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An Experimental Study of the Nozzle Lip Thickness Effect on Supersonic Jet Screech Tones

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It is well known that screech tones of supersonic jet are generated by a feedback loop driven by the instability waves. Near the nozzle lip where the supersonic jet mixing layer is receptive to external excitation, acoustic disturbances impinging on this area excite the instability waves. This fact implies that the nozzle lip thickness can influence the screech tones of supersonic jet. The objective of the present study is to experimentally investigate the effect of nozzle-lip thickness on screech tones of supersonic jets issuing from a convergent-divergent nozzle. A baffle plate was installed at the nozzle exit to change the nozzle-lip thickness. Detailed acoustic measurement and flow visualization were made to specify the screech tones. The results obtained obviously show that nozzle-lip thickness significantly affects the screech tones of supersonic jet, strongly depending on whether the jet at the nozzle exit is over-expanded or under-expanded.

Key Words : Shock-Associated Noise, Supersonic Jet, Screech Tone, Shock Wave, Nozzle-Lip Thickness

Nomenclature

D	Nozzle exit diameter, jet diameter
f	Frequency
M	Mach number
OASPL	Overall sound pressure level
p	Pressure
r	Radial distance from the nozzle exit
SPL	Sound pressure level
S_t	Strouhal number
T	Temperature
t	Nozzle lip thickness
t_b	Baffle plate thickness
u	Jet velocity
γ	Ratio of specific heats
θ	Angle with respect to the jet axis

Subscripts

0	Stagnation state in the plenum chamber
b	Ambient state
d	Design condition at the nozzle exit
j	Fully expanded condition of the jet
p	Peak spectrum value for the broadband shock-associated noise
s	Screech tone

1. Introduction

Supersonic jet noise problems have long been a very important issue in many diverse engi-

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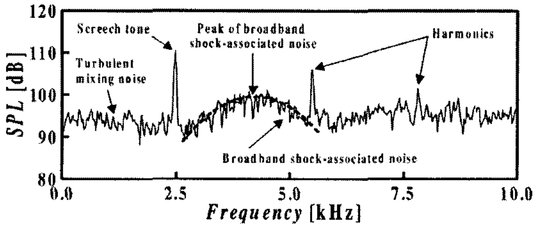


Fig. 1 Typical far-field noise spectrum of supersonic jet

neering applications such as supersonic aircraft, jet propulsion thrust vectoring, fuel injector for supersonic combustion, soot blower device, thermal spray device, etc (Strykowski, 1996 ; Ramesh et al., 2000 ; Jameel et al., 1994 ; Yumoto et al., 2003 ; Lee et al., 2003). In general, it is known that the supersonic jet noise consists of three major components : the turbulent mixing noise, the broadband shock-associated noise, and the screech tones, as typically shown in Fig. 1.

With regard to the screech tone in supersonic jet, Powell (1953a, b) first proposed that the screech tone and its harmonics are generated by a resonant feedback loop which is composed of : (1) instability wave growth in the shear layer of shock-containing supersonic jet, (2) the interaction of the instability wave and shock-cell system to generate acoustic waves, (3) the acoustic feedback of acoustic wave upstream outside the supersonic jet to produce another instability wave (disturbance), and (4) receptivity processes at the nozzle-lip to produce the coupling of instability waves in shear layer with external acoustic waves.

Figure 1 shows typical noise spectrum of supersonic jet. Of the major components consisting of the jet noise, in general, the screech tone has a strong directivity and high intensity, and thus can cause sonic fatigue failure of aircraft structures (Hay and Rose, 1970 ; Seiner et al., 1988). Physical understanding of screech tone is of practical importance to find out noise suppression strategies as well as to obtain mixing enhancement in genius applications of jet screech tones.

A great deal of experimental and theoretical researches has been carried out to specify the screech tones. Umeda and Ishii (2001) made an experimental work to investigate the sound sources of screech tones radiated from a sonic jet, and showed that the sound source is located near the third shock cell. Panda (1998, 1999) investigated the generation and cessation of screech tones in under-expanded jets, and obtained a screech frequency formula using the standing wavelength (not the shock spacing). Raman (1997, 1998) argued that the cessation of screech tone in highly under-expanded rectangular jets is due to the acoustic feedback to the nozzle lip, which is blocked by the excessive expansion of jet boundary. Raman (1997, 1998) further showed that for rectangular jets, the screech tones are reactivated when the nozzle lip becomes thicker, and a small variation in lip thickness can change the screech amplitude up to about 20dB.

Abdel-Fattah (1988) investigated the relationship between screech tones and shock-cell dimensions. According to his experiment results, the wavelength of screech tone and the length of the second shock-cell are inversely proportional to the throat diameter of convergent-divergent nozzle. Powell et al. (1992) and Umeda and Ishii (2002) investigated the oscillation modes of under-expanded jets, and reported that depending on the jet pressure ratio, the under expanded jet has four characteristic oscillation modes, such as an axially symmetric (varicose, torroidal) mode, a sinuous (lateral, flapping) mode, a helical mode, and another sinuous mode.

