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Journal of Sound and Vibration 297 (2006) 167–182

JOURNAL OF SOUND AND VIBRATION

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Control of supersonic jet noise using a wire device

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Received 11 October 2004; received in revised form 25 January 2006; accepted 17 March 2006
Available online 30 May 2006

Abstract

The present study describes a new technique for the reduction of supersonic jet noise using a control wire device that is placed into the supersonic jet stream. The control wire device is composed of long cylinders with a very small diameter and its location is varied to investigate the control effectiveness of supersonic jet noise. The jet pressure ratio is varied to obtain the supersonic jets which are operated in a wide range of over-expanded to moderately under-expanded conditions. A high-quality Schlieren optical system is used to visualize the flow field of supersonic jets both with and without the control wire device. In order to quantify the control effect of the wire device on a supersonic jet, pressure measurements are also accomplished. Acoustic measurements are performed to obtain the overall sound pressure level and noise spectra. The results obtained show that the present wire device effectively breaks the shock-cell structure, reduces the shock strength, and consequently leads to a substantial suppression of supersonic jet noise. The location of the control wire device is an important factor in reducing the supersonic jet noise. The present wire device suppresses the screech tones and the broadband shock-associated noise as well as the overall sound pressure level, when it is placed at a location smaller than three times the exit diameter of nozzle in the downstream of the nozzle exit. For over-expanded jets, the noise control effectiveness of the wire device appears more significant, compared to under-expanded jets.

1. Introduction

Supersonic jets have long been used in many diverse fields of engineering applications such as supersonic aircraft, jet propulsion thrust vectoring, fuel injector for supersonic combustion, soot blower device, thermal spray device, etc. [1–4]. It has been well known that the time-mean structure of supersonic jet is determined by jet pressure ratio and nozzle configuration. A considerable deal of researches has been made to understand the noise generation in supersonic jet and to obtain the noise control methods appropriate to suppress the jet noise. Recently, the supersonic jet noise is being a very important issue to be resolved from the practical point of view of performance of fluidic device [5,6] as well as environmental noise problem [7].

In general, it is well known that supersonic jet noise consists of three major components [8]: the turbulent mixing noise, the broadband shock-associated noise, and the screech tones. The turbulent mixing noise

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doi:10.1016/j.jsv.2006.03.033

Nomenclature

d_w	wire diameter
D	nozzle exit diameter
D_t	nozzle throat diameter
f	frequency
M	Mach number
NPR	jet pressure ratio ($= p_0/p_b$)
p	pressure
r	radial distance from the nozzle exit
SPL	sound pressure level
ΔSPL	sound pressure level relative no control wire device ($= \mathrm{SPL}_{\mathrm{wire}} - \mathrm{SPL}_{\mathrm{no\ control}}$)
x	location of the wire device
x_a	axial distance from the nozzle exit
γ	ratio of specific heats
θ	angle with respect to the jet axis

Subscripts

0	stagnation state in the plenum chamber
ave	average value
b	ambient state
d	design condition at the nozzle exit or fundamental screech tone
i	impact pressure
j	fully expanded condition

appears in subsonic jets as well as supersonic jets, but the other two noise components are only present in an imperfectly expanded supersonic jet because they are radiated due to the strong interaction between large-scale turbulent structure and shock-cell structure.

With regard to the screech tone, Powell [9] first proposed that the screech tone and its harmonics are generated by a resonant feedback loop between the oscillating shock-cell structures and the nozzle exit [10]. Of major components of the supersonic jet noise, the screech tone has a strong directivity and high intensity, and thus, it can cause structural fatigue failure of fluid devices [11,12].

A great number of experimental studies have been performed on the reduction of supersonic jet noise. Most of the previous studies mainly concentrated on modifying the shear layer generated at the nozzle exit to reduce the jet noise. Tabs, grooves, asymmetric nozzle, porous plug, etc. have been used in these control techniques, which have been successful in suppressing the supersonic jet noise. For instance, the effective reduction of the screech tone was obtained by using small tabs installed at the nozzle exit [13–15]. Norum [16] tested a variety of asymmetric nozzle configurations for the screech tone suppression, and reported that a significant reduction of screech amplitude can be obtained by using asymmetric nozzles. Vishnu and Rathakrishnan [17] investigated the effect of grooved nozzle on the acoustic characteristics of supersonic jet, and showed that the grooved nozzle gives weaker shock-cell structures, compared to a simple based nozzle. However, these methods give rise to a large total pressure loss and jet thrust penalty [18].

Kibens and Wiezien [19] and Das and Dosanjh [20] investigated the technique for the reduction of jet noise using a porous plug-nozzle, and found that the perforations of plug-nozzle produce a series of weak compression and expansion waves and reduce the jet noise. Yu and Chen [21] and Neemeh et al. [22] tested the effect of swirl stream on the jet noise, and showed that the swirling jet reduces the shock-cell length and the screech tones.

