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Keynote Paper

MODERN DEVELOPMENT AND GENERAL PERFORMANCE OF JET NOISE SUPPRESSORS

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Abstract Review of the theoretical and experimental researches of jet noise has been firstly presented. The mechanism of screech tone and broadband shock associated noise have been traced back and summarized with clear understanding. Histories of development of jet noise suppressors have followed in the second section. Finally, devices for reducing jet noise were tested and evaluated from the aerodynamic and aeroacoustic points of view. Investigated suppressors were slotted tubes and perforated tubes. Slotted tubes were varied in the number and the length of slot. As for the perforated tube, the effect of perforation angle that is the angle between the perforation axis and the tube axis were investigated as well as the effect of porosity. The length, the exit diameter and the thickness were fixed to 50, 10 and 2mm respectively in the present report. Sound pressure level and thrust of devices for reducing noise were measured and compared with each other. Slotted tubes showed rather preferable performance with respect to thrust while perforated tube exerted better noise reducing effect.

Keywords: Noise suppressor, Slotted tube, Perforated tube, Thrust

INTRODUCTION

There are many types of devices for reducing jet noise including nozzle with tabs, slotted tubes perforated tubes, chuted nozzle, lobed nozzle and multi-tube nozzle for example. In most cases the attachment of a noise suppressor incurs undesirable byproduct, increase of weight and thrust loss. In the present paper, all the devices contrived in the past have been compared and reviewed. Furthermore, experimental examination of the performance of perforated tubes and slotted tubes have been carried out and reported.

MECHANISM OF JET NOISE

The pressure fluctuations in the nearfield region of the jets are found to be composed of two components: acoustic and hydrodynamic. The latter is due to the potential field of the turbulent fluctuations present in the jet shear layer. An experiment with spark schlieren photographs shows that the major part of the turbulent fluctuations is due to large, periodic coherent vortices that propagate with flow. The nearfield, root-mean-square pressure fluctuation data, at the screech frequency, show the presence of two interconnected standing wave patterns. The first one is along the jet boundary, and the second one is along a diagonal line that marks the boundary of forward propagation of the fundamental frequency. It is demonstrated that both of the patterns are the outcome of a standing wave formation between the hydrodynamic and acoustic pressure fluctuations. Noise characteristics are a result of the competing influences of turbulent mixing, convective amplification and acoustic shielding. High velocity flow put on the outside and low velocity flow on the inside can cause less noisy flow than fully mixing flow. The inverted profile produced a substantially less low frequency noise but more high frequency noise. [B.Gordon, '77].

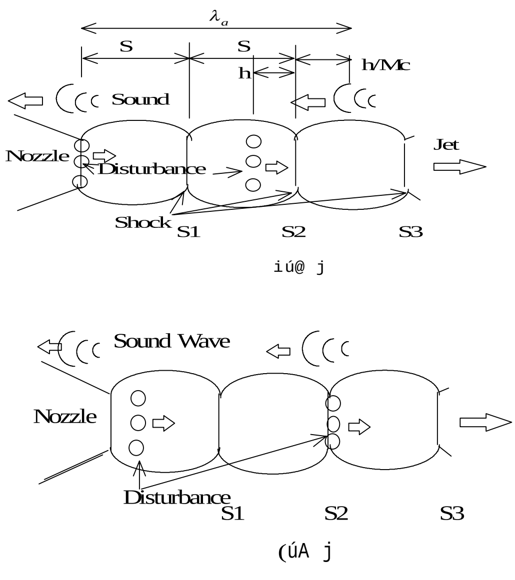

Fig. 1 Mechanism of screech tone

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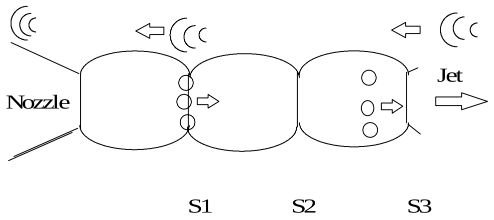

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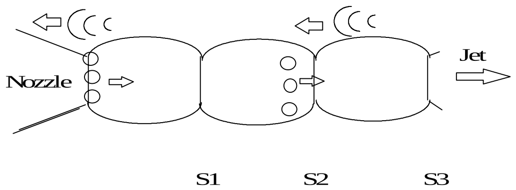

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Fig. 1 Mechanism of screech tone (contd.)

1. Mechanism of Screech Tone

It is also shown that an exact expression of the screech frequency can be obtained by a standard statistical result of Harper-Bourne and Fisher's analysis (1973):

$$\frac{\overline{F_m(t)F_n(t+\tau)}}{\Delta\omega} = S_{mn}(\omega)\cos\left[\omega(\tau - \frac{x_n - x_m}{u_c(\omega)})\right] \qquad (1)$$

where $F_m(t)$ and $F_n(t+\tau)$ are a signal of fluctuation at point m and n and at time t and t+τ respectively. $S_{mn}(\omega)$ means spectral amplitude of the cross correlation function contained in a narrow frequency band $\Delta\omega$ centered of frequency ω. x_n , x_m and u_c are coordinates corresponding to position m and n and convection velocity of disturbance respectively. From the above relation they suggested that the shock associated noise might exhibit a peak value at a frequency given by

$$f_p = \frac{u_c}{L(1 - M_c\cos\theta)} \qquad (2)$$

where L , M_c and θ are typical length, convection Mach number and observation angle measured from the direction of jet flow.

