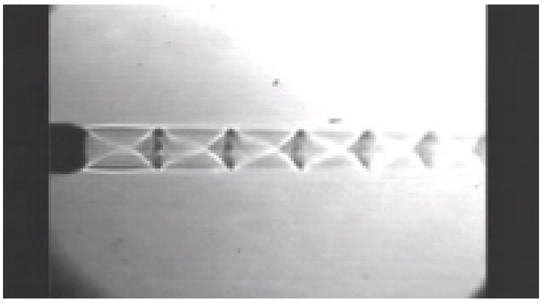
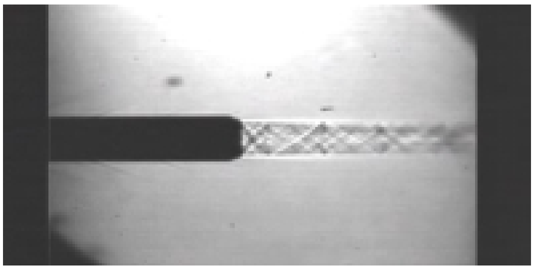


Figure 3 Variation of OASPL with jet pressure ratio (measured at 30 degrees).



(a) Base tube



(b) O-type tube

Fig. 4 Schlieren photograph with a high-speed video camera,(a) base tube, (b) O-type perforated tube. Jet pressure ratio = 3.6.

The fluid dynamic behavior of forward slanted perforated tube was evaluated with a visual observation through a high-speed video camera. The modifications of shock structure and the oscillations of shock cells of the jet with this perforated tube were examined in the experiment. The results of the optical observations of the jets exerted from the base tube and O-type perforated tube at a pressure ratio of 3.6 are shown in Fig. 4. Strong shock structures were eliminated with an O-type perforated tube instead of a base tube, which is shown in Fig. 4.

Comparisons with other Perforations

The suppression of overall sound pressure level with an O-type perforated tube was compared to that with different types of perforated tubes. The normal perforated tubes (N1-type, N2-type) and backward slanted perforated tubes (B1-type, B2-type) were used in the current experiment. The specifics of those tubes are shown in Table 1. The porosities of B1, N1 and O-type perforated tubes were same while the porosities of B2 and N2 tubes were enlarged for checking the porosity effect. The results of these comparisons are shown in Fig. 5 for measurements at 90 degrees. By B1 perforated tube maximum 3dB OASPL suppression was obtained compared to the base tube and about 7dB compared to the nozzle for the measurements at 90 degrees. Similarly maximum 4dB and 8dB OASPL reductions were provided by N1 tube compared to the base tube and the nozzle respectively for 90-degree measurements. Whereas for the measurements of the same direction an O-type perforated tube with same porosity as N1 suppressed OASPL by around 10dB and 15dB compared to the base tube and the nozzle respectively. Similar results were obtained also in the case of 30-degree measurements. The porosity of N2 perforated tube was about 5.6 times higher than that of N1 and O-type perforated tubes. Figure 5 shows that the performance in noise suppression through N1 perforated tube could be improved by the increment of porosity (N2 perforated tube). Similarly the porosity of B2 perforated tube was enlarged about 3.8 times higher than that of B1 and O-type perforated tubes. The improvement of performance in noise suppression at 90-degree measurement by enlarged porosity was not so remarkable compared to normal perforated tubes, whereas, the improvement of noise suppression by backward perforated tube with enlarged porosity was found at downstream measurements (30 degrees). However, the improvement of noise suppression by normal perforated tubes or backward slanted perforated tubes even with enlarged porosity was smaller than that by O-type perforated tube. In Fig. 5 it is found that at higher-pressure ratios N1 perforated tube was even noisier than the base tube. Perforated tube with higher porosity could alleviate under-expansion and decrease jet noise in spite of the increase of wall roughness. On the other hand, for measurements at both directions, O-type perforated tube showed the best performance in overall noise reduction in spite of its small porosity.

Table 1: Specifics of perforated

Perforated tube	θ, degree	ϕ, mm	Porosity
O-type	30	1.5	0.031
N1-type	90	1.5	0.031
N2-type	90	1.5	0.176
B1-type	150	1.5	0.031
B2-type	150	3.0	0.120

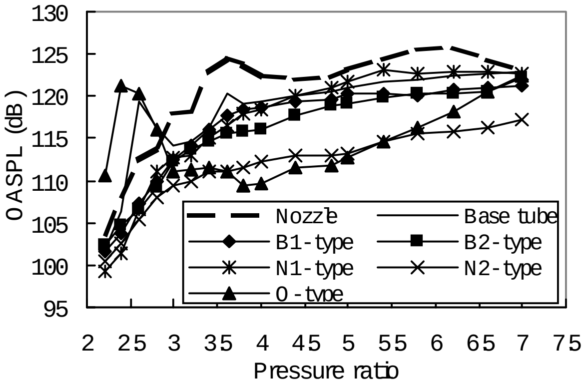


Figure 6 Comparison of OASPL among different perforated tubes (measured at 90 degrees).

Improvement of Performance of Forward Slanted Perforated tube

It is seen in the previous discussions that the forward slanted perforated tube (O-type) can reduce the supersonic jet noise effectively. However, at the lower pressure ratio, a kind of discrete tone of higher amplitude was created. The discrete tone was considered to be generated by the sharp edges at the inner surface of the tube with oblique perforations. When the inner edges were removed, the discrete tone was eliminated as shown in Fig. 7.