According to the research results mentioned above, the screech tone is very sensitive to the nozzle geometry. In actual, most of supersonic jet devices have some objects near the nozzle exit. These objects can influence the development of the initial shear layer of the supersonic jet and consequently affecting the acoustic feedback loop. Harper-Bourne and Fisher (1973) showed that a sound reflector can significantly influence the screech tone, and the reflector diameter is an important factor to determine the screech frequency. Nagel et al. (1983) reported that the change of the reflector location is important to eliminate the jet screech tone. However, Antonov et al. (1977) pointed out that a reflector can reinforce the screech tone and can reduce the length of supersonic jet core.

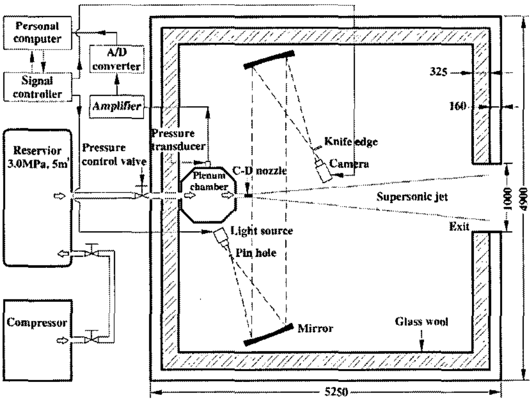
Norum (1983) made experimental works over a wide range of nozzle pressure ratio, and showed that the screech tone is significantly influenced by the position of the reflector which controls the acoustic feedback loop. Ponton and Seiner (1992) and Shen and Tam (2000) investigated the effect of nozzle-lip thickness on screech tones, and showed that the nozzle lip thickness affects the jet dynamics through an alteration of the initial entrainment and/or through an increased amplification of initial shear layer disturbances. They further showed that an increase in the nozzle lip thickness causes an important variation of the screech tones, depending on the jet oscillation modes.

Until now, many works have been made to reveal the effects of reflector geometry and nozzle-lip thickness on screech tone. These works are mainly limited to under-expanded supersonic jets issuing from a convergent nozzle. It has been well known that supersonic jet structure is strongly dependent on the jet pressure ratio as well as the nozzle configuration. For over-expanded jets, the jet structure is different from that of under-expanded jets, and the screech tone characteristics may be influenced by the jet expansion state at nozzle exit. Under these situations, the effect of the nozzle lip thickness on the screech tones will be different. For instance, the screech tones can be different depending upon whether the jet at nozzle exit is over-expanded, correctly expanded or under-expanded. However, at present, the screech tone characteristics in over-expanded jets discharged from convergent-divergent nozzles are not fully investigated. The objective of the present study is to experimentally investigate the effect of the nozzle lip thickness on the screech tone of the supersonic jets, which are discharged from a convergent-divergent nozzle operating at a wide range from over-expanded to moderately under-expanded conditions.

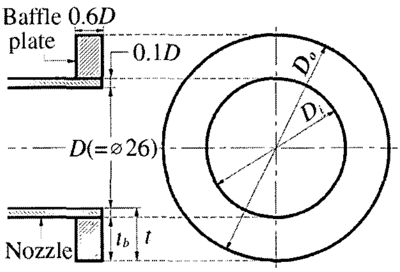
An anechoic test facility has been fabricated to investigate the screech tones of supersonic jets having a design Mach number of 2.0. A baffle plate is installed at the nozzle exit to alter the nozzle-lip thickness. Acoustic characteristics of screech tones, such as screech frequency, and amplitude are measured at far field and these are analyzed to quantitatively specify the effect of the nozzle lip thickness on the screech tone. The supersonic jet flow is visualized by a high-quality Schlieren optical system with a 20 ns pulse duration.

2. Experimental Facilities

Experimentation has been performed in an anechoic test room that is schematically shown in Fig. 2. The anechoic test room having a dimension of 5.3×4.9×4.9 m has been constructed to test supersonic jet screech tones. Compressed dry air is stored in a high-pressure tank that has a capacity of 5 m^3, and is supplied to the plenum chamber, in which a honeycomb system reduces flow turbulence. A convergent-divergent nozzle with a design Mach number of 2.0 is installed on the end wall of the plenum chamber. The pressure inside the plenum chamber is controlled by



(a) Experimental facility



(b) Baffle plate

Fig. 2 Schematic diagram of experimental facility and baffle plate a pressure regulator valve which is located upstream of the plenum chamber.