Recently, Anderson et al. [23] tried to reduce the jet noise by attaching a flexible filament on nozzle exit plane, and found that the filament reduces the shock-associated noise. Debiasi and Papamoschou [24] investigated the effect of annular coaxial stream on the noise components of the supersonic jets operated at over-, correctly-, and under-expanded conditions. They found that the addition of the annular coaxial stream to the supersonic jet can reduce the screech tones and effectively suppress Mach wave emissions.

More recently, Papamoschou [25] also suggested the jet noise suppression methods for commercial turbofan engines using coaxial jets. According to his experimental results, a substantial noise reduction is achievable by reshaping the coaxial nozzle configuration to be eccentric. Zoppellari and Juve [26] tried to suppress the jet noise by using water that is injected into the supersonic jet stream through the multiple injectors near the nozzle exit. They showed that the far-field jet noise decreases by about 10 dB, when a large amount of water, corresponding to several times the jet mass flow, is injected into the shear layer at the nozzle exit. Krothapalli et al. [27,28] further investigated the effect of the water injection mass flow on the jet noise and found that the near-field noise reduces by about 2–6 dB, depending on the location of the injection and the water mass flow rate.

From practical point of view, it is required that the technique for jet noise reduction is easy to implement and to minimize penalties in weight and thrust. Very annoying jet noises are frequently encountered in many industrial applications of high-speed jet technologies, such as the purge burner of city gas, the blow-off line of stream gas in power plants, etc. In these situations, the noise control has to meet the needs of low cost and a simple structure.

In the present study, a new technique for the suppression of supersonic jet noise using a control wire device is investigated. The wire device has a simple structure and is easy to implement. The objective of the present study is to experimentally investigate the control effectiveness of the wire device on the structures and acoustic fields of supersonic jet, and to get insight into physical mechanism that is related to the jet noise reduction. The present experimental results show that the wire device is effective for the practical applications with regard to the suppression of jet noise.

2. Experimental facilities

The present work is accomplished in an anechoic test room that is schematically shown in Fig. 1(a). The anechoic test room has a dimension of 5.3 m × 4.9 m × 4.9 m. The interior walls of the anechoic test room are covered with sound absorption material (glass-wool foam) of 325 mm thickness. Preliminary acoustic tests show that the present room is anechoic for frequency components above approximately 120 Hz and a background noise is about 10 dB.

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 $M_d = 2.0$ is installed in the end wall of the plenum chamber, based upon the method of characteristics. The nozzle has a throat diameter of $D_t = 20\,\mathrm{mm}$, an exit diameter of $D = 26\,\mathrm{mm}$, and a straight section near the exit of the nozzle. The pressure inside the plenum chamber is controlled by a pressure regulator valve that is located upstream of the plenum chamber.

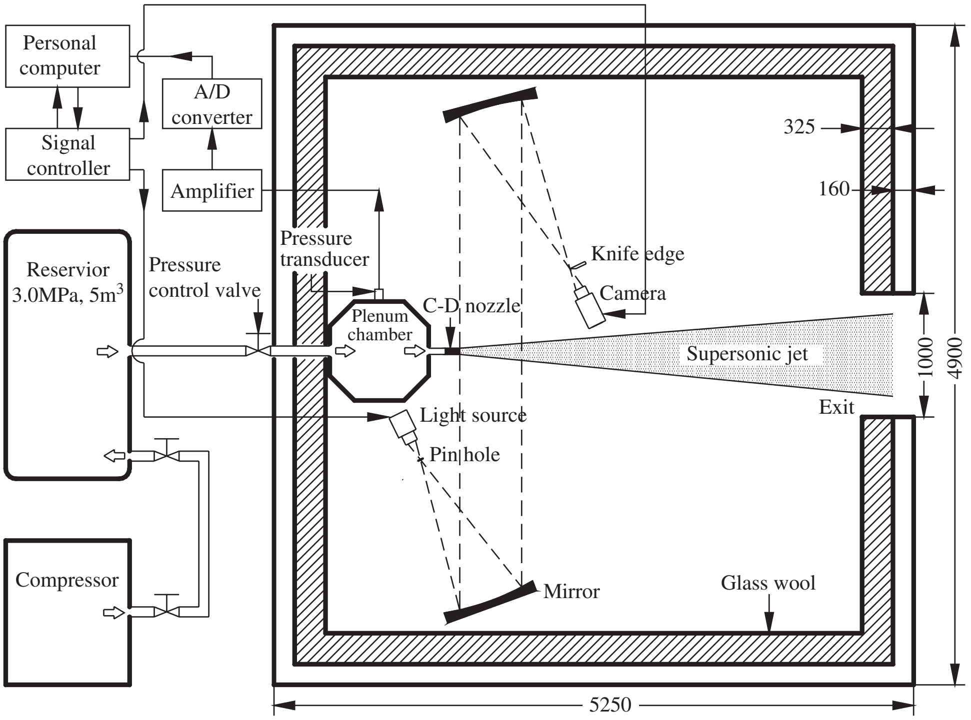
The temperature in the plenum chamber is measured by a thermocouple, and is constant at room temperature (approximately 293 K) during a test. The pressure is measured by a pressure transducer (Toyoda PMS-5-200 K) that is flush mounted on the top wall of the plenum chamber. The transducer is calibrated prior to each test. The uncertainty in pressure and temperature measurements is estimated to be less than $\pm 2\%$. These uncertainties are based on the maximum observed fluctuations in the measurements.

