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Aeroacoustic Characteristics of Perforated Wall and Cavity

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Abstract

A perforation in a wall over which air flows may be considered to have both noise generating and noise absorbing effects. The authors have experimentally investigated the effects of perforated wall with and without shroud or cavity on noise reduction. First, aerodynamic characteristics has been improved by arranging the perforation according to cross area change of a De-Laval nozzle. Next, a perforated tube has been combined with a shroud in order that no leakage occurs through the perforation and acoustic transmission loss increases. Third the length of the shroud has been extended longer than the main tube to give it an effect of a cavity. The cavity containing tube has some cut-off frequency and augments turbulence mixing which is good for combustion and reduces noise in some case. For those three cases, the authors investigated the effects of the porosity, the size of the perforation, the intersection angle between the axes of the perforation and the main flow and the perforation pattern. The directional angle of the perforation has been found to have influence on the performance of the perforated tube.

1 INTRODUCTION

For a convergent nozzle, if the ratio of jet pressure to ambient pressure is above a critical value, the jet becomes underexpanded flow. It contains shock waves and generates jet screech [1]~[5]. In the previous papers by one of the present authors, it was reported that the attachment of a perforated tube to the nozzle exit changed the underexpanded jet into nearly complete expanded jet and canceled jet screech [6]. Furthermore it was demostrated that covering of perforated tube with a shroud improved the efficiency of noise suppression and aerodynamic property like thrust [7].

In previous research, we could obtain about 13dB noise reduction in case of pressure ratio 3 to 4.5 by using a perforated tube. The exit velocity through the perforated tube was nearly equal to the case of isentropic expansion. Furthermore we examined in detail the effect of the porosity and tube length (expressed by the ratio of the length, L, to the diameter, D, of the tube) on the acoustic and aerodynamic characteristics of the perforated tubes. In an ordinary case that the perforation is set normal to the tube surface, the optimum length ratio was around 5 and porosity was about 0.22. It was pointed out that the characteristics of a perforated tube depends on the distribution of porosity. It exerts a similar effect when the porosity of the area element at an axial location is similar. If a perforated tube has an adequate porosity, it behaves like a De-Laval nozzle, while an excess porosity exerts an effect of a sudden expansion of a nozzle.

In the present paper, we focused attention on the configuration of each perforation. The change of the effect due to the combination of a shroud has also been examined. In the present experiment, the length of the perforated tube has been fixed to 5 times diameter of the nozzle exit. We examined the effect of the direction of the perforation. Usually each perforation is drilled normal to the surface of a tube. This time we investigated the case that the direction of the perforation was slanted from the normal to the surface in two fashions except the usual case. In one case, the inclinations were made in planes perpendicular to the axis of a tube. Thus the ejected flows from perforations were resulted in a spiral component of the flow. In another case, the perforations were inclined in planes including the axis. Flow may more easily go out from the inside of the tube. Those modifications were effective in reducing jet noise and augmenting aerodynamic performance. Next, the effect of the distribution of porosity was studied by comparing the case of uniform distribution and the varying distribution according to a De-Laval nozzle. Finally the effect of a shroud has been experimentally investigated. Change in noise reducing effect by extending the shroud has also been examined.

2 EXPERIMENTAL

2.1 Apparatus

Schematic diagram of the experimental apparatus is shown in Fig.1. The air compressed by a reciprocating air compressor was stored in strage tanks after separation of oil mixture and being dried through an air cooling separator and a refrigerating air dryer. Then it was conducted to a semi-anechoic chamber of 3.5x3x2m through a nozzle with the jet pressure being manually controlled by a sluice valve. Pressure ratio was defined as the ratio of jet pressure to the ambient pressure and expressed as P. As in Fig.1, coordinates are taking according to a right-hand system with z coincident with jet axis and with the origin placed in the center of the exit. Coordinates are expressed in the ratios to the exit diameter of a used nozzle(D).