Harper-Bourne and Fisher's suggestion was supported by C.K.W.Tam in 1986. He made a statement that within experimental accuracy the spectral characteristics of the fundamental screech tone may be considered, to a good approximation, as the limit of broadband shock associated noise as θ tends to 180˚. He doubted however the mechanism proposed by Powell by stating that "In any feed back loop the phase change taken over the entire loop must be equal to an integral multiple of 2π . In many self-exited oscillation systems such as those for cavity tones and edge tones this phase integral condition is known to be the controlling factor in selecting the frequency of oscillation. In the case of the screech tones of imperfectly expanded supersonic jets, this does not appear to be so. The main reason for this is that in the case of edge or cavity tones the feedback path length is more or less fixed by the geometry of the problem. However, for jet screech tones the feedback point downstream or the location of the acoustic noise source could vary so that there is no fixed feedback length inherent in the problem."

He proposed the following formula for the frequency of the nth spectral peak of broadband shock associated noise:

$$f_n = u_c k_n / [2\pi(1 - M_c\cos\theta)], \quad n = 1,2,3.. \qquad (3)$$

where k_n means the nth wave number. His result is essentially equivalent to Harper-Bourne and Fisher's result. He put a kind of doubt concerning the existence of a definite noise source location first proposed by A.Powell in the expression.

$$f_s = \frac{u_c}{h\ (1 + M_c)} \qquad (4)$$

where h stands for the distance of noise source from a nozzle exit..

His original expression took the following form.

$$\frac{N + p}{f_s} = \int \frac{dh}{u_c} + \frac{h - \ell\lambda_a}{c} \qquad (5)$$

where N, p and ℓ are integer or real number. If u_c is constant , $\ell = 1$, and $N = p = 0$, then above equation is obtained. However there remained an ambiguity concerning the noise source distance h .

The Powell's model was again experimentally proved by detailed observation by J. Panda in 1996, although he adopted a spatial periodicity instead of the shock cell spacing. He considered two oppositely moving wave system of the same angular frequency, ω , and different wavelength λ_s and λ_h . The resultant fluctuation can be written as:

$$f = \sin\left(\frac{2\pi}{\lambda_s}x + \omega t\right) + \sin\left(\frac{2\pi}{\lambda_h}x - \omega t\right) \qquad (6)$$

The mean-square of the resultant fluctuation is calculated as:

$$\overline{f^2} = \frac{\omega}{2\pi \int_0^{2\pi/\omega} f^2 dt} = 1 - \cos 2\pi\left(\frac{1}{\lambda_s} + \frac{1}{\lambda_h}\right)x \qquad (7)$$

The above equation shows that a standing wave pattern is expected with a spatial periodicity L_{SW} that satisfies

$$\frac{1}{L_{SW}} = \frac{1}{\lambda_s} + \frac{1}{\lambda_h} \qquad (8)$$

Since $\lambda_s = c/f_s$ and $\lambda_h = u_c/f_s$

$$\frac{1}{L_{SW}} = \frac{f_s}{c} + \frac{f_s}{u_c} \quad (9)$$

Rearranging,

$$f_s = \frac{u_c}{L_{SW}(1+\frac{u_c}{c})} \quad (10)$$

He approximated L_{SW} as L the shock cell spacing.

The present author gives a physical explanation of the model. Figure 1 shows a model of an expanded jet issued from a nozzle that contains shock waves s_1, s_2, s_3 and so on. Each shock cell span is assumed constant and put *S*. Sound waves are directed upstream while disturbances are convected downstream. Let us begin with the case that a sound wave arrives at the nozzle lip and a new disturbance pressure is generated at the nozzle exit (case (i) of Fig. 1). At the same time, another sound wave follows the preceding wave with the span of λ_a and another disturbance is located h from the second shock wave s2. The span λ_a corresponds to the acoustic wave length.