2.1. Flow visualization

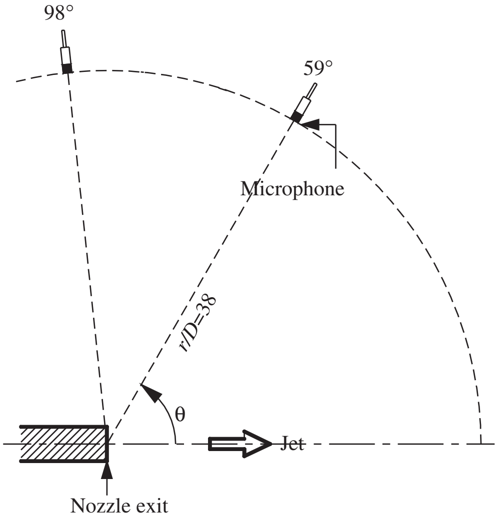
A schlieren optical system is employed to visualize the qualitative structures of supersonic jet. It consists of two concave mirrors that have a diameter of 150 mm and a focal length of 1000 mm. The light source is a nano-spark with a light intensity 10 kW/sr and a duration time of 20 ns. Still camera (Nikon F4) instantaneously images the turbulent structures in the supersonic jet.

2.2. Impact pressure measurement

A pitot probe is used for impact pressure measurements along the jet axis. The pitot probe has an inner diameter of 0.9 mm and a length of 20 mm. The output of pitot probe is connected via a stainless tube with an inner diameter of 4 mm to a pressure transducer (Toyoda PMS-5M-2). The output signals of the pressure transducer are recorded via a 12 bit A/D converter with a sampling frequency of 1 kHz. The resulting time-averaged values are yielded to obtain the pitot probe pressure. The accurate positioning of the probe in the jet stream is accomplished by a two-axis traverse mechanism. Considerable attention is given to ensure that the axis of the probe tip is oriented parallel to the nozzle centerline. In the supersonic jet test, the vibration of the pitot probe can cause some fluctuations in the pressure measurement. Thus, a rigid support is attached to the pitot probe to prevent the vibration during the test.



(a) Experimental facility (Unit : *mm*)

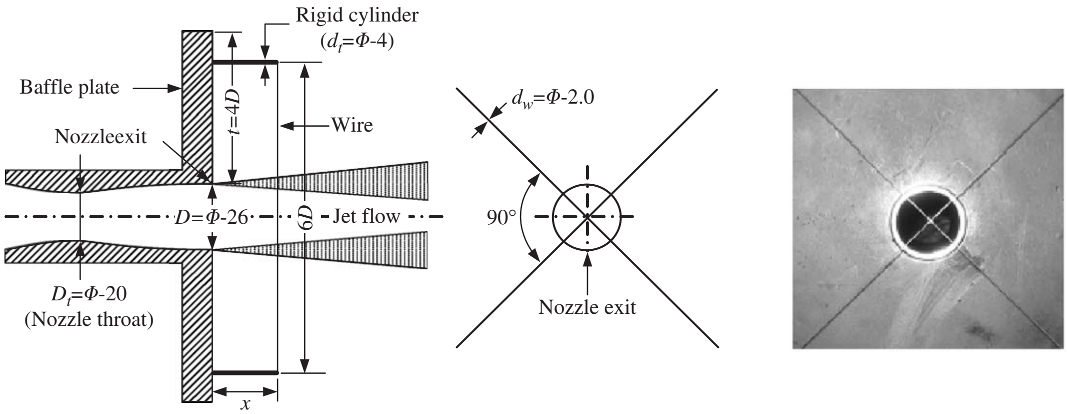


(b) Measuring points

Fig. 1. Schematic diagram of experimental facility and measuring points.

2.3. Acoustic measurement

Acoustic measurements are made using a condenser microphone (Ono Sokki MI-6420) that has a diameter of 6 mm, sound pressure sensitivity of $-17\,\mathrm{dB}\pm3\,\mathrm{dB}$ ($0\,\mathrm{dB} = 1\,\mathrm{V/Pa}$), and the maximum sound pressure level of 140 dB. The uncertainty in acoustic measurements is estimated to be less than $\pm1\,\mathrm{dB}$. As schematically illustrated in Fig. 1(b), two microphones are located at 59° and 98° along a circular arc of radius $38D$ away



(a) Wire device (unit : mm) (b) Picture (front view)

Fig. 2. Arrangement of control wire device.

from the exit of nozzle. The acoustic signals are analyzed by using a FFT analyzer (Ono Sokki Model DS0221). A FFT analysis provides the power spectra, sound pressure level, and spectral data in the range of 0–40 kHz. The power spectra are averages of 20 samples, each of which contains 4096 data points. The overall sound pressure level (OASPL) can be obtained by a numerical integration of the spectra, $\mathrm{OASPL} = 20\log_{10}\int_0^{40\,\mathrm{kHz}} S(f)\,\mathrm{d}f$.