2.2 Perforated Tubes and Shrouds

The baseline nozzle was axially symmetric and convergent. The exit diameter and the convergence angle was 10mm and 30deg respectively. A perforated tube was attached to the nozzle. Those configurations are shown in Fig.2 and 3. We used 5 kinds of perforated tubes as follows.

(i) Normal-perforated tube (**N-type**): The direction of perforation is normal to the wall surface and porosity is 0.18.

(ii) Spiral-perforated tube (**S-type**): The direction of perforation is nearly tangent to the wall surface in a plane normal to the axis of the tube. The porosity was 0.23. The number and the diameter of perforation was same with the above.

(iii) Oblique-perforated tube with uniform porosity **(OU-type)**: The direction of perforation was slanted downstream by 30deg from the normal to the surface. The porosity was 0.052.
(iv) Oblique-perforated tube with porosity increasing downstream **(OL1-type)**: The diameter of perforation was 1.5mm while the direction of the perforation was same with OU-type. The mean porosity was 0.031.
(v) Oblique-perforated tube with porosity increasing downstream **(OL2-type)**: The diameter of perforation was 1mm while the direction of the perforation was same with OU-type. The mean porosity was 0.053.

Inner diameter and length of the tube were fixed in the present report. They are 10mm and 50mm respectively. In addition to the above mentioned tube, a solid tube without perforation was used for comparison.

We studied also the effect of the coverage of a perforated tube with a shroud. The ratio of the inner diameters of the shroud and the perforated tube were set to 1.7 and 2.0. Let the ratio be denoted by SID. The change in the effect by extending the shroud was also examined. The range of the extension was 0 to 7D done at the step of 0.5D. The extended length divided by D is symbolized by GAP.

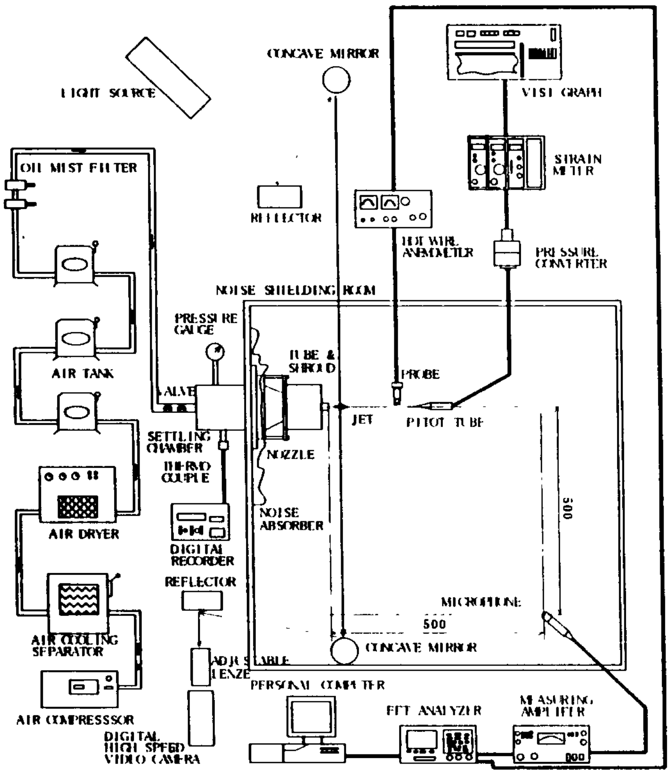
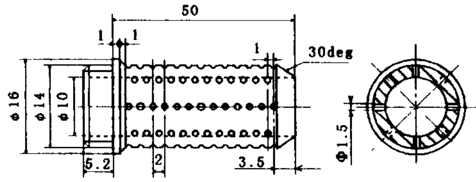
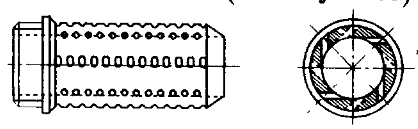