The proposed condition for the generation of screech tone is **"each sound wave should meet with a disturbance pressure wave at each shock wave."** Let us call it **Sound-Disturbance-Resonance (SDR) condition.** To satisfy the condition, another sound wave should be located downstream of the second shock wave s_2 by h/M_c. Let call the sound wave SW1. When SW1 encounters the preceding disturbance at s_2, the newborn disturbance is convected by h taking time of h/u_c. The remaining time for the disturbance to reach the shock wave s_1 is $(S-h)/u_c$ and SW1 takes S/c to arrive there. The both time should equal to each other. Hence

$$\frac{S}{c} = \frac{S}{u_c} - \frac{h}{u_c} \quad (11)$$

where h is a distance between an initial row of disturbance and the second shock, and *S*, u_c and *c* stand for shock cell span, convection velocity of disturbance and acoustic velocity, respectively.

$$\therefore \frac{h}{u_c} = \frac{S}{u_c} - \frac{S}{c} \quad (12)$$

and

$$h = S(1-M_c) \quad (13)$$

As seen from the disposition of Fig. 1

$$\lambda_a = 2S + h/M_c = S(2+1/M_c - 1) = SM_c(1+M_c) \quad (14)$$

Hence,

$$f_s = c/\lambda_a = c/SM_c(1+M_c) = u_c/S(1+M_c) \quad (15)$$

The expression proves that S is theoretically taken for L_{SW}. Putting for the acoustic pressure p_a

$$p_a = A\exp(i\omega(t - \frac{x-x_1}{c})) \quad (16)$$

and fluctuation pressure of disturbance p_d can be put as

$$p_d = D\exp(i\omega(t - \frac{x-\xi_1}{u_c})) \quad (17)$$

where x_1 and ξ_1 are axial distance of acoustic wave and disturbance pressure wave at t=0. As seen from Fig.1 (i), we obtain,

$$\frac{x_1 - 2S}{c} = \frac{2S-\xi_1}{u_c} \quad (18)$$

$$\xi_1 = 2(1+M_c)S - M_c x_1 \quad (19)$$

where, $M_c = u_c/c$ (20)

At x=0, the difference of the both phase should be integer multiply of 2π.

$$\omega(\frac{x_1}{c} - \frac{\xi_1}{u_c}) = \omega(\frac{x_1}{c} - \frac{2S(M_c+1) - M_c x_1}{u_c}) =$$

$$\omega(\frac{x_1}{c} - \frac{2S(M_c+1)}{u_c} + \frac{x_1}{c})$$

$$= \omega(\frac{2x_1}{c} - \frac{2S(M_c+1)}{u_c} = 2n\pi \quad n = 0,1,2,3,....$$

Since again as seen from Fig. 1(i), $x_1 = \lambda_a$ and $\omega = 2\pi f_s$,

$$2\pi f_s(\frac{2\lambda_a}{c} - \frac{2S(M_c+1)}{u_c}) = 4\pi(1 - \frac{f_s S(M_c+1)}{u_c} = 2n\pi$$

$$\therefore 2 - \frac{2f_s S(M_c+1)}{u_c} = n$$

$$f_s = (2-n)\frac{u_c}{S(M_c+1)} \quad (21)$$

Since f_s is positive, n should equal to 0 or 1.

2. Broad Band Shock Associated Noise

Let us consider the spectral feature of shock associated noise. First assume that a sound wave is emitted when a disturbance pressure arrive at a shock wave s_i. The sound wave takes time r_i/c to reach an observation point P where r_i is the distance between P and s_i. According to the SDR condition, another sound wave is emitted when the disturbance arrives at s_{i+1} delaying by S/u_c. By the new sound emitted at s_{i+1} arrives at the observation point P after leaving the shock wave s_i, there should be n cycle of sound wave along the route of r_i. By introducing period T of the sound wave, the following expression holds accordingly:

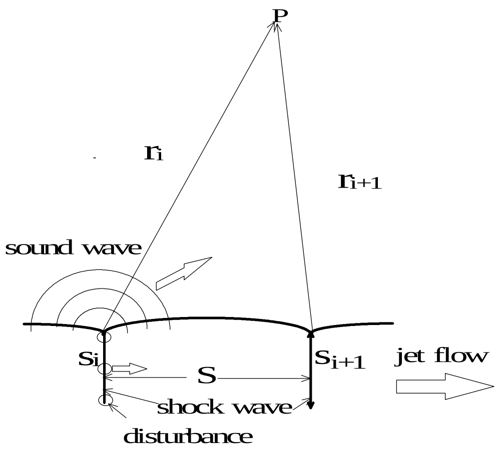

Fig. 2 Mechanism of shock associated noise

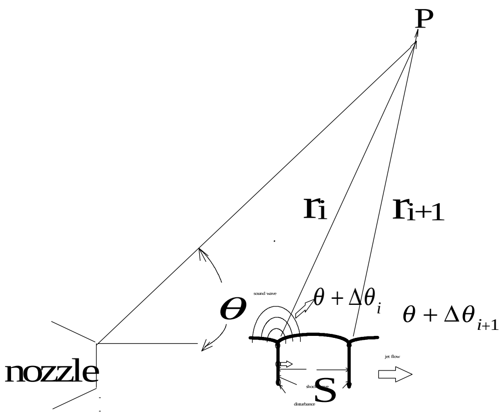

Fig. 3 Sound emitted from shock wave

$$\frac{S}{u_c} + \frac{r_{i+1}}{c} - \frac{r_i}{c} = nT \qquad (22)$$

$$\therefore f_s = \frac{1}{T} = \frac{1}{n} x \frac{1}{\frac{S}{u_c} + \frac{r_{i+1} - r_i}{c}} = \frac{u_c}{nS(1 - M_c \frac{r_i - r_{i+1}}{S})} \qquad (23)$$

$$\approx \frac{u_c}{nS(1 - M_c \cos(\theta + \Delta\theta_i))} \approx \frac{u_c}{nS(1 - M_c \cos\theta)}$$