2.4. Control wire device

The wire device is illustrated in Fig. 2. It is placed perpendicular to the supersonic jet stream. The wire device is composed of two long stainless cylinders, which have an extremely small diameter (d_w). Two stainless cylinders are crossed by an angle of 90°. The end of a wire is supported to a rigid cylinder. The rigid cylinder is tightly bolted to the baffle plate installed at the nozzle exit. The location (x/D) of the wire device is changed. The center of the wire device is made on the jet axis.

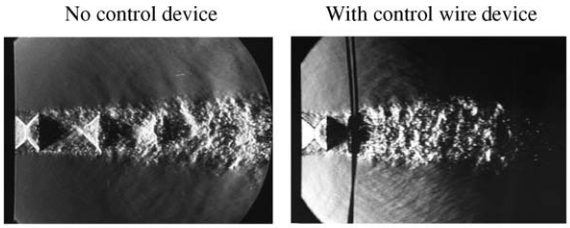
2.5. Experimental conditions

In the present study, the jet pressure ratio, NPR ($=p_0/p_b$) 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 $\mathrm{NPR} = 7.8$. Thus, the jet pressure ratio applied in the present study covers the range from over-expanded to moderately under-expanded conditions. Ambient pressure and temperature in the test room are measured at $p_b = 101.3\,\mathrm{kPa}$ and $T_b = 293\,\mathrm{K}$, respectively.

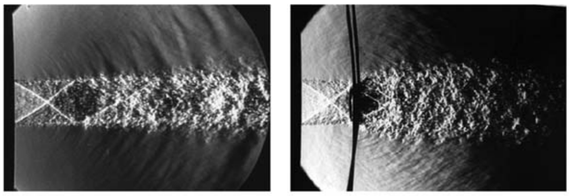
3. Experimental results and discussion

3.1. Effect of wire device on jet structure

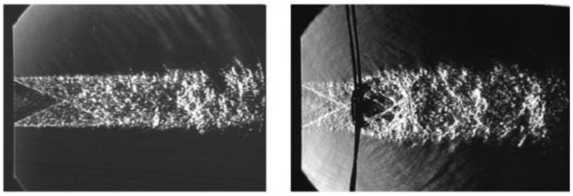
Fig. 3 shows the visualization pictures of supersonic jets with and without the wire device. The location of the wire device is $x/D = 1.0$. Over-expanded jets are obtained for the pressure ratios less than $\mathrm{NPR} = 7.8$. For over-expanded jet without the wire device at $\mathrm{NPR} = 4.0$, oblique shock waves are generated inside the nozzle, and these waves are reflected from the jet axis and form a Mach disk. The reflected shocks are reflected again toward the jet axis at the jet boundary, and lead to the repeated shock-cell structure. When the wire device is placed at $x/D = 1.0$, as also shown in Fig. 3(a), the wire device breaks the shock-cell structure downstream of the device, and causes strong instability waves that propagate both upstream and downstream. It seems that



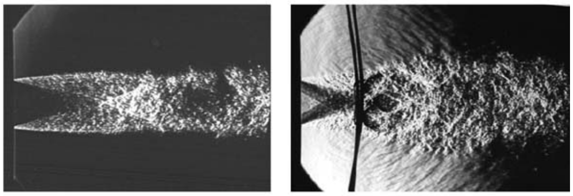
(a) NPR=4.0 (M_j=1.56)



(b) NPR=6.0 (M_j=1.83)



(c) NPR=7.8 (M_j=2.0)



(d) NPR=12.0 (M_j=2.27)

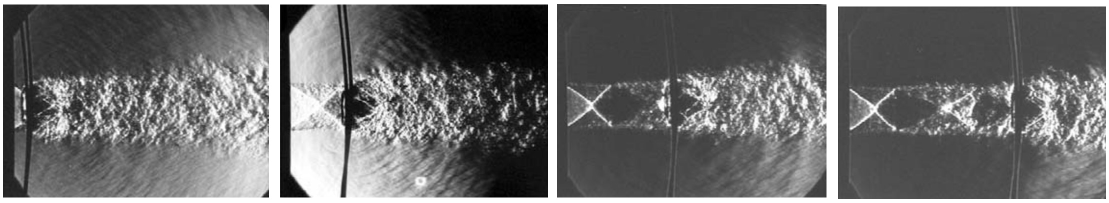
Fig. 3. Schlieren pictures of supersonic jets without (left) and with (right) the control wire device ($x/D = 1.0$).

the wire device increases somewhat the spreading rate of a jet due to the increased turbulence in the presence of the wire device.