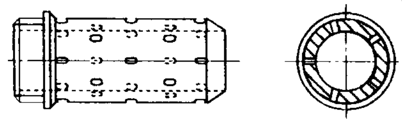
Figure 1. Experimental Apparatus



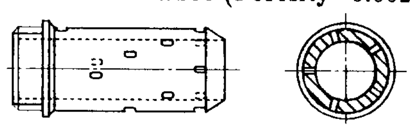
N-type Perforated Tube (Porosity=0.18)



S-type Perforated Tube (Porosity=0.23)



OU-type Perforated Tube (Porosity=0.052)



OL1-type Perforated Tube (Porosity=0.031)

Figure 2. Perforated Tubes

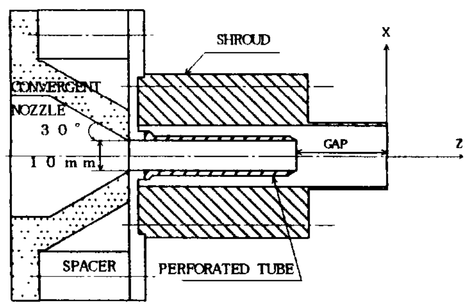


Figure 3. Shroud Attached Perforated Tube.

2.3 Acoustic Measurement

Signals taken by a 1/2 inch condensor microphone (B&K 4165) were amplified by measuring amplifer (B&K 2610) and sound pressure level of flat characteristics as well as acoustic spectra were obtained through a FFT analyzer (A&D AD-3525) and were processed by PC (personal computer). The measuring point is 500mm apart from the exit plane and the axis as shown in Fig.1. The pressure ratio (P) were set 1.1 to 4 changed at the step of 0.1 (in the range of 1.1 to 2) or 0.5 (in the range of 2.5 to 4).

2.4 Velocity Measurement

2.4.1 Mean Velocity Profile Pressure probes for measuring total pressure and static pressure were used to obtain Mach number contours in the exit plane. Total temperature of flow was measured in a settling chamber by using a thermocouple to calculate acoustic velocity. Those data were recorded by a multi-channel digital recorder. The pressure ratio were set 1.1 to 4 changed at the step of 0.1 (in the range of 1.1 to 2) or 0.5 (in the range of 2.5 to 4). In calculating Mach number, we used Rayleigh pitot-tube formula for supersonic flow and isentropic relation for subsonic flow. Also we investigated the spiral components of flow through S-type tube.

2.4.2 Turbulence Profile To investigate the correlation between sound and fluctuation of flow, we measured turbulence and compared the spectrum of sound and turbulence. A hot wire anemometer was utilized for the turbulence measurement.

3 RESULTS AND DISCUSSIONS

3.1 Porosity

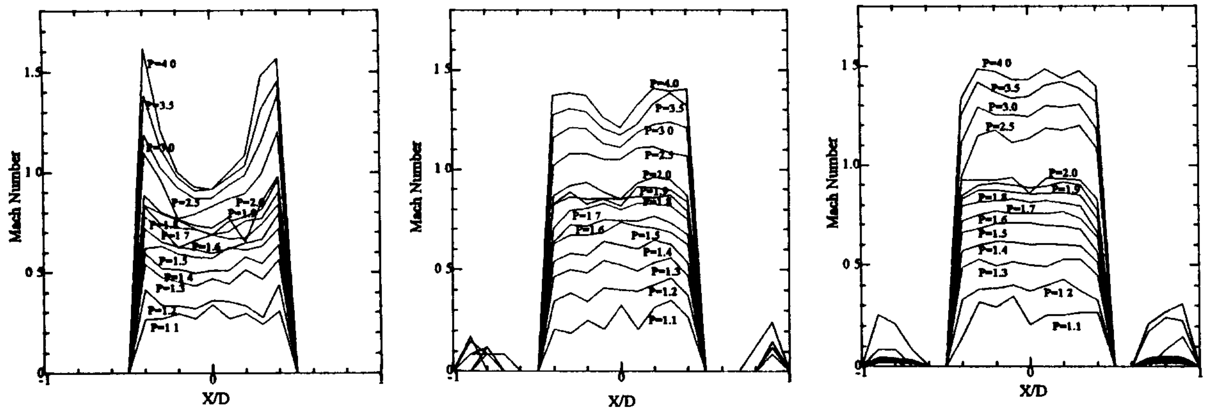
Mach number profile in the exit plane of a nozzle, OL1-type and S-type perforated tube are shown in Fig.4(a),(b) and (c), respectively. Here shroud of SID=2 and GAP=0 was attached to those perforated tubes. Mach number profile of the nozzle flow shows typical underexpanded characteristics at any pressure ratio greater than 1.9. Perforated tubes keep a flat-top configuration still at higher pressure ratios. The variation of Mach number at the center of the exit plane as a function of P (pressure ratio) is shown in Fig.5. S-type is seen to generate nearly isentropic expansion. Over-all sound pressure level as a function of exit jet velocity is depicted in Fig.6. S-type nearly obeys 8^{th}-power law [8].