The result is coincident with Harper-Bourne and Fisher's result. However, Since there is no strong emission of sound from s_i until the time when the new disturbance reaches s_{i+1}, integer n should be unity, though we could not deny a possibility that a weak sound of same phase may be produced at s_i. This may be an answer to Tam's question why Harper-Bourne and Fisher's model predicts the spectral levels of all the higher harmonics to be comparable to that of the fundamental which is in direct contradiction to experimental observations.

3. Effect of Reflection

When a perfectly rigid reflector is placed at a upstream distance d from the nozzle exit, the effect is replaced by

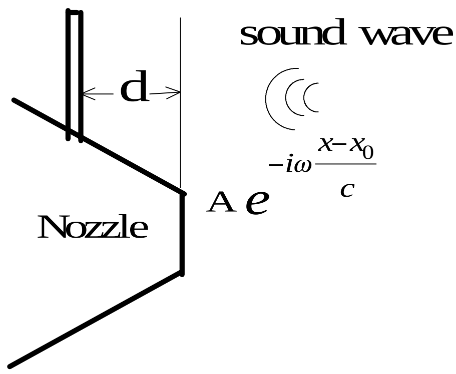

Fig. 4 Model of a sound wave near a reflector

a set of image sources, symmetrically placed with respect to the reflector plane, with both source and its image radiating into unbounded space. By omitting the temporal term, a sound pressure is represented by

$$Ae^{-i\omega\frac{x - x_0}{c}}$$

The effect of reflector is represented by

$$Ae^{i\omega\frac{x - x_0 + 2d}{c}}$$

The total pressure p is

$$p = Ae^{-i\omega\frac{x - x_0}{c}} + Ae^{i\omega\frac{x - x_0 + 2d}{c}}$$

$$= Ae^{-i\omega\frac{d}{c}}(e^{\frac{i\omega d}{c}} e^{-i\omega\frac{x-x_0}{c}} + e^{\frac{i\omega d}{c}} e^{i\omega\frac{x-x_0}{c}}) = Ae^{\frac{i\omega d}{c}}\{e^{-i\omega(\frac{x-x_0}{c}-\frac{d}{c})} + e^{i\omega(\frac{x-x_0}{c}-\frac{d}{c})}\}$$

$$= 2A\cos\frac{\omega(x - x_0 - d)}{c} e^{\frac{i\omega d}{c}} = 2A\cos\frac{\omega(x - x_0 - d)}{c}(\cos\frac{\omega d}{c} - i\sin\frac{\omega d}{c}) \qquad (24)$$

The real part of p is

$$A\cos\frac{\omega(x - x_0 - d)}{c}\cos\frac{\omega d}{c} \qquad (25)$$

Hence if

$$\frac{\omega d}{c} = \frac{\pi}{2}(2m - 1) \quad m = 1,2,3.... \qquad (26)$$

or

$$\mathrm{d} = \frac{c(2m-1)\pi}{2\omega} = \frac{(2m-1)\lambda}{4} \qquad (27)$$

acoustic pressure is theoretically cancelled. On the other hand when d is 0, the amplitude of p is doubled at each cycle of feedback loop of screech tone and final increase of the amplitude will be enormous.

JET NOISE SUPPRESSOR

The kind of jet noise may fall in three categories, turbulent mixing noise, jet screech and broadband shock associated noise. Of course the latter two noise only occur in supersonic flow. Since the energy of jet noise is proportional to the 8^{th} power of flow velocity, noise problem becomes more crucial in the case of supersonic flow.

Generally speaking, there are two methods of noise control; active control and passive control. The classification of noise suppressors are listed in Table 1. Here ANC and PNC mean Active Noise Control and Passive Noise Control respectively. In the present paper let address ourselves to the latter method. Passive control of jet noise may also fall in two categories, exit velocity reduction method and mechanical method. The methods in former classification are a ducted fan-engine, bypass-engine, exhaust nozzle with an ejector and enlargement of exit area of exhaust nozzle. Those in the latter classification are also separated into three groups, modification inside a nozzle and devices applied at the exit or outside of the exit of a nozzle and shielding by flow or heat gradient or acoustical cancellation. Noise control method applied inside a nozzle are sound absorbing material lined at inside wall of an exhaust nozzle or an engine inlet, perforated wall or material applied at the wall of exhaust nozzle. Especially perforated wall exerted an effective noise reducing effect to jet noise including a screech tone.