At NPR = 6.0, the Mach disk is no longer formed, and the regular reflections of oblique shocks are observed (see Fig. 3b). Mach waves are generated from the shear layer of the jet and propagate downstream at velocity corresponding to local convective Mach number. The wire device destroys the shock-cell structures, but weak oblique shocks are observed just downstream of the wire device.

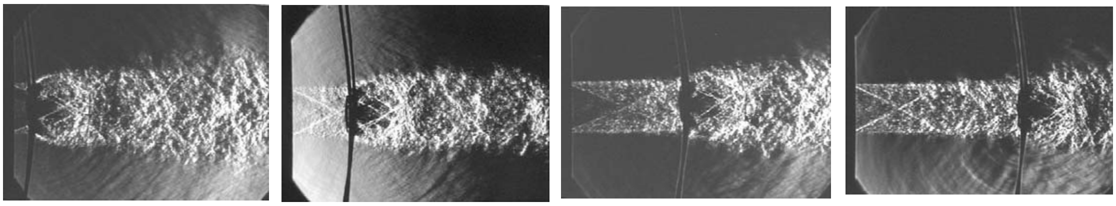
At NPR = 7.8, the jet is in correct expansion condition at the nozzle exit, and the pressure at the exit of nozzle is matched to the ambient back pressure. In this case, the jet boundary is nearly parallel to the jet axis. The weak oblique shock waves observed at the exit of nozzle are due to the effect of boundary layer. At the pressure ratios higher than NPR = 7.8, the jets are under-expanded, as shown in Fig. 3(d). The jet boundary is expanded because the expansion waves are generated at the exit of nozzle. From the visualization pictures in Figs. 3(c) and (d), it is observed that the wire device increases the spreading rate of a jet. This is due to the increased turbulent mixing in the presence of the wire device. It is also noted that the present wire device is somewhat bended due to the impact of the supersonic jet.

For three jet cases, namely, over-, correctly and under-expanded condition, the effect of the location of the wire device is shown in Figs. 4–6. The location of the wire device plays a significant role on the shock-cell structure and the spreading rate of a jet. At $x/D = 0.2$, the wire device almost completely breaks the shock-cell



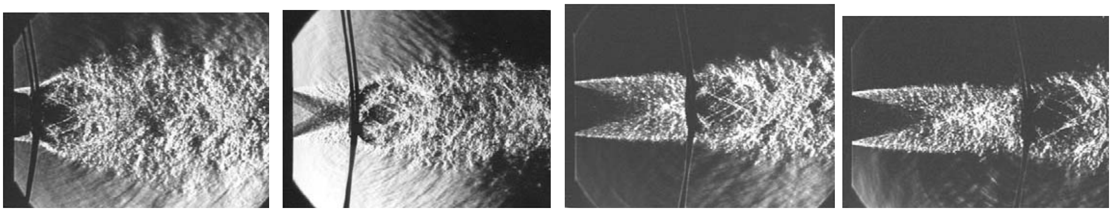
(a) $x/D=0.2$ (b) $x/D=1.0$ (c) $x/D=2.0$ (d) $x/D=3.0$

Fig. 4. Over-expanded jets with the control wire device (NPR = 5.0).



(a) $x/D=0.2$ (b) $x/D=1.0$ (c) $x/D=2.0$ (d) $x/D=3.0$

Fig. 5. Correctly expanded jets with the control wire device (NPR = 7.8).



(a) $x/D=0.2$ (b) $x/D=1.0$ (c) $x/D=2.0$ (d) $x/D=3.0$

Fig. 6. Under-expanded jets with the control wire device (NPR = 12.0).

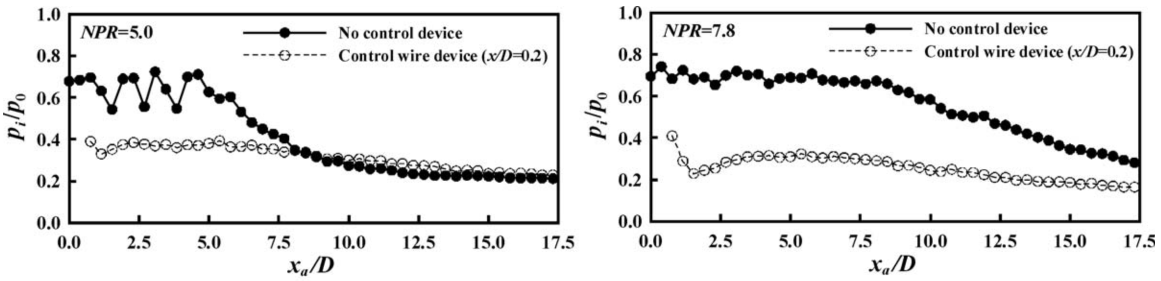
structure. When the wire device is located at a distance of several times the shock-cell spacing, the jet structure upstream of the wire device does not change in the presence of the device. It is also interesting to note that the location of the wire device significantly affects the instability waves. Additional instability waves are produced by the complex interaction between the convective turbulent structures and the wire device.