3.2 Perforation Pattern

The effect of perforation on flow expansion depends not only on porosity but also on perforation pattern. To examine the effect of perforation pattern, we compared noise reducing effects of OU-type and OL1-type. As is shown in Fig.7 which shows the over-all sound pressure level of jets from the tested tubes, almost the same performance has been obtained by OU- and OL1-type up to P=3.1. The tested tubes have been combined with a shroud of SID=2 and GAP=0 (without extension). It should be noticed that the porosity of the latter is smaller than the former by about 3:5. Furthermore, high sound levels caused by a kind of resonance in a shroud at lower pressure ratios have been diminished in the latter case.

3.3 Perforation Direction

3.3.1 Oblique Perforation We tested three cases of oblique perforation, OU-, OL1- and OL2-type. In our previous researches, it was reported that the porosity of 0.22 afforded by apertures of 1mm was most effective in reducing noise. N-type tube of the present paper has characteristics similar to that effective tube.



(a) Nozzle (b) OL1-type Perforated Tube (c) S-type Perforated Tube

Figure 4. Mach Number Profile

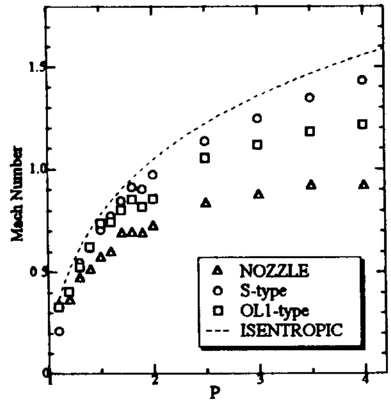


Figure 5. Mach Number v.s. P at X/D=0.

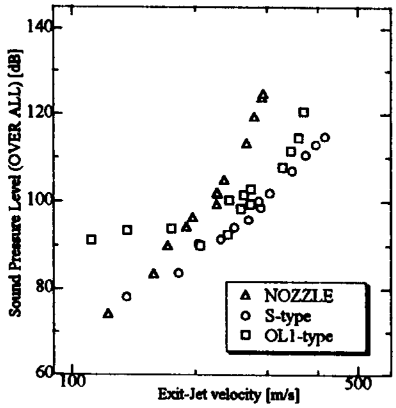


Figure 6. OASPL as a Function of Jet Velocity.