In early days, A.Powell studied the effect of notched appendage, cambered radial vanes, disc appendage at the nozzle exit and gauze extension in reducing jet screech. He proposed a condition for a feedback loop that is $q\eta_s\eta_t\eta_d \geq 1$, where q denotes the amplification of the disturbance in the stream, η_s an efficiency by which it creates sound, η_t and η_d similarly referring to the transmission of sound to the orifice and the creation of a new stream disturbance. According to SDR condition, however, η_s should include the influence of upstream propagating sound wave. His idea of the noise suppressor looks good but was too coarse to be of practical use.

In 1983, Seiner, J.M. reviewed that porous plug nozzle and inverted velocity profile coannular jet with critical Mach number ratio between the two streams deserve special merit. Chute/lobe type combined with plug is practical type of jet noise suppressors. However there is a limit in improving the efficiency of noise reduction and the thrust loss and weight addition should be decreased more. Rather recently, experiments were conducted at Boeing Interior Noise Test Facility (INTF) to evaluate the reduction of jet noise by a small diameter cord in a cold underexpanded jet plume. Different cord diameters, length and styles were used to determine the optimum configuration. The optimized configuration of the cord was multi-stranded Kevlar fibers, 3 jet diameters long and having thickness of 2% of the jet diameter. A small knot at the downstream tip of the cord stabilized it along the jet centerline. The test were performed using a single jet and coaxial cold coflowing jets. The primary jet Mach number was M=1.2, and the secondary flow was set at M=0 or 0.876

Table 1: Classification of noise suppressor

<table>
<tr><td rowspan="3">ANC</td><td colspan="3">Fan/Turbine Noise Control</td></tr>
<tr><td colspan="3">Active Flow Control for Noise reduction</td></tr>
<tr><td colspan="3">Ejector Control</td></tr>
<tr><td rowspan="16">PNC</td><td rowspan="2">Reduction of Exit Velocity</td><td colspan="2">Turbine Bypass Engine</td></tr>
<tr><td colspan="2">Variable Flow Control Engine</td></tr>
<tr><td rowspan="14">Mechanical Device</td><td rowspan="2">Internal Device</td><td>Lining with Sound Absorber</td></tr>
<tr><td>Perforated Wall</td></tr>
<tr><td rowspan="9">Exit/External Device</td><td>Multitube</td></tr>
<tr><td>Chute/Lobe</td></tr>
<tr><td>Plug</td></tr>
<tr><td>Tab</td></tr>
<tr><td>Shroud</td></tr>
<tr><td>Slot</td></tr>
<tr><td>Ejector</td></tr>
<tr><td>Filament</td></tr>
<tr><td>Irregular Exit</td></tr>
<tr><td rowspan="3">Shielding or Cancellation by flow or Heat Gradient</td><td>Coaxial Flow with Inverted Velocity Profile</td></tr>
<tr><td>Exit Velocity with Temperature Gradient</td></tr>
<tr><td>Cancellation Baffle</td></tr>
</table>

Acoustic and flow visualization data showed substantial decrease of the jet noise and a significant change in the flow structure. The shock waves present in the core of the underexpanded jet were weakened and helical structures in the shear layer were suppressed. The strongest effect observed was the complete suppression of the screech toned and reduction of up to 30 dB in the shock-associated noise. This effect was stronger in the single jet than in the coaxial jet and was most noticeable in the region perpendicular to the jet at the nozzle plane. A substantial decrease of the turbulent mixing noise was obtained in the entire range of measured frequencies up to 40 kHz. This effect was most pronounced in the aft region of the jet. The filament changed both the magnitude and directivity of the sound emission.

The problem is the loss of thrust , though Anderson, B.A. et al. (1999) mentioned that the method presents an effective technique for jet noise reduction which is easy to implement and which does not carry heavy penalty in extra dead weight, loss of thrust and reduced propulsion efficiency. They did not measured the loss of thrust and propulsion efficiency.

Norum,T.D. (1983) noted that the amplitude of screech tone was reduced about 10dB when the lip thickness of nozzle was eliminated and another 10 dB when the periphery was disrupted by slots. In more detail, small slots increased the suppression over that obtained from thin-lipped configuration for the B-mode screech, but appeared to destroy the C-mode screech. (There are three modes, A, B and C for the change of acoustic spectrum with jet pressure ratio according to A.Powell). The tubes with long slots were shown to exert extensive suppression at all pressures. K.seto and Lee,D.H. carried out more systematic investigation of the effect of slots and showed a tube with four slots of 1D in length and 0.2D in width where D is the exit diameter is very effective in reducing jet noise, although the jet screech is more effectively reduced by a well designed perforated tube.