A convergent-divergent nozzle is manufactured based upon the method of characteristics. The nozzle has a throat diameter of 20 mm and an exit diameter (D) of 26 mm. It has a straight section near the exit of the nozzle. A baffle plate is made of an annular metal plate, and is installed at the exit of the nozzle to change the nozzle-lip thickness, as shown in Fig. 2(b). In the present study, the thickness t_b of the baffle plate is varied in the range from 11 mm ($t/D=0.5$) to 102 mm ($t/D=4.0$).

The temperature in the plenum chamber is measured by using a thermocouple, and it maintains constant at room temperature (approximately 293K) during test. The pressure is measured by a pressure transducer (Toyoda PMS-5-200K) flush mounted on the top wall of the plenum chamber. The transducer is calibrated prior to each test. The uncertainty in pressure and temperature measurements is estimated to be less than ±2 per cent. These estimations are based on the maximum possible fluctuations in the measurements.

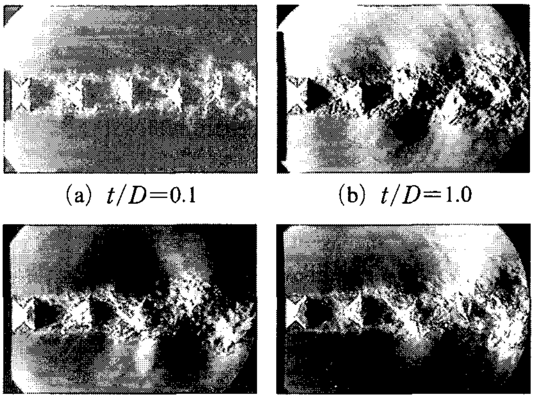
Acoustic measurements are made using a condenser microphone (Ono Sokki MI-6420) with a diameter of 6 mm. It has a sound pressure sensitivity of -17dB ±3dB (0dB=1V/Pa), and measures the maximum sound pressure level up to 140dB. The uncertainty in acoustic measurements is estimated to be less than ±1dB. Four microphones are located at a radial distance of 50D away from the exit of nozzle, and measure the sound pressures at a 12° interval between 60° and 96°. The acoustic signals are analyzed by using a 4-channel FFT analyzer (Ono Sokki Model DS0221). A FFT analysis is conducted to obtain the power spectra and sound pressure level, and providing the spectral data in the range from 0 to 40 kHz, with a frequency band width of 25 Hz.

A Schlieren optical system is employed to visualize the supersonic jet, as schematically shown in Fig. 2(a). It consists of two concave mirrors that have a diameter of 150 mm and a focal length of 1000 mm. The light source is a nano-spark with a light intensity 10 kW/sr and a duration time of 20 ns, and an open shutter camera (Nikon F4) obtains the instantaneous images enough to freeze turbulent structures in the supersonic jet.

In the present study, the jet pressure ratio, p_0/p_b is defined as the ratio of the pressure (p_0) inside the plenum chamber to atmospheric pressure (p_b), and it is varied between 2.0 and 18.0. For the present convergent-divergent nozzle with a design Mach number of 2.0, the correct expansion at the nozzle exit is obtained at $p_0/p_b=7.8$. Thus, the jet pressure ratio applied in the present study covers the supersonic jets ranging from over-expanded to moderately under-expanded conditions. Ambient pressure and temperature in the anechoic test room are measured at $p_b=101.3$ kPa and $T_b=293$ K.

3. Results and Discussion

Figure 3 shows the effect of the nozzle-lip thickness on the over-expanded jet and the resulting near-acoustic field, where $p_0/p_b=4.0$. Strong near-acoustic field is visible as the alternate dark and light regions outside the jet boundary. For a very thin nozzle-lip thickness of $t/D=0.1$, the jet is nearly symmetric. However, as t/D increases, the jet appears rather asymmetric, and seems to oscillate irregularly. For $t/D\geq 1.0$, the jet is seen to produce large sinuous oscillations, and the large-scale turbulent structures strongly interact with the shock-cell structures.

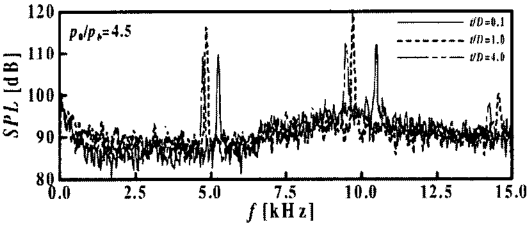

(a) $t/D=0.1$ (b) $t/D=1.0$

(c) $t/D=2.0$ (d) $t/D=3.0$

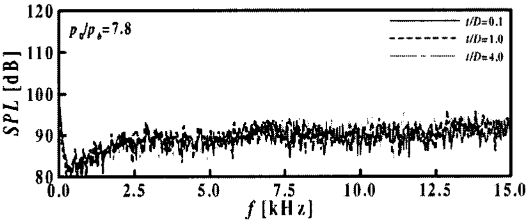
Fig. 3 Schlieren pictures showing over-expanded jets ($p_0/p_b=4.0$)

For three jet cases of over-expanded, correctly-expanded and under-expanded jets, Fig. 4 shows the far-field noise spectra measured at the location of $r/D=50$ and $\theta=96°$. For over-expanded jets of $p_0/p_b=4.5$, the screech tones have several dominant peaks with the fundamental frequency and its harmonics. For instance, the screech tones for $t/D=0.1$ have the fundamental frequency at about 5.3 kHz and the harmonics at about 10.7 kHz and 14.6 kHz. It is interesting to note that t/D alters the frequencies of the screech tones. An increase in t/D causes the frequencies of the screech tones to slightly reduce. Furthermore, t/D changes the amplitudes of the screech tones, which is dominant compared with the broadband shock-associated and turbulent mixing noises.