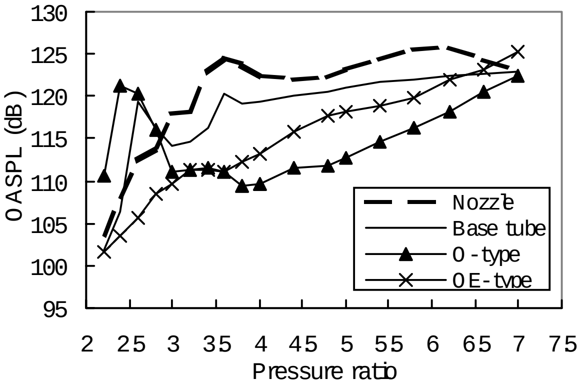


Fig. 8 Comparison of OASPL between O-type tubes with and without inner edges of perforations (measured at 90 degrees)

The improved perforated tube is noted in the figure as OE-type. The porosity and other parameters of OE-type tube are same as that of O-type perforated tube. It is found in the figure that the reduction of OASPL at the pressure ratio of 2.4 was more than 17dB by blunting the inner edges of the tube.

Effect of Perforation on Thrust loss

The aerodynamic performance of different perforated tubes was analyzed by evaluating the thrust of exerted jet through each tube. The thrust was determined by measuring the load caused by the impingement of a jet against the plate with a load cell. The plate was placed vertically inside the jet at a distance of 5D from the nozzle or tube exit as explained in section 2. The experimental results were compared with a theoretical result and plotted against jet pressure ratios. The theoretical thrust was calculated by the jet momentum equation [6]. The results are shown in Fig. 9. The thrust of N2 perforated tube was smaller than that of N1, B1 and O-type perforated tubes. The porosity of N2 tube was about 5.6 times larger than the O-type perforated tubes. The thrust of B2 tube was reduced to almost half of the thrust of base tube. The diameter of perforation of B2 tube was double that of B1 tube. B1 and N1 tubes suffered similar thrust loss. The thrust loss was smaller than that of B2 or N2 tubes and larger than that of O-type perforated tubes that had the same porosity. OE –type perforated tube suffered a little bit larger thrust loss than O-type tube at higher-pressure ratios. It suffered, however, smaller thrust loss than N2 tube. Namely, O-type perforated tube suffered the smallest thrust loss among all perforated tubes tested.

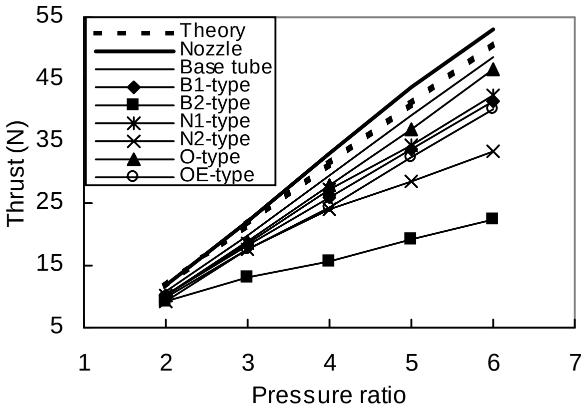


Fig. 11 Comparison of thrust of different perforated tubes, base tube, nozzle and a theoretical value.

4. CONCLUSIONS

A forward slanted perforated tube (O-type) showed very good performance in noise reduction of the under-expanded supersonic jet. The shock cell structure of the jet flow was eliminated and the OASPL was effectively suppressed.

Discrete noise components generated at lower pressure ratios due to the forward slanted perforation could be removed by eliminating the inner sharp edges of the tube.

Thrust loss of a forward slanted perforated tube is found minimum among different types of perforated tubes. Thus the lower thrust loss and the higher noise reduction are considered the merits of the forward slanted perforated tube as a practical noise suppressor.

6. REFERENCES

1. Seiner, J. M., 1984, "Advances in High Speed Jet Aero-acoustics", *AIAA Paper 84 - 2275*, pp. 1 - 40.
2. Tam, C. K. W., 1995, "Supersonic Jet Noise", *Annu. Rev. Fluid Mechanics*, 27: 17-43.
3. Ribner, H. S., 1985, "Cylindrical Sound Waves Generated by Shock-Vortex Interaction", Journal of AIAA, 23: 1708-1715.
4. Seto, K., 1988, "Modification of the Characteristics of Under-expanded Jets by Using an Extended Perforated Tube as a Noise Suppressor", Journal of Noise Control Engineering, 30: 119-125.
5. Seto, K. and Matsuoka, M., 1988, "Study of Porous Tubes as a Noise Suppressor: 2nd Report, Experimental Study on the Effects of the Shroud and Other Parameters", Trans. Japan Society of Mechanical Engineering (in Japanese), 54: 2061-2066.
6. Seto, K., Khan, Md. T. I., Xu, Z., 2002, "Improvement of Aero-Acoustic Performance of A Perforated Tube by Oblique Perforation", *Proc. Of 9th Int. Congress On Sound and Vibration, Orlando, Florida, USA*, pp.1-8.