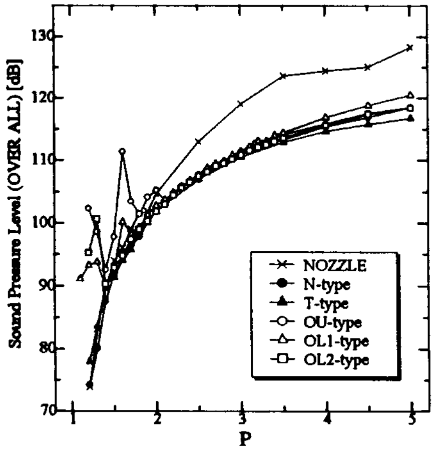


Figure 7. Acoustic Performance of Perforated Tubes (SID=2.0 GAP=0)

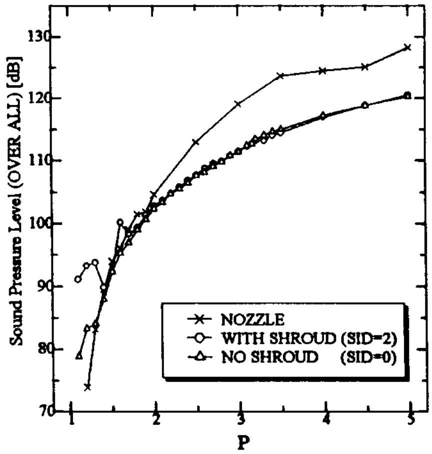


Figure 8. Effect of Shroud in the case of OL1-type Perforated Tube (GAP=0).

As is shown in Fig.7, however, OU-type tube can reduce noise as much as N-type one in the range of P above 2 in spite of much smaller porosity. In the range of P below 2, on the other hand, tubes of oblique perforation generate extra noise related to resonance in a tube. By removing the shroud, the extra noise can be removed too as is indicated in Fig.8. The resonance may be caused by an edge tone at the leading edge of the oblique perforation. The wave length of the peak frequency was nearly twice of the perforation interval. It may be stated that the edge tone from the perforation is amplified in a shroud under a suitable flow condition. Flow velocity at the edge plays an important role in generating the edge tone. When the pressure is relatively low, the condition appears to be satisfied.

3.3.2 Spiral Perforation To provide ejected flows with spiral characteristics, the direction of the perforation was slanted in the cross sectional plane of a tube so that it is nearly tangent to the surface of a tube. In this way, the removal of edge tone resulted as is illustrated in Fig.7. Also increase in porosity was realized using the same perforations. It should be noticed that N-type tube and S-type one have the same number and the same diameter of perforation with each other. By the inclination of a plane of intersection of the column of perforation with the surface of a tube, perforated area is broadened. As a result, noise reducing effect is improved in higher pressure region such as P greater than 2, while in lower pressure region it is aggravated as is shown in Fig.7.

3.4 Effect of Shroud

3.4.1 Shroud Inner Diameter (SID) OASPL's of flow through nozzle and S- and N-type perforated tubes are illustrated in Fig.9(a) and (b). Fig.9(a) includes the case of shroud without extension and Fig.9(b) contains the data of shroud corresponding to GAP 3. We took the abscissa for P. Noise reducing effect is evident in the range of P above 2 and more than 10dB reduction in noise has been obtained in the range 3 to 4.5. Shroud of SID=2 is more effective in reducing noise than a narrower shroud of SID=1.7 in the both case of N- and S-type in the range of P above 2. However in the range below 2, SID 2 shroud aggravated the performance worse than SID 1.7 due to edge tone effect of shroud.

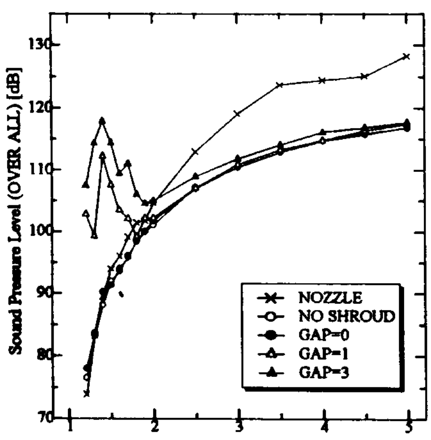


Figure 9(a). Effect of Shroud Extension in the case of OL1-type Perforated Tube (SID=2.0).