Tam, K.W and Zaman, K.B.M.Q. (2000) observed that nozzle geometry modification into simple elliptic or rectangular shape is not an effective way to suppress jet noise. They showed that for jets from nonaxisymmetric nozzles with two planes of symmetry and small thrust loss, the radiated sound field was axisymmetric. The sound intensity was the same as that of an equivalent circular jet (same nozzle exit area). In other words, nozzle geometry modification into simple elliptic or rectangular shape was not an effective way to suppress jet noise. Nozzles with tabs can modify the spectrum of radiated sound and it may be possible to tailor the noise spectrum of a tabbed jet. In 1977 Tanna, H.K. showed that tab (projection inside a nozzle) and wrapping of nozzle lip with sound absorbing material was effective in reducing screech tone. Thereafter, several researches of tabs have been carried out and the effect of tabs was confirmed. Tabs can stabilize the underexpanded jet and reduce η_d . The optical observation around a tab indicated the presence of streamwise vortices (Reeder,M.F., 1995). Furthermore, thrust loss due to the attachment of tabs has been reported comparatively low.

EXPERIMENTAL STUDIES OF PERFORATED TUBE AND SLOTTED TUBE

1 Apparatus

The convergent nozzle of 30 degree convergence angle along with a perforated tube of 10mm in diameter were used. The conditions and parameters of the perforated tube are shown in Fig. 5. The perforation angle (angle between the perforation axis and the tube axis), θ, diameter of perforation and thickness of the tube were varied for different experiments (Table 1). Slotted tubes with fixed slot width of 2mm were tested where slot length (S) and slot number (N) were made to change (Table 2). The effective length (L) and the inside diameter (D) of perforated tubes and slot tubes were 50mm and 10mm respectively.

2 Sound Measurements

Air compressor, air cooling separator, air dryer, oil mist filter were used to maintain the dry unheated jet through the convergent nozzle and different perforated and slotted tubes. The sound generated from the under-expanded supersonic jet was measured inside a semi-anechoic chamber (3.5x3x2m internal dimension) by a 12.7 mm (1/2 inch) condenser microphone (B&K) and FFT analyzer. The microphone was placed at 600mm away from the center (For the nozzle only, the center of nozzle exit was used) of the slot or perforated tube exit and it was placed in the same horizontal plane with those tubes making angles of 30 and 90 degrees from jet axis. The pressure ratios were changed from 1.2 to 3.0 at the step of 0.2. Moreover, 3.4, 3.8, 4.0, 4.8, 5.2, 5.6 and 6.0 pressure ratios were also used.

3 Thrust Measurements

A disk of diameter 200mm was installed vertically toward the way of jet. The pressure that was pressed by the jet to disk was measured by load cell. A strain gauge-type censor was utilized to measure the pressure. The signal of the strain gauge was amplified and sent to a galvanometer to read the pressure.. The distance to the disk from the nozzle and tube exit and pressure ratios were maintained as 1.0cm, 5.0cm, 10.0cm, 20.0cm, 30.0cm and 1.0, 2.0, 3.0, 4.0, 5.0 respectively.

4 Experimental Results

4.1 Sound measurement

Overall sound pressure level of various perforated tubes of B-type, O-type, N-type and a nozzle with and without a straight tube with thin lip thickness are shown in Fig.6. For the measurement, a microphone was placed in the direction of 30 deg.

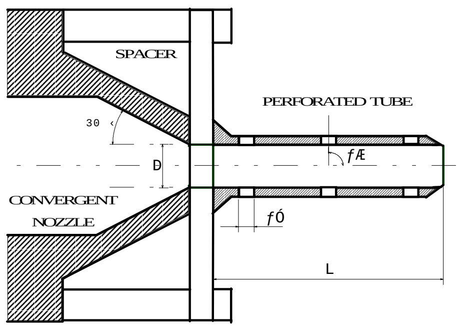

Fig.5 Configuration of a Convergent Nozzle and a Perforated Tube

Table 2: Dimension of Parameter

Perforated Tube	θ	ϕ	Porosity
O-type	30°	1.5mm	0.063
N-type	90°	1.5mm	0.164
B1-type	150°	1.5mm	0.063
B2-type	150°	3.0mm	0.240
B3-type	150°	3.0mm	0.300

Table 3: Dimension of Parameter

Slotted Tube	N	S/D
4SL5	4	0.5
4SL10	4	1.0
4SL20	4	2.0
8SL5	8	0.5
8SL10	8	1.0
8SL20	8	2.0

from the jet axis. As for B-type having upstream directed perforations, about 2 to 6 dB reduction was obtained by B-1 type while maximum 11 dB reduction was obtained by B-2 type perforated tube with reference to a straight tube attached to the convergent nozzle.

If compared to the convergent nozzle, maximum 13dB reduction was obtained. B-3 type perforated tube exerted similar reduction of noise. O-type perforated tube has perforation directed downstream making an acute angle of 30 deg with tube axis. It was very effective in reducing screech noise measured at 90 deg much better than B-type. However, in the range of lower pressure ratio, a discrete tone was generated and the noise level increased. The discrete tone is considered as a kind of edge tone.