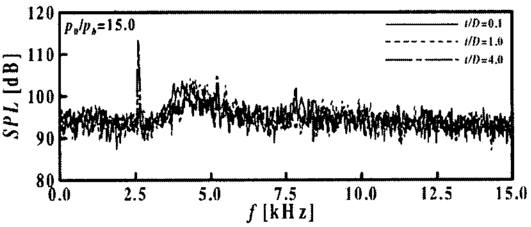
For the correctly-expanded jet of $p_0/p_b=7.8$, there are no distinct peaks regarding the screech tones, but the turbulent mixing noises with the broadband frequencies. No shock-cell structures are found in the correctly-expanded jet. In this case, t/D does not affect the jet noise spectrum. However, in the cases of under-expanded jets of $p_0/p_b=15.0$, the screech tone for $t/D=4.0$ has the dominant frequency at about 2.7 kHz, but the harmonics do not appear appreciable, although there are some weak frequency components near 5.2 kHz and 8.0 kHz. In the cases of $t/D=0.1$ and 1.0, there are no distinct peaks related to the screech tones. The present data clearly show that when the nozzle-lip thickness is increased further, the amplitude of fundamental screech tone increases and the screech tone can be also reactivated at higher nozzle pressure ratios in under-expanded jets.



(a) Over-expanded jet ($p_0/p_b=4.5$)



(b) Correctly-expanded jet ($p_0/p_b=7.8$)



(c) Under-expanded jet ($p_0/p_b=15.0$)

Fig. 4 Far-field noise spectra of supersonic jets

The above data showed that t/D remarkably change the screech tone frequencies of over-expanded jets rather than correctly expanded jets and under-expanded jets. In order to confirm this again, Fig. 5 shows the noise spectra of over-expanded jet of $p_0/p_b=6.0$, where $r/D=50$ and $\theta=96°$. The noise spectrum for $t/D=1.0$ has a dominant fundamental screech tone and its harmonics at frequency $f=4.15$ kHz and 8.30 kHz, respectively. For $t/D=2.0$, there are two fundamental screech tones which have the frequency components at $f=4.10$ kHz and 4.64 kHz, each of these two frequencies having the sound pressure levels of approximately 96dB and 105dB, respectively.

Figure 6 shows the relationship between Strouhal number (S_t) and M_j, where S_t is defined using the fundamental screech tone frequency (f_s), the diameter of nozzle exit (D) and the fully expanded jet velocity (u_j), and M_j means the fully expanded jet Mach number. The present experimental data are compared with those obtained by Norum and Seiner (1982). For reference, they

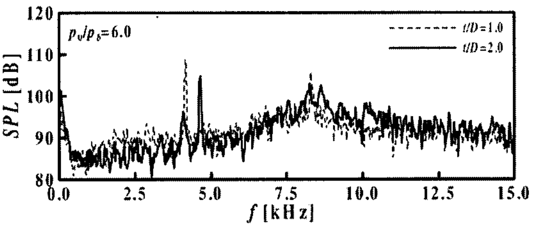
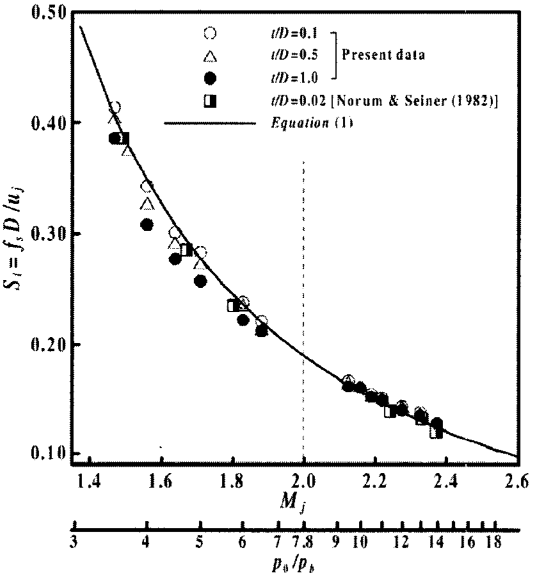
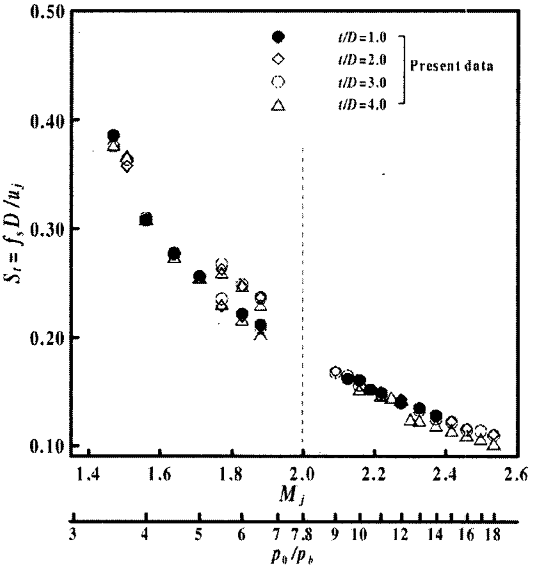