Here it should be noted that, when the wire device is placed downstream of the nozzle exit, two different tones can be generated. One is the screech tone due to the interaction between large-scale turbulent structures and shock-cell structures. The other is the impingement tone due to turbulent structures impinging on the wire device, as will be described later.

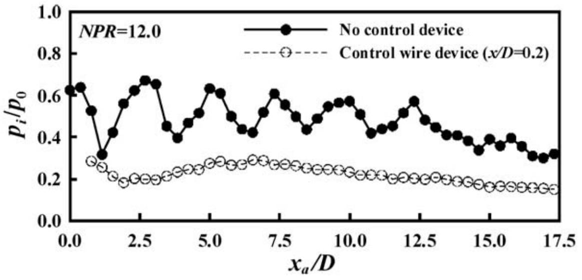
3.2. Effect of wire device on axial impact pressure distribution

The impact pressure distributions for supersonic jets with and without the wire device are shown in Fig. 7, where p_i and x_a are the impact pressure measured by a pitot probe and the axial distance from the nozzle exit along the jet axis, respectively. For the jet stream with the wire device, the pressures are measured at only the downstream of the wire device because it is difficult to move the traverse mechanism upstream of the wire device. As can be expected in the flow visualization pictures of Figs. 3–6, the pressure distribution upstream of the wire device may be nearly the same as that of no control device.

For over-expanded jet operated at NPR = 5.0, the effect of the wire device on the axial impact pressure distribution is presented in Fig. 7(a). When there is no control device in the jet stream, the jet has strong shock



(a) NPR=5.0 (M_j=1.71) (b) NPR=7.8 (M_j=2.0)



(c) NPR=12.0 (M_j=2.27)

Fig. 7. Effect of wire device on axial impact pressure distribution ($x/D = 0.2$).

cell structures that lead to the fluctuation in the axial impact pressure at the range of $x_a/D < 5.0$. The presence of the wire device in the jet stream considerably decreases the axial impact pressure, while the axial impact pressure somewhat increases at the range of $x_a/D > 8.0$, compared to the uncontrolled jet. Unlike the case of uncontrolled jet, the impact pressure distribution for the jet with the wire device is no longer fluctuated. For correctly expanded jet in Fig. 7(b), the impact pressure for uncontrolled jet does not fluctuate because there are no shock-cell structure in the jet flow. When the wire device is placed in the jet stream, the flow experiences considerable pressure loss due to the spreading effect of the flow caused by the wire device. Similar qualitative tendency is also found in the pressure distribution for under-expanded jets. The increase in the amplitude of impact pressure oscillations denotes the presence of strong shocks in the supersonic jet. As shown in Figs. 7(a) and (c), the reduced amplitude of impact pressure oscillations by the presence of the wire device suggests that the shock-cell structure is significantly weakened.

From these results, it is believed that the wire device disperses the kinetic energy of the jet flow to radial direction with respect to the jet axis. This leads to both weakening the shock-cell structure and enhancing the mixing of the jet. Furthermore, the presence of the wire device in the jet stream causes a detached shock wave to occur ahead of it. The resulting jet flow just downstream of the detached shock wave becomes nearly sonic or subsonic, consequently leading to considerable pressure loss. Meanwhile, it has been now well known that the third and fourth shock cells can be the sound sources of shock-associated noise. Thus, weakening or diffusing these shock-cells using the present wire device can result in significant reduction of screech tones and broadband shock-associated noise. As shown in Fig. 7, the present wire device effectively weakens the shock-cell structures.

3.3. Acoustic measurement results

Fig. 8 shows the typical noise spectra of over-expanded jets with and without the wire device, where NPR = 5.0, and x/D is the streamwise location of the wire device. For the case of no wire device, it is observed that there are three discrete peaks, referred to as the screech tone. It is interesting to note that the wire device eliminates the screech tone and considerably suppresses the broadband shock-associated noises as well, when it is located upstream of $x/D = 2.0$. However, for the wire device located at $x/D = 3.0$ and 6.0, the discrete