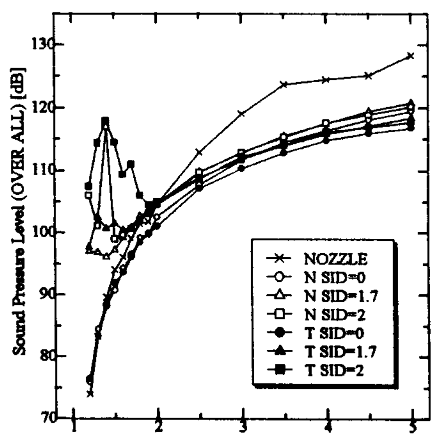
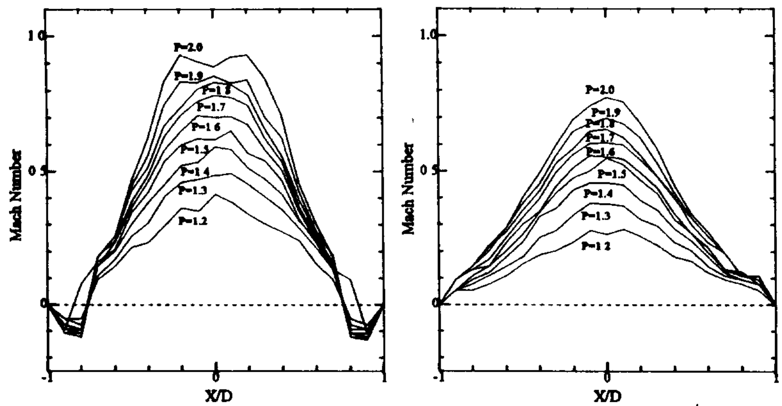


Figure 9(b). Influence of Shroud Diameter on the Performance of Perforated Tubes (GAP=3).

3.4.2 Shroud Extension (GAP) The Mach number profiles at the exit of S-type tube has already been depicted in Fig.4(c). For the case of extended shroud, Fig.10(a) and (b) are added. When the shroud is not extended (GAP=0), a region of main flow and of ejected flow from perforations is clearly separated. We could detect a spiral component of flow at the exit of the tube by measuring the direction of flow in the cross sectional plane. When the shroud was extended such as GAP=7.0, a merged flow took place (Fig.10(b)). With a shroud of medium length such as GAP=3.5, a reversed flow was induced by the entrainment of main flow (Fig.10(a)). In that case of the shroud, particular tones of noise were observed.



(a) GAP=3.5 (b) GAP=7.0

Figure 10. Mach Number Profile of S-type Perforated Tube (SID=2.0).

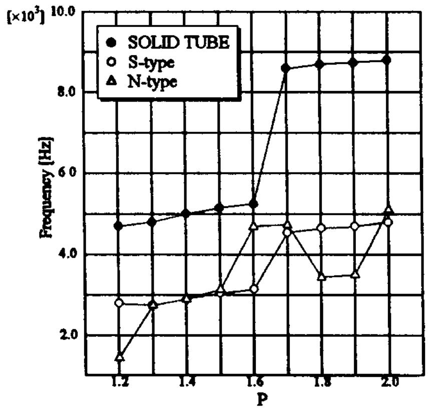
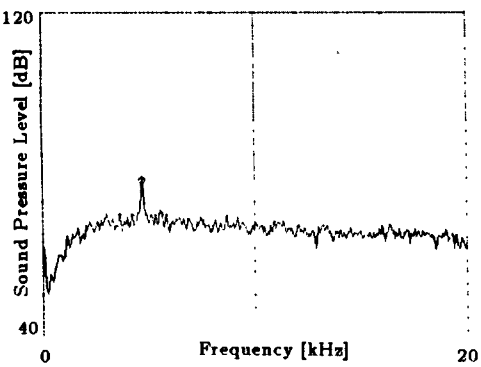
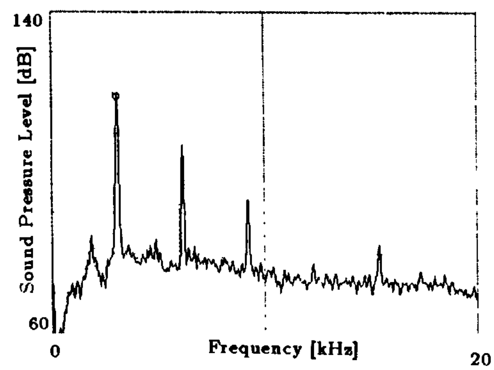