Fig. 5 Far-field noise spectra of supersonic jets ($p_0/p_b=6.0$)

measured the sound pressures at $r/D=72$ and $\theta=60^\circ\sim150^\circ$ using a convergent-divergent nozzle with a design Mach number of 2.0, and the diameter of the nozzle exit $D=49.9$ mm, and the nozzle-lip thickness $t/D=0.02$. Figure 6 also includes the theoretical prediction curve by Tam et al. (1986) and the screech tone frequency formula is given as a function of M_j in Eq. (1),



(a) $t/D=0.1\sim1.0$



(b) $t/D=2.0\sim4.0$

Fig. 6 Relationship between screech tone Strouhal number and M_j

$$f_s=0.67u_j(M_j^2-1)^{-1/2}/D_j\left[1+0.7M_j\left(1+\frac{(\gamma-1)}{2}M_j^2\right)^{-1/2}\left(\frac{T_b}{T_0}\right)^{1/2}\right]^{-1},\ (1)$$

where T_b and T_0 are the ambient temperature and the total temperature of jet, respectively. In the present study, T_b/T_0 is assumed to be unity. In Eq. (1), the fully expanded jet diameter D_j is related to the diameter of nozzle exit D through the condition of conservation of mass flux, which leads to

$$\frac{D_j}{D}=\left[\frac{1+(\gamma-1)M_j^2/2}{1+(\gamma-1)M_d^2/2}\right]^{(\gamma+1)/4(\gamma-1)}\left(\frac{M_d}{M_j}\right)^{1/2},\ (2)$$

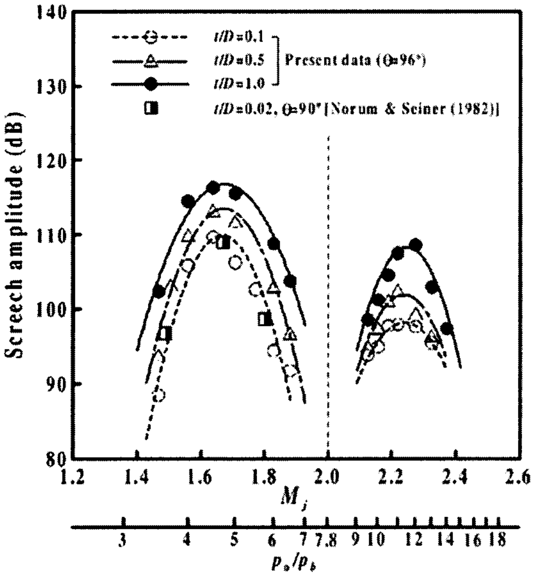
where γ is the ratio of specific heats of the gas ($\gamma=1.4$), and M_d is the nozzle design Mach number. M_j is related to the nozzle pressure ratio p_0/p_b, as given in Eq. (3),

$$M_j=\sqrt{\frac{2}{\gamma-1}\left\{\left(\frac{p_0}{p_b}\right)^{(\gamma-1)/\gamma}-1\right\}},\qquad(3)$$

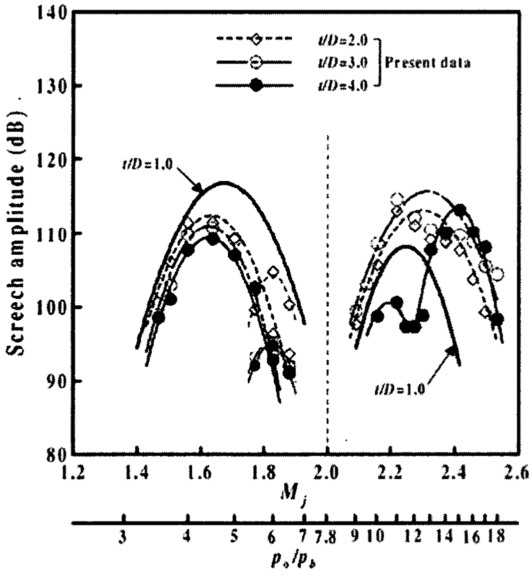
The present experimental data for three t/D values are well compared with those by Norum and Seiner (1982) and the theoretical curve (Tam et al., 1986). The Strouhal number decreases with an increase in Mach number M_j and p_0/p_b. For over-expanded conditions ($M_j<2.0$ or $p_0/p_b<7.8$), t/D significantly affects the Strouhal number. An increase in t/D reduces the Strouhal number. For instance, for $t/D\leq1.0$, the Strouhal number decreases with an increase in t/D, but for $t/D>1.0$, it does no longer change with t/D. The theoretical curve by Tam et al. (1986) slightly overpredicts the present experimental data. However, the present experimental data for $t/D=0.1$ are nearly the same to the theoretical curve.