N-type perforated tube has similar performance in reducing screech tone measured at a 90 deg measuring point. However for the noise measured at 30 deg, the noise reducing effect was smaller than those of B-2 and B-3 type as shown in Fig.6. Also B-2 type exerted better performance than B-3 type in spite of small porosity. Figure 7 shows overall sound pressure levels of slotted tube measured at 30 deg. 4-slot tube of 1D in length (D is exit diameter) exerted best performance among all tested slotted tubes. The lip thickness of the tube was 2mm. It obtained maximum 7 dB reduction compared to the base tube (a straight tube) or

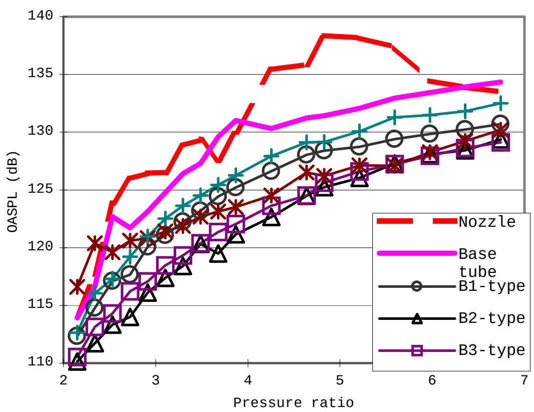

Fig. 6 Variation of OASPL with jet pressure ratio (measured at 30deg)

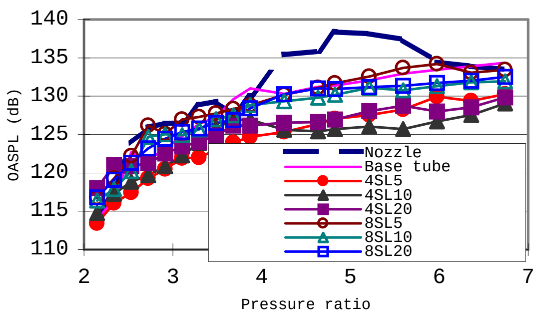

Fig. 7 Variation of OASPL with jet pressure ratio (measured at 30deg)

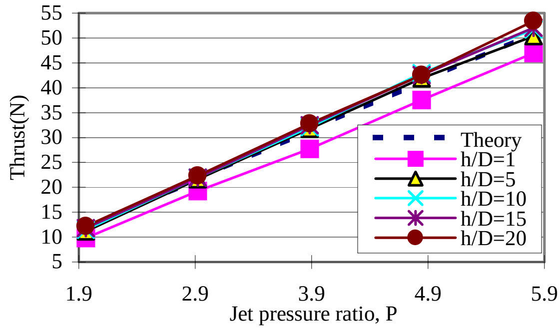

Fig.8 Comparison between measured and theoretical thrust of nozzle

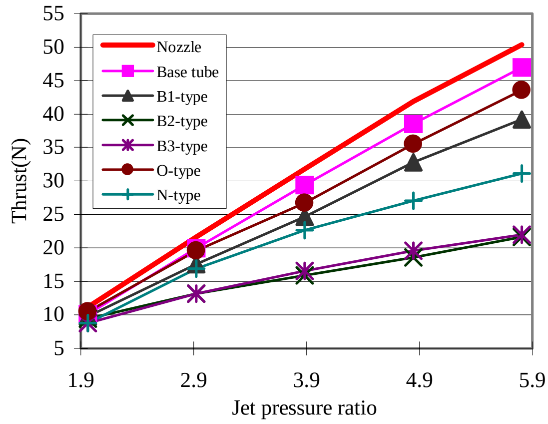

Fig.9 Variation of Thrust with Jet Pressure Ratio for Perforated Tube

maximum 13 dB reduction compared to the convergent nozzle. The number of 4 was better than the number of 8.

4.2 Thrust measurement

Theoretical thrust is given as follows;

$$F = \dot{M}V_j + (P_j - P_0)A \qquad (28)$$

where $\dot{M}$, V_j , P_j , P_0 and A are mass flux, exit velocity, static pressure at the nozzle exit, atmospheric pressure and nozzle exit area, respectively.

Figure 8 shows the comparison between the theoretical thrust calculated by Eq. (28) and the measured thrust measured at several distances from the exit plotted against jet pressure ratio (the ratio o jet pressure to the atmospheric one). In the figure, D and h are exit diameter and the distance from the exit, respectably. The diameter D was fixed to 10mm in the experiment. All the data looked converged except the case of h/D=1. The data of h/D=5 happened to be most close to the theoretical value. So we made avail of the circumstances. Measured thrust of perforated tubes, the nozzle and the base tube are plotted against pressure ratio and shown in Fig. 9. The thrust of B-2 and B-3 type was reduced by almost half compared to the base tube. We have seen that noise reduction of B-2 was greater than that of B-3 in spite of the lower porosity. As for thrust, thrust reduction of B-2 also greater than that of B-3 showing rather reasonable result.B-1type had the greatest thrust among B-type perforated tube while it was inferior to O-type of the same porosity.