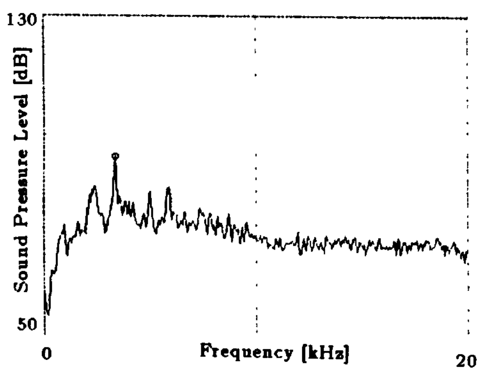
Figure 11. Frequency of Discrete Tone v.s. P (SID=2.0 GAP=3.5).



(a) GAP=0



(b) GAP=3.5



(c) GAP=7.0

Figure 12. Acoustic Spectrum of S-type Perforated Tube (SID=2.0).

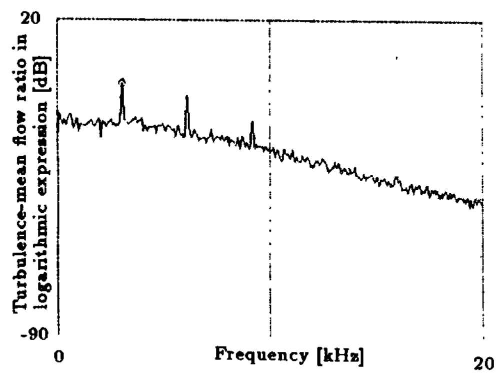


Figure 13. Turbulence Spectrum of S-type Perforated Tube (SID=2.0 GAP=3.5).

Measured frequency as a function of P is depicted in Fig.11. Frequency jump for each combination of a tube and a shroud at a value of P is indicated in the figure. Acoustic spectra and a turbulence spectrum are given in Fig.12((a),(b) and (c)) and Fig.13, respectively. Fig.12(b) and Fig.13 correspond to a same condition and produced similar spectra. The high sound pressure level at low pressure ratio was caused by the generation of the above mentioned tone. The discrete tone was correlated with the fluctuation of flow near the edge of the extended shroud with GAP of 3.5. In fact, jet boundary in this case did not touch the edge of the shroud. However an entrained flow round the edge was sensitive to a disturbance generated at the exit of the main tube. Sound pressure caused by the fluctuation of an entrained flow propagates upstream, interacts with shear layer disturbance at the exit of the main tube and amplifies it. It may be stated, hence, a feedback loop is constructed and a kind of edge tone is generated. The length of GAP 3.5 corresponds to the wave length of the tone of frequency 9kHz indicated in Fig.11. Other frequencies appear sub-harmonics of the tone. In the case of GAP=7.0, an acoustic feed back loop may be formed between the lip of the main tube and the point of the impingement on the inner wall of the shroud. The estimated frequency was nearly coincident with the observed one.

4 CONCLUSIONS

- Inclination of perforation in downstream direction increased the performance of perforated tubes in reducing noise and improving aerodynamic characteristics.
- Suitable perforation pattern also improved the performance of perforated tubes.
- Attachment of a shroud of equal length to S-type tube could improved the performance of perforated tubes.
- Extension of shroud aggravated the acoustical performance of perforated tubes.

5 ACKNOWLEDGEMENTS

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