Here it is noted that for the over-expanded jets of $1.7<M_j<1.9$, the Strouhal number data are related to two fundamental frequencies, as mentioned previously in Fig. 5. The large sinuous instability wave generated by thicker nozzle-lip propagates downstream and grows in amplitude. According to the results by Shen and Tam (2002), Powell et al. (1992) and Gutmark et al. (1989), the interaction between such an instability wave and the shock cells is capable of generating two types of acoustic disturbances. Both of them propagate upstream to excite the jet shear layer and the instability waves near the nozzle lip form a feedback loop. The slight difference in the two ways by which the feedback is accomplished can lead to different fundamental screech tone frequencies. In the present study, this tendency is also observed in Figs. 5 and 6(b).

Meanwhile, there is no data for correctly-expanded jet, since f_S was not obtainable in the present experiment. For under-expanded jets of $M_j > 2.0$, the dependence of t/D on the Strouhal number is relatively weak, compared with the over-expanded jets. In this case, the theoretical curve somewhat underpredicts the present experimental data. The present data clearly show that t/D does not significantly affect the Strouhal number, but in case of $t/D = 4.0$, the experimental data for high M_j values slightly differ from those of $t/D < 4.0$.



(a) $t/D = 0.1 \sim 1.0$



(b) $t/D = 2.0 \sim 4.0$

Fig. 7 Relationship between screech tone amplitude and M_j

Figure 7 shows the amplitude of the fundamental screech tone measured at $r/D = 50$ and $\theta = 96°$. The present data appear quite similar to those obtained by Norum and Seiner (1982), although the experimental conditions are somewhat different in both the experiments. It is interesting to note that the amplitude has respective peak values for both the conditions of over-expanded and under-expanded jets, regardless of t/D values applied (see Fig. 7(a)). For instance, in the case of over-expanded jets, it has a peak at M_j=about 1.7, while in the cases of under-expanded jets, the peak amplitude is at M_j=about 2.3. However, this tendency does not appear for $t/D = 4.0$.

According to the works by Love et al. (1959) and Norum and Seiner (1980), the peak in the screech tone amplitudes is closely related to the formation of the Mach disk in the first shock-cell of the jet. The effect of t/D on the fundamental screech tone amplitudes can be also found in Fig. 7. For $t/D < 1.0$, the amplitude increases as t/D increases, regardless of whether the jet is over-expanded or under-expanded. However, the trend for $t/D > 1.0$ is quite different. In the cases of over-expanded jets, the amplitude decreases as t/D increases, but this is no longer found in the cases of under-expanded jets.

Far-field directivity of fundamental screech tone is shown in Fig. 8. According to the work by Norum and Seiner (1982), the directivity pattern of the fundamental screech tone shows strong radiation in the upstream direction to the jet. In the present study, the noise measurements were not possible due to the presence of the plenum chamber upstream of the nozzle. Nevertheless, it can be found that the present data are similar to those by Norum and Seiner (1982), and showing a significant influence of nozzle-lip thickness on the directivity pattern, as reported in the work by Norum and Seiner (1982).

Figure 9 shows the directivity pattern for broadband shock-associated noise, where f_p indicates the peak spectrum frequency, as described by the dotted line in Fig. 1. Norum and Seiner's results show that the peak Strouhal number for the broadband shock-associated noise decreases with an increase in θ. While for a given pressure ratio, the screech tone frequency is the same, regardless of θ, the peak frequency of shock noise strongly depends upon the measuring angle θ to the jet. When the nozzle-lip thickness is further increased, the peak Strouhal number decreases.