Change in thrust of slotted tube is shown in Fig.10. In the figure, data of pressure ratio below 2.9 were neglected since any discrimination was not seen. Thrust loss of slotted tube was found less than that of perforated tube. Especially, 4SL5 (slotted tube with 4-slot of 5mm in length) and 4SL20 suffered comparatively small thrust loss, though the difference between those and 4SL10 was small. 8-slot tube showed similar trend.

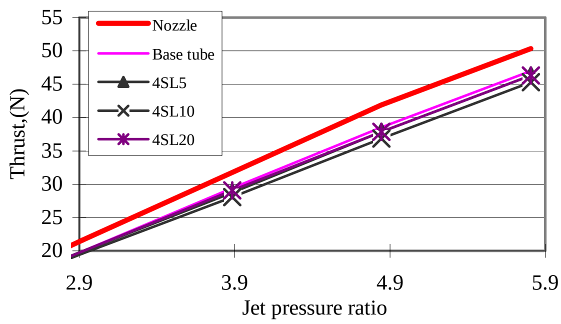

Fig.10 Variation of Thrust with Jet Pressure Ratio for Slotted Tube

4.3 Discussions

The attachment of a perforated tube or a slotted tube accelerate flow by the efflux through the perforation or slot in the case of underexpanded flow and super pressure is eliminated, and flow approaches to complete expanded flow. The complete expanded flow generates greater thrust than underexpanded flow of the same stagnation pressure. In the present experiment, any tube could not give greater thrust than the nozzle or the base tube. One of the reasons for the fact may be an overestimate of thrust due to the super pressure. In the case of the nozzle and the base tube, super pressure expands in atmosphere and causes greater force at the baffle while perforated tube or slotted tube causes correct thrust at the baffle. Furthermore, the effect of friction of the bearing used for the baffle is not negligible and only a lower value may be obtained.

As for perforated tubes, those with smaller angle of θ showed desirable performance from the standpoint of noise reduction and thrust loss. On the other hand for slotted tubes, 4-slot tube exerted better performance than 8-slot tube. Slot length ratio (S/D) of unity showed the greatest noise reduction among tested slotted tubes. Thrust loss, however, was rather smaller in the case of S/D=0.5 and S/D=2.0.

In order to evaluate the thrust loss due to inserting of perforated tube or slotted tube, the value of the quantity, thrust of the base tube – thrust of each tube)/thrust of the base tube, was calculated and is plotted in Fig. 11 against pressure ratio. As is shown, B-2 type and B-3 type perforated tube suffered from large thrust loss in all the range of pressure ratio. It amounted to 54 % at the pressure ratio of 6. B-1 type showed almost constant value of 16% in the range of pressure ratio above 4. O-type tube suffered from the smallest thrust loss among tested perforated tubes. The maximum loss was 9%. On the other hand, slotted tubes showed desirable features concerning the thrust loss. In the range of pressure ratio below 3, thrust augmentation was obtained by 4SL tube. Even above 3, thrust loss was utmost 2 to 4 %. Overall sound pressure level of each tube was divided by the thrust and is plotted against jet pressure as shown in Fig.12. O-type perforated tube and 4SL5 showed the best performance in this respect.

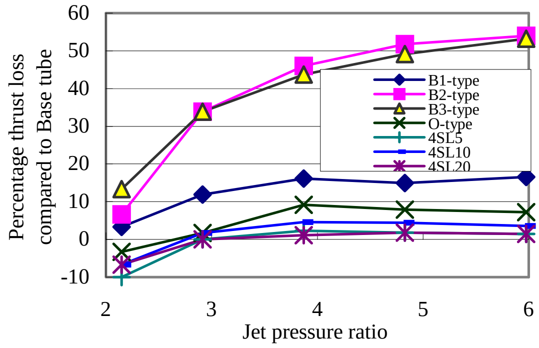

Fig.11 Thrust Loss by attachment of a variety of tubes

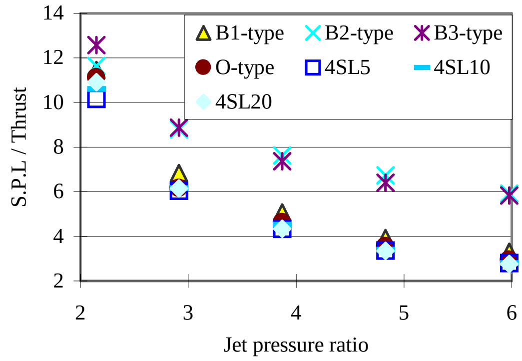

Fig.12 Sound Pressure Level per thrust

CONCLUSIONS

(1) O-type perforated tube and 4SL10 slotted tube showed good performance of reducing noise with low thrust loss.
(2) Tab is considered one of the promising device since it can stabilize flow and can reduce shock-associated noise without heavy thrust loss.
(3) Mechanism of screech tone is clearly explained by Sound-Disturbance-Resonance conditions.

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