Experimental Investigation of Supersonic Jet Noise Reduction Using Microjet Injection

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Abstract

Experiment of active noise control on supersonic jet noise was conducted by use of microjet injection. The microjets were injected to the shear layer of the main jet through 22 small holes at the lip of a rectangular nozzle. Based on the measurement of far-field sound pressure, it was found that the jet noise was effectively reduced by several dB (in some cases up to 10 dB). The power levels of all measurement points were also reduced by use of microjet injection. The microjet affected not only the broadband noise but also the screech tone noise. The sound pressure level, the frequency of the screech tone, and the structure of the jet could be changed by the microjet. Flow visualization with schlieren technique was also made to observe the effect of microjet on the flow field.

Introduction

One of the basic requirements in developing supersonic transports is to reduce intensity of jet noise radiated from their propulsion nozzles at a minimum loss in the thrust efficiency. Therefore, many researches have been carried out so far on the effects of various kinds of methods for reducing the jet noise. Some of the techniques (mostly passive) are modification of the nozzle exit, use of non-axisymmetric nozzle shapes, and use of tabs or chevrons. Though these techniques have shown several promises, there are definite scope and demand for considering alternative techniques, in particular those which do not interfere with the primary nozzle flow and which may also be amenable to active control toward highly efficient noise reduction.

One such technique is the use of microjet at the nozzle exit. Alvi *et al.* [1)] found that the use of microjets could be very effective in eliminating screech and impingement tones from supersonic jets. Arakeri *et al.* [2)] experimentally studied the effect of microjets on the flow field of a Mach 0.9 round jet, using particle image velocimetry, and found a significant reduction in near-field turbulent intensities. Castelain *et al.* [3)] experimentally studied the effect of microjets on supersonic round jet. They found that the maximum number of microjets did not imply maximum SPL reduction, but the flow interaction between too close microjets might limit their efficiency.

In the previous studies on microjet injection technique, the nozzle geometries were limited to circular ones. In the present study, experiments on the reduction effect of microjet injection on supersonic jet noise have been conducted concerning a high aspect-ratio rectangular nozzle with forty-four evenly spaced micro-nozzles at the long sides of the nozzle exit. It was expected that combination of non-circular nozzle and microjet injection could be very effective for supersonic jet noise reduction based on the literature knowledge of low noise characteristics of non-circular nozzle. So far, noise reduction of up to about 10dB was observed with the total mass flux ratio of 3.2% between microjets and main jet.

Experimental Apparatus and Method

Test Facility

Experiments were conducted in a supersonic anechoic chamber. The chamber and the high-aspect ratio supersonic nozzle are schematically shown in Fig.1.

A high-pressure air compressor, which is capable of supplying air at a maximum storage pressure of 0.83MPa, drives the facility. The jet exhausts into an anechoic chamber that measures 5m wide, 7m long and 3.7m high. Large storage tanks provide a total capacity of 60m^3. After leaving the storage tanks, the air is separated for main jet and microjet. The total pressure of main jet and microjet can be controlled independently.

Figure 2 shows the supersonic jet nozzle with microjet injection. A two-dimensional converging-diverging nozzle of Mach 1.5 was used. The nozzle had a width of 72mm, a throat height of 6 mm and an exit height of 7mm. The microjets were introduced through converging micro-nozzles that had diameters of 0.8mm at the nozzle exit. The number of the micro-nozzles was 44, and they were evenly spaced at both the upper and the lower nozzle exits. The microjets were injected to the main jet at an angle of 60 degrees with respect to the upstream jet axis. The angle was selected according to the experiments by Greska et al. [4)]

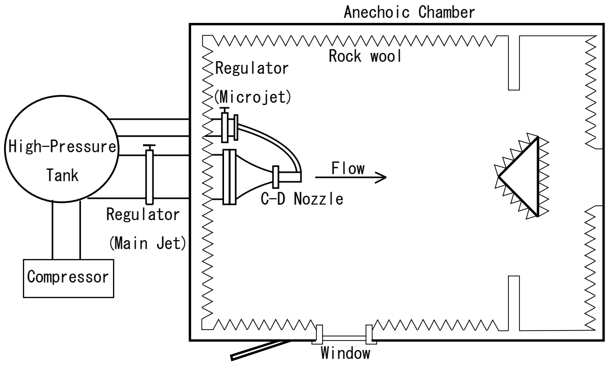

Fig.1 High-Pressure Tank and Anechoic Chamber

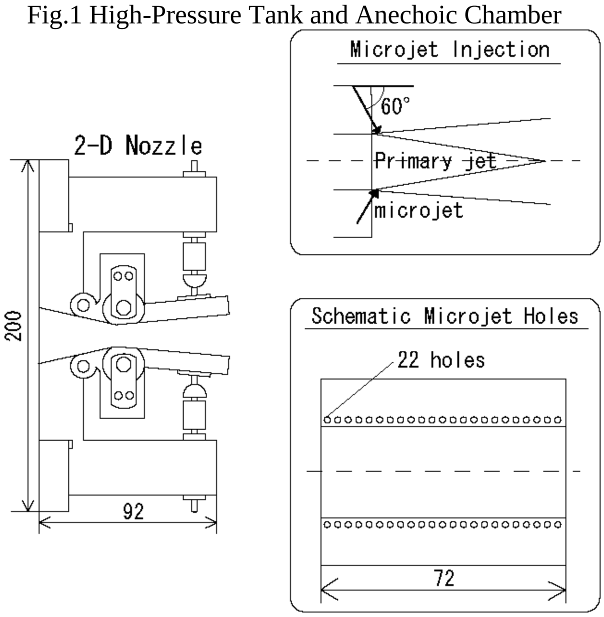

Fig.2 Nozzle with Microjet Injection Holes

Data Acquisition and Analysis

The measurement system of the experiment is shown in Fig.3. In acoustic measurement, the spectrum, directivity and intensity of jet noise were measured in the far field with two B&K 1/4 inch free-field microphones. As shown in Fig.4, they were positioned on 1/6 spherical surface of radius 0.75m. The center of this sphere is the nozzle exit. The angle θ represents elevation angle, while the angle ϕ represents azimuthal angle. The measurement range of angles of θ and ϕ were from 0 to 120 degrees, from 0 to 90 degrees, respectively, with interval of 10 degrees. However, the measurements were not conducted when microphones were located in the main flow, that is, both θ and ϕ were smaller than 30 degrees. The frequency range of acoustic measurement was from 0 Hz to 50 kHz. The measured acoustic data were analyzed with a FFT analyzer and computers, and the acoustic effects of microjets were evaluated by the analysis results of narrow band spectra, OASPL (Overall Sound Pressure Level), and acoustic power level. The sound pressure level (SPL) at each discrete frequency can be determined with the following well known equation:

$$SPL = 10\log_{10}\left(\frac{P}{P_{ref}}\right)^2 \qquad (1)$$

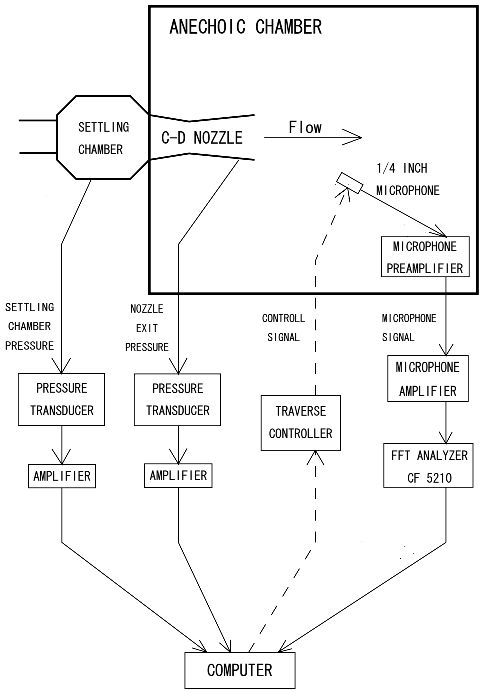

Fig.3 Measurement System

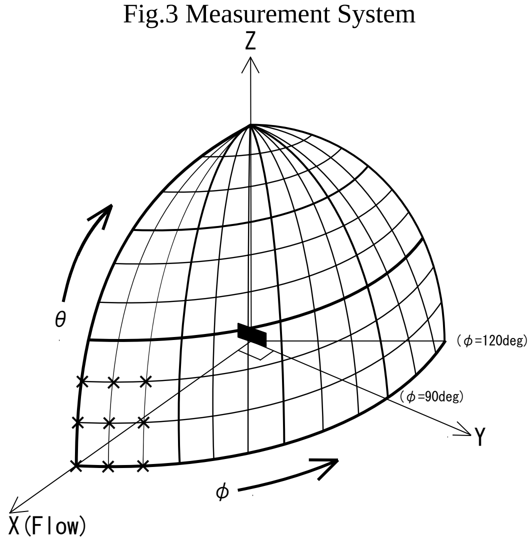

Fig.4 Measurement Points

where P_{ref} is a reference pressure, 20 μ Pa in this case.

In order to clarify the change in the jet structure due to microjet injection, the flow field was visualized with schlieren technique.

Flow Condition

The operating condition of the experiment is summarized in Table1. Note that microjets were injected from every other hole in Table 1, because most of the results presented in this paper are the ones by injecting microjets from every other hole. The total pressure of main jet and that of microjet were changed to control the exit Mach number of the main jet and the mass flux ratio of microjet against the main jet. The mass flux ratio was calculated from the total pressure of main jet and microjets, the area of nozzle throat and that of microjet holes. The experiments were conducted for the following three cases; all microjets were injected, every two holes of microjets were injected, and every three holes of microjets were injected. The corresponding numbers of microjet were 44, 22, and 14, respectively. Since the case with every two holes injection was the most effective, the case will be described mainly in the following sections.

Table 1 Experimental Operating Conditions

P[MPa]	*P*m[MPa]	*M*	ψ[%]
0.20	—	1.04	—
0.20	0.20	1.04	5.1
0.20	0.30	1.04	7.7
0.20	0.41	1.04	10.2
0.20	0.51	1.04	12.8
0.36	—	1.45	—
0.36	0.20	1.45	2.8
0.36	0.30	1.45	4.3
0.36	0.41	1.45	5.7
0.36	0.51	1.45	7.1
0.39	—	1.47	—
0.39	0.20	1.47	2.7
0.39	0.30	1.47	4.0
0.39	0.41	1.47	5.4
0.39	0.51	1.47	6.7
0.41	—	1.49	—
0.41	0.20	1.49	2.6
0.41	0.30	1.49	3.8
0.41	0.41	1.49	5.1
0.41	0.51	1.49	6.4

Results and Discussions

Power Spectrum

Supersonic jet noise is known to consist of three basic components except in the case of perfect expansion; the turbulent mixing noise, the broadband shock-associated noise, and the screech tones. From the present experiment, it is found that microjets affected all of these three components.

Figure 5 shows power spectra in the case of *P*=0.20MPa and *P*m=0.51MPa. The location of the microphone is at θ=60deg and ϕ=0deg. The noise spectrum is observed not to change much by microjet injection. Since Mach number of the main jet is about 1 in this case and hence only the turbulent mixing noise is generated, the microjet effect is thought to be weak on the turbulent mixing noise.

Figures 6 and 7 show power spectrum when *P*=0.36MPa. The locations of the microphone are at θ=60deg, ϕ=0deg in Fig.6 and θ=60deg, ϕ=120deg in Fig.7. In these figures, the shock-associated noise which has a peak around 5000Hz is greatly reduced. It is believed that the shock-associated noise is caused by the interaction between jet turbulence and the shock cell structure. Hence, the microjet injection could affect both the turbulence and the shock cell structure. It is also seen in Fig.7 that the SPL of high frequency noise increased by microjet injection, but the SPL increase of high frequency noise cannot be seen in Fig.6. This suggests that, as Greska et al. [5] mentioned, the scale of vortex structure could be affected and breaks into smaller one, which is the cause of the high frequency noise, by microjet injection. Therefore, high frequency noise from this small vortex structure might radiates especially to the side of the nozzle.

Addition to this, compared with these figures, it is found that the frequency of the screech tone noise around 10000Hz shifted to the higher frequency. Though the mechanism of frequency shift is not clarified yet, the microjets might affect the feedback loop of the pressure fluctuation between the shock cell and the nozzle exit, which feedback is thought to be an important factor of the screech tone noise.

Figure 8 shows a power spectra when *P*=0.41MPa. From this figure, it can be seen that the shock associated noise which has a peak around 5000[Hz] was reduced to the flat distribution, and the screech tone whose fundamental frequency was about 8000Hz and its harmonics were entirely eliminated. This is because the feedback loop was broken by microjet injection. Therefore, overall SPL was also greatly reduced. These reduction leads to the OASPL reduction by 10dB.

Under the present experimental condition, the microjet injection was found to achieve effective reduction of the jet noise.

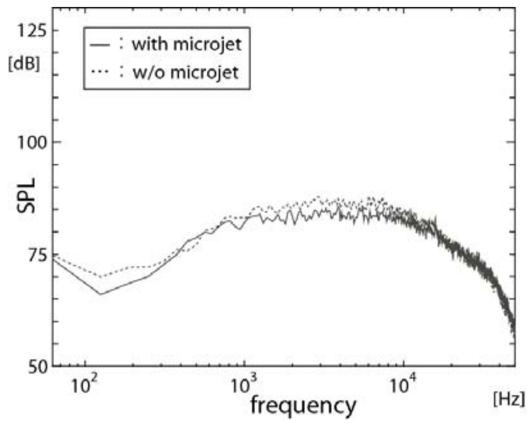

Fig.5 Power Spectrum (*P*=0.20MPa, *P*m=0.51MPa at θ=60deg, ϕ=0deg)

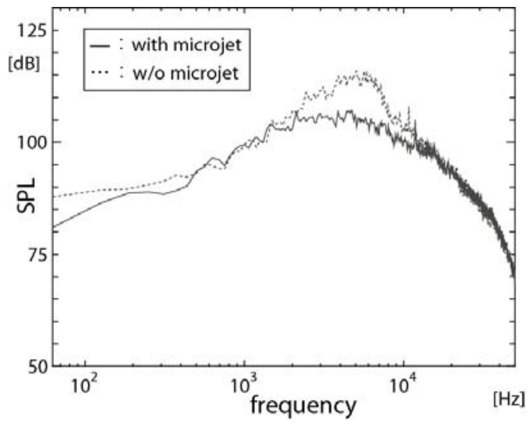

Fig.6 Power Spectrum (*P*=0.36MPa, *P*m=0.51MPa at θ=30deg, ϕ=0deg)

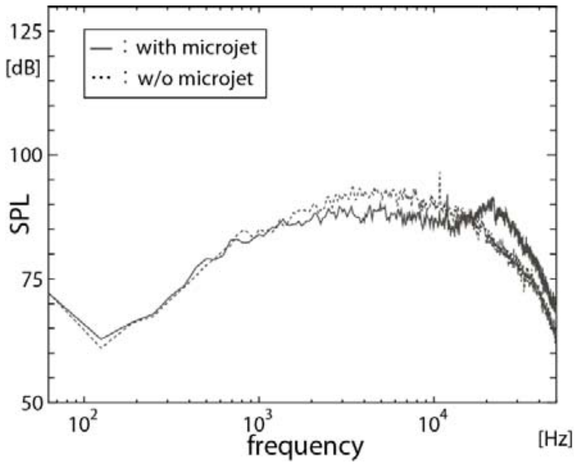

Fig.7 Power Spectrum (*P*=0.36MPa, *P*m=0.51MPa at θ=30deg, ϕ=120deg)

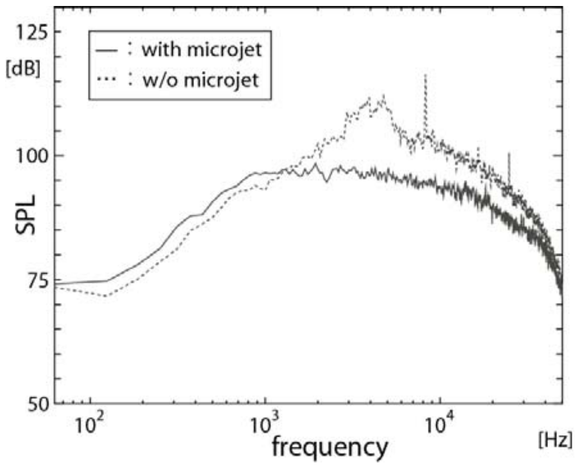

Fig.8 Power Spectrum (*P*=0.41MPa, *P*m=0.51MPa at θ=60deg, ϕ=0deg)

Overall Sound Pressure Level

Figures 9, 10 and 11 present ⊿OASPL distributions under the condition that *P* is 0.41MPa at θ=0, 30 and 60 degrees. The ⊿OASPL is defined as the difference of OASPL between the cases with and without microjet injection. The negative value means noise reduction. Clearly, the OASPL reduction is achieved in all these cases, and the reduction increases with increasing total pressure of the microjet in general. Compared with the reduction in the case with *P*m=0.20Mpa, the decrease in OASPL dramatically becomes large for the case of 0.30MPa of *P*m, and the ⊿OASPL is almost the same for the larger values of *P*m (0.30, 0.41 and 0.51MPa). In the results of Figs.9 and 10, the peaks of noise reduction are observed at around ϕ =40deg. The best noise reduction is found in Fig. 11 for θ =60deg where as much as 10dB is obtained.

Figure 12 shows OASPL distribution with and without microjet injection when *P*=0.41MPa, *P*m=0.51MPa at θ =60deg. From this figure, the OASPL is seen to increase monotonously with decreasing ϕ, with or without microjet injection, though the change is not large.

Sound Power Level

Figure 13 shows measured sound power level against microjet pressure, *P*m. The sound power level can be evaluated with the following equation:

$$L_w = 10\log_{10}\left(\frac{\frac{7}{12}\pi r^2}{\rho a \times 10^{-12}}\right) + 10\log_{10}\left\{\frac{1}{n}\sum_{i=1}^{n}\left(\left(2.0\times10^{-5}\right)^2 \times 10^{\frac{OASPL_i}{10}}\right)\right\} \quad [dB] \quad (2)$$

From Fig.13, it can be clearly seen that the jet noise can be more effectively reduced when the total pressure of microjet is set higher. The reduction of sound power level is as much as about 8dB when *P*m=0.51MPa.

Figure 14 shows the reduction of sound power level against *P*m for various numbers of microjets. The largest noise reduction is achieved when every two holes of microjet are active. In the case of using all holes, the close microjet spacing may cause sound generation due to an interaction between two adjacent microjets.

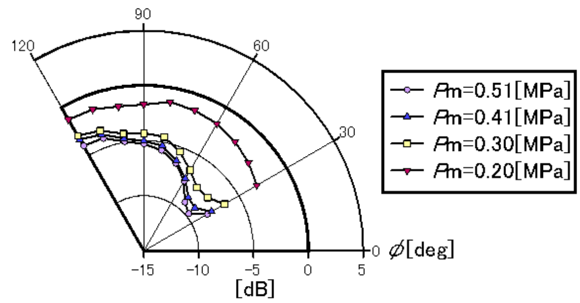

Fig.9 ⊿OASPL Distribution (θ=0deg)

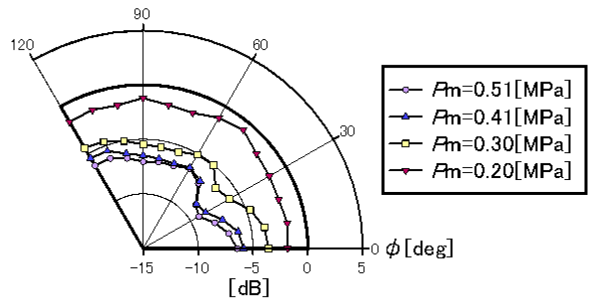

Fig.10 ⊿OASPL Distribution (θ=30deg)

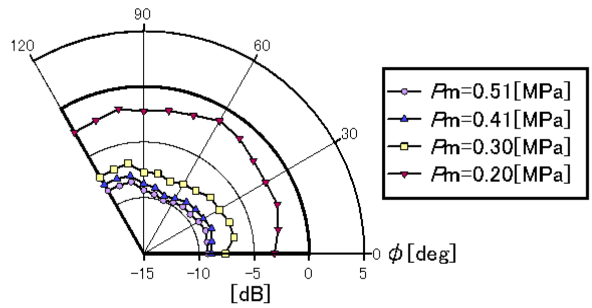

Fig.11 ⊿OASPL Distribution (θ=60deg)

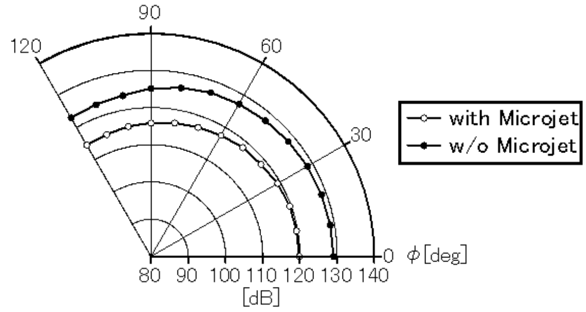

Fig.12 OASPL Distribution
(θ=60deg, *P*m=0.51MPa)

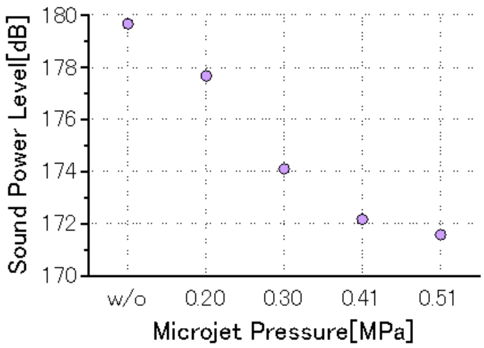

Fig.13 Sound Power Level (*P*=0.41MPa)

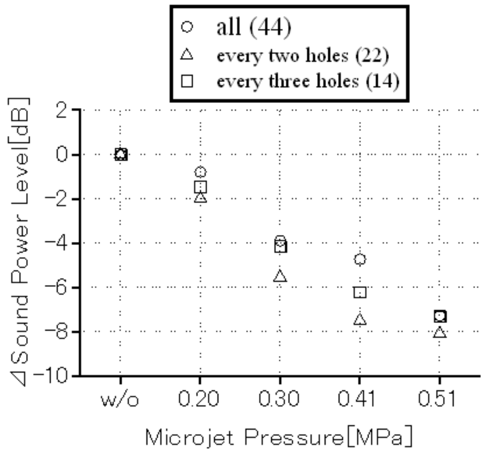

Fig.14 Sound Power Level (*P*=0.41MPa)
(numbers: the number of microjet injection)

Flow Field Visualization

Figure 15 and 16 are the schlieren pictures of the jet showing the change in flow field due to the microjet injection.

From Fig.15, it is found that the length of the potential core is shortened and the mixing layer of the main jet is thickened in the case with microjet injection. This is because the mixture of the mainjet and the ambient air is promoted by microjet.

In Fig.16, it can be seen that the mixing layer of the main jet is thickened and the shock cell structure of the main jet is also changed by microjet injection. In this case, a flapping mode oscillation of the jet is expected, which is a fundamental factor of the generation of screech tone noise. With the flapping mode, the jet oscillates up and down resulting in the large vague area around the shear layer shown in the picture of Fig.16(a). In Fig.16(b), it can be seen that the flapping mode oscillation is dramatically alleviated by the use of microjet injection. The screech tone is thus entirely eliminated as seen in Fig.8.

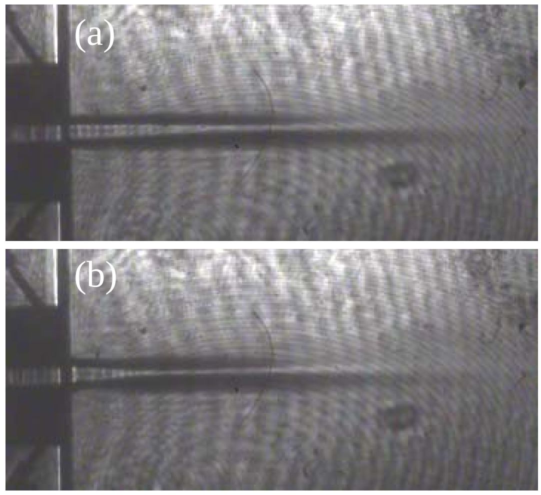

Fig.15 Schlieren Picture (*P*=0.20MPa, *P*m=0.51MPa, (a): w/o microjet, (b): with microjet)

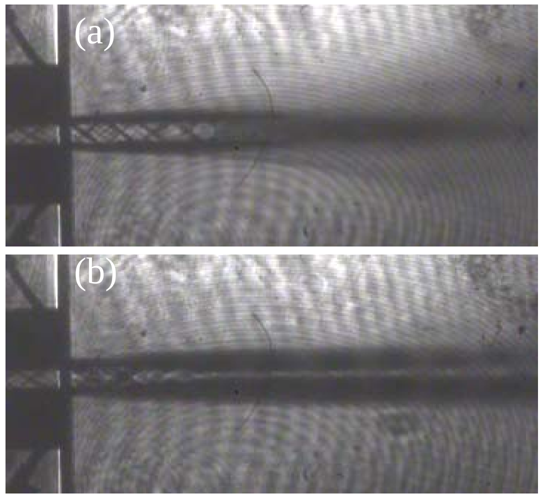

Fig.16 Schlieren Picture (*P*=0.41MPa, *P*m=0.51MPa, (a): w/o microjet, (b): with microjet)

Conclusions

Active suppression method of jet noise with microjet injection was experimentally studied for rectangular supersonic jet over the jet Mach number range from 1.04 to 1.49. The conclusions are summarized as follows.

1. The jet noise was reduced by the use of microjet injection. Overall sound pressure level was reduced up to 10dB. The power spectra showed that, with microjet injection, low frequency noise was much reduced while in some cases high frequency noise was slightly increased.
2. Microjet injection influenced all components of supersonic jet noise, that is, turbulent mixing noise, shock-associated noise and screech tone noise.

3. Due to the microjet injection, the screech tone noise disappeared in some cases, and its frequency changed in other cases. It could also be generated by microjet injection.
4. From the flow visualization results, the change in shock structure and flapping motion of jet were found due to the microjet injection. The mechanism of the jet noise reduction is, however, not clarified yet, and the detailed measurements and/or numerical simulation of the flow will be further needed to obtain thorough understanding.

Nomenclature

dB	decibel	[-]
P	total pressure of main jet	[Pa]
M	Mach number of main jet	[-]
ψ	mass flux ratio between main jet and microjets	[%]

Subscript

m	microjet

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