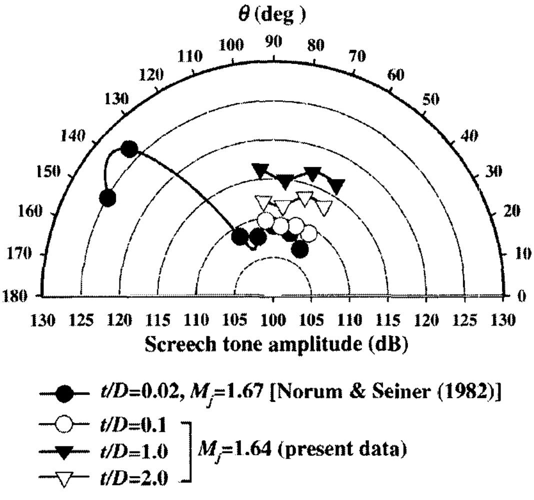
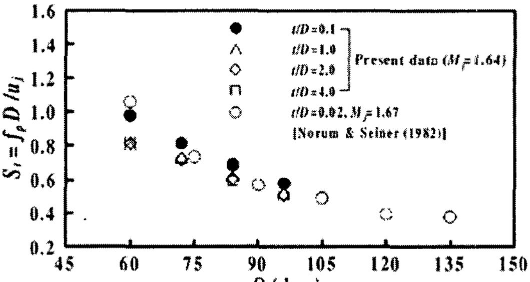
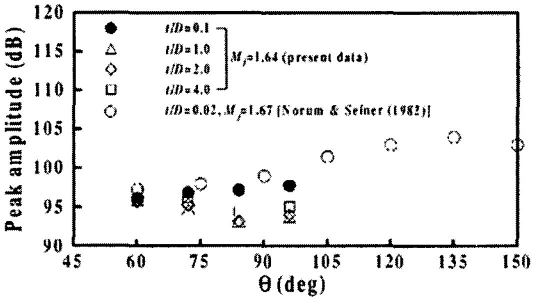


Fig. 8 Far-field directivity of fundamental screech tone



(a) S_t vs θ



(b) Peak amplitude vs θ

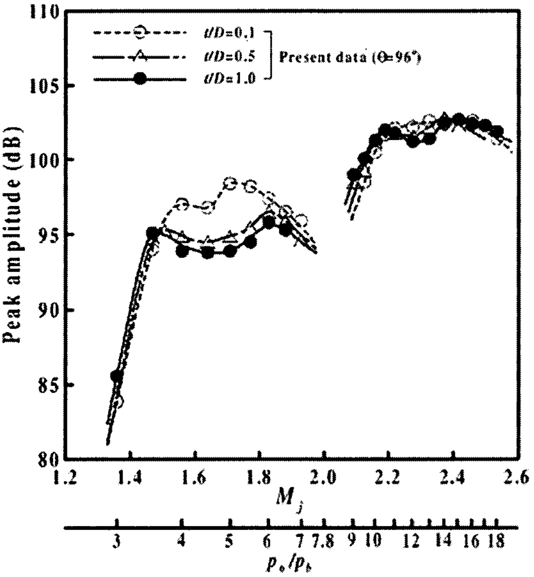
Fig. 9 Far-field directivity of broadband shock-associated noise

The relationship between the peak amplitude of the shock noise and θ is shown in Fig. 9(b). The experimental work by Norum and Seiner (1982) indicates clearly that the peak amplitude of broadband shock-associated noise increases with increasing θ. For very thin nozzle-lip thickness, the present data are similar to those by Norum and Seiner (1982), with a little difference in the amplitude. However, when the nozzle-lip thickness is increased, the peak amplitude of shock noise decreases.

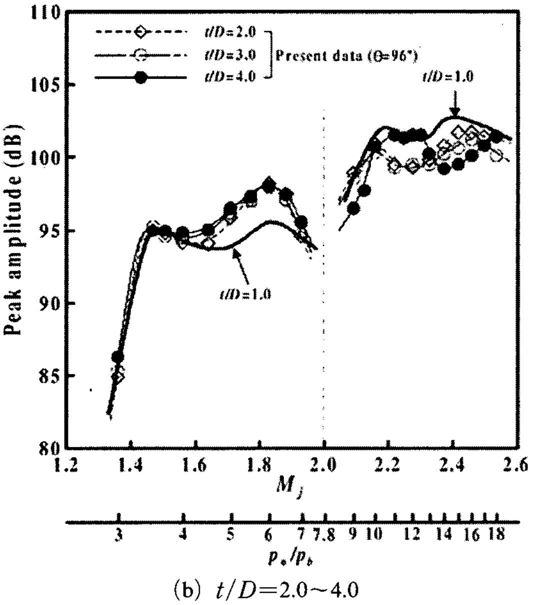
Figure 10 shows the relationship between the peak amplitude of broadband shock-associated noise and M_j. For over-expanded conditions, the peak amplitude increases as M_j increases, slightly decreasing after having the first local peak. It somewhat increase to reach the second local peak, and then sharply decreases near the correctly-expanded condition. Similar trend in the peak amplitude is also found for under-expanded conditions, but the peak amplitudes are much higher than those in the over-expanded jets. The effect of t/D on the peak amplitude is also found in Fig. 10. In cases of $t/D \leq 1.0$, the peak amplitude of the broadband shock-associated noise seems to increases as t/D decreases. However, for $t/D > 1.0$ the peak amplitude in the over-expanded conditions somewhat decreases with an increase in t/D, whereas in the under-expanded conditions, this trend is not found, as shown in Fig. 10(b).

Figure 11 shows the overall sound pressure levels (OASPL) measured at $r/D=50$ and $\theta=96°$. The present experimental data are compared with those obtained by Seiner and Norum (1979). For reference, they measured the sound pressures at $r/D=72$ and $\theta=135°$ using a convergent-divergent nozzle with a design Mach number of 2.0, and the diameter of the nozzle exit $D=50.8$

mm, and the nozzle-lip thickness $t/D=0.02$. The present data are somewhat lower than those by Seiner and Norum (1979), although both the results show the same trend of OASPL. The difference between Seiner and Norum's results and the present data would result from the far-field directivity pattern of fundamental supersonic jet screech tones. OASPL increases as M_j increases, but decreases for the range of $M_j=1.7$ to 2.0. It again increases to reach a constant level at $M_j=2.2$. The present data show that for $M_j=2.0$, the OASPL has a local minimum value, because the noise components for the correctly-expanded jet are due to entirely the turbulent mixing. It is also found that the OASPL somewhat increases as t/D increases.



(a) $t/D=0.1\sim1.0$



(b) $t/D=2.0\sim4.0$

Fig. 10 Relationship between peak amplitude of broadband shock-associated noise and M_j

As described above, the present data indicate that the change in the nozzle-lip thickness alter the acoustic characteristics not only in the fundamental screech tone but also in the broadband shock-associated noise. These significant acoustic differences may be because the nozzle-lip thickness affects the jet dynamics through an alteration of the initial entrainment, momentum thickness and etc. According to the numerical work by Jorgenson and Loh (2002), the thick nozzle-lip shows a large amount of flow entrainment, leading to a counter rotating vortex upstream of the nozzle-lip, while this vortex is not seen in the thin lip case. Thus, as the acoustic waves propagate upstream, these waves are split by the entrainment vortex. Ponton and Seiner (1992) argued that an increase in momentum thickness is caused by an increase in nozzle-lip thickness, while the differences are small. When acoustic waves traveling upstream are reflected and scattered by the larger

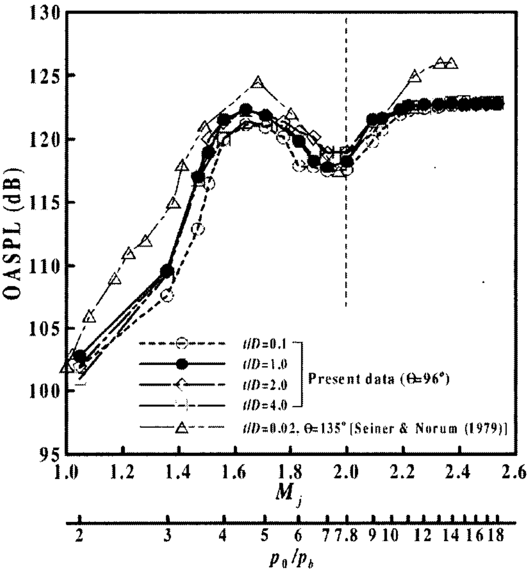


Fig. 11 Relationship between OASPL and M_j

nozzle-lip, the pressure amplitude at the lip surface should be maximum, which leads to higher sound pressure levels at the nozzle lip (Raman 1997). Such scattering effect produces a broadband spectrum of wavelength and more large-scale instability wave near the nozzle lip, leading to increasing both the receptivity of the initial shear layer and the screech tone.

4. Conclusions

The present study addresses an experimental work to investigate the effect of nozzle-lip thickness on screech tones in supersonic jets. Experiment was performed over a wide range from over-expanded to moderately under-expanded conditions. A baffle plate was installed at nozzle exit to alter the nozzle-lip thickness. A Schlieren optical system was used to visualize the supersonic jet. Overall sound pressure levels and noise spectra were obtained using a microphone.

The results obtained show that the screech tone frequency decreases and the wavelength increases, as the fully expanded jet Mach number or the nozzle pressure ratio increases. The nozzle-lip thickness affects the acoustic characteristics of the screech tones, strongly depending on whether the jet is over-expanded or under-expanded at the nozzle exit. For over-expanded jets, an increase in the nozzle-lip thickness causes the frequency and wavelength of the screech tone to increase, while for under-expanded jets, the effect of nozzle-lip thickness on the screech tone frequency is relatively small, and for correctly-expanded jet, the nozzle-lip thickness does not affect the screech tones. The screech tone amplitude reaches a peak value at a certain fully expanded Mach number in both the conditions of over- and under-expanded jets, regardless of the nozzle-lip thickness. The present data clearly show that the nozzle-lip thickness significantly affects the overall sound pressure level in over-expanded jets rather than under-expanded jets.

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