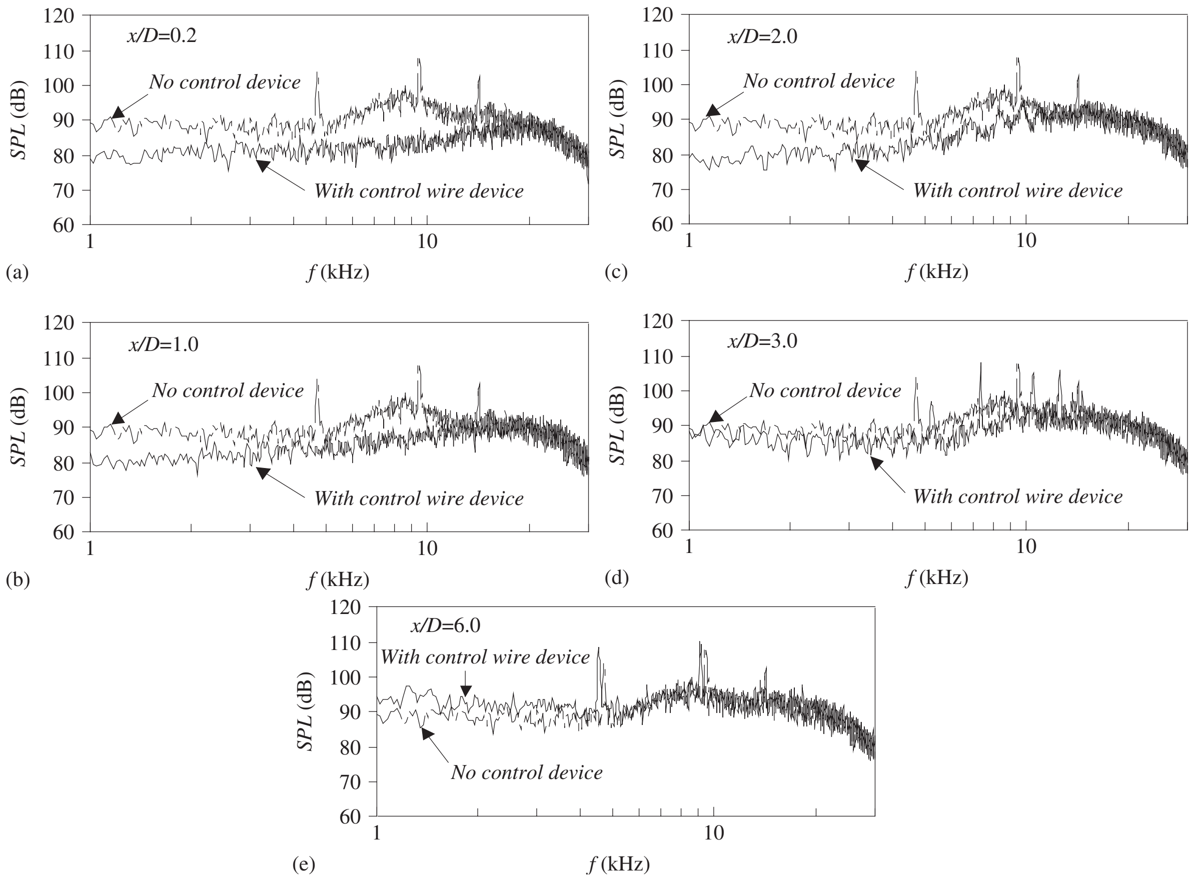


Fig. 8. Noise spectra of over-expanded jets without and with the control wire device (NPR $= 5.0$, $\theta = 98°$).

tones appear again, but their frequencies are changed, depending on the location of the wire device. Moreover, in the frequency range below 10 kHz, the sound pressure levels associated with the broadband shock-associated noise increase in the presence of the wire device (see Fig. 8e). It is, thus, believed that the present wire device is effective in suppressing the screech tones and the broadband shock-associated noise in over-expanded jet, provided that the wire device is located upstream of $x/D = 3.0$. This indicates that it is easy to implement the wire device since there is enough margin in the location of the wire device to control the supersonic jet noise.

Fig. 9 shows the typical noise spectra of correctly expanded jet with and without the wire device. For the case of no wire device, there are no discrete tones in the spectra. This is the same for all x/D. When the wire device is placed upstream of $x/D = 3.0$, the noise spectra are nearly the same to those of no wire device. However, there are several discrete tones associated with the impinging tones, when the wire device is located at $x/D = 3.0$ and 6.0. In these cases, the sound pressure levels related to the broadband shock-associated noise are increased due to the presence of the wire device.

The typical noise spectra of under-expanded jet with and without the wire device are shown in Fig. 10, where NPR $= 15.0$. For the case of no wire device, there is a screech tone at a frequency of about 2.6 kHz. However, with the wire device, no discrete tone is found in the noise spectra.

In order to investigate the noise control effectiveness of the wire device, Fig. 11 shows the relative sound pressure levels ΔSPL, where ΔSPL is defined as $\Delta\mathrm{SPL} = \mathrm{SPL}_{\mathrm{wire}} - \mathrm{SPL}_{\mathrm{no\ control}}$. For NPR $= 5.0$, it is found that the present wire device reduces the sound pressure levels by about 10 dB in the range of a frequency less than l0 kHz, and by about 5 dB between 10 and 20 kHz. The maximum SPL reduction of about 25 dB is obtained at the screech tone frequency of $f = 9.5$ kHz. However, for the cases of NPR $= 7.8$ and 15.0, ΔSPL is

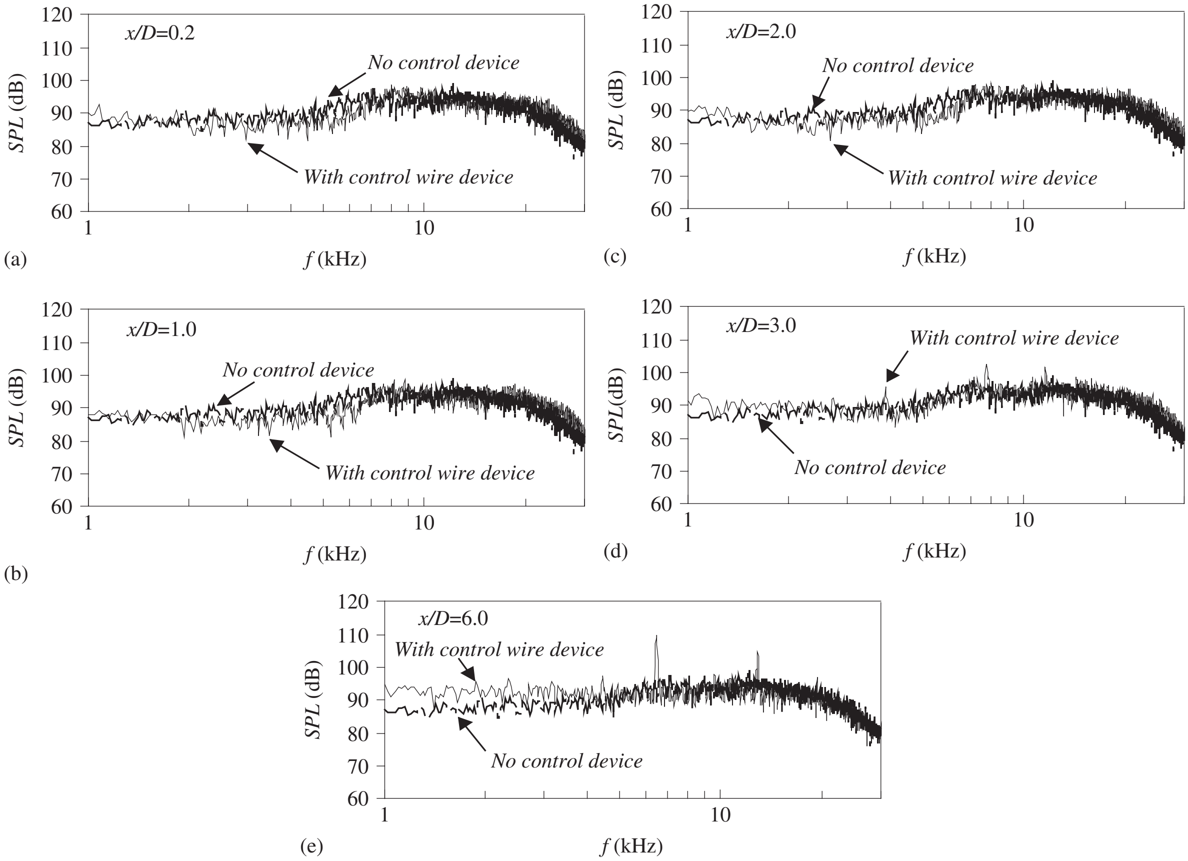


Fig. 9. Noise spectra of correctly expanded jets without and with the control wire device (NPR = 7.8, $\theta = 98^\circ$).

nearly zero in the entire frequency range. The wire device is useful in reducing the noise of over-expanded jets, but is less effective for under-expanded jets.

Fig. 12 shows the average value of ΔSPL that is defined in Eq. (1) as follows:

$$\Delta \mathrm{SPL}_{\mathrm{ave}} = \frac{1}{\Delta f}\int_0^{20\,\mathrm{kHz}} \Delta \mathrm{SPL}(f)\,\mathrm{d}f. \tag{1}$$

Although the acoustic measurements have been carried out below 40 kHz, $\Delta \mathrm{SPL}_{\mathrm{ave}}$ is obtained in the frequency range below $f = 20$ kHz (i.e., human's audible frequency range). As can be seen in the present noise spectra, the jet noise control effect by the wire device is less in the frequency range over $f = 20$ kHz. The negative value of $\Delta \mathrm{SPL}_{\mathrm{ave}}$ means the jet noise reduction by the wire device. For over-expanded jets, the control effectiveness of the wire device is strongly dependent on the location of the wire device, x/D, while for under-expanded jets, the location of the wire device does not influence the noise control. For the wire device placed at $x/D = 0.2$, the control effectiveness seems to be maximized. It is further noted that the present control method is most suitable for the noise suppression in over-expanded jet operated at NPR = 4.0. But the noise control of the wire device is not effective when the wire device is placed far downstream.

For under-expanded jets, the present control method is not effective in suppressing the jet noise. In the present experiment, the location of the wire device is limited to a distance less than $x/D = 6.0$ due to the limitation of the experimental test rig. The experimental work by Seiner and Yu [29] shows that the noise source in under-expanded jets is located on the third shock-cell. From the present visualization results for under-expanded jets, the third shock-cell is observed at a location beyond $x/D = 6.0$. Thus, it requires that the wire device should be placed more downstream in order to get substantial effect for the noise reduction in an under-expanded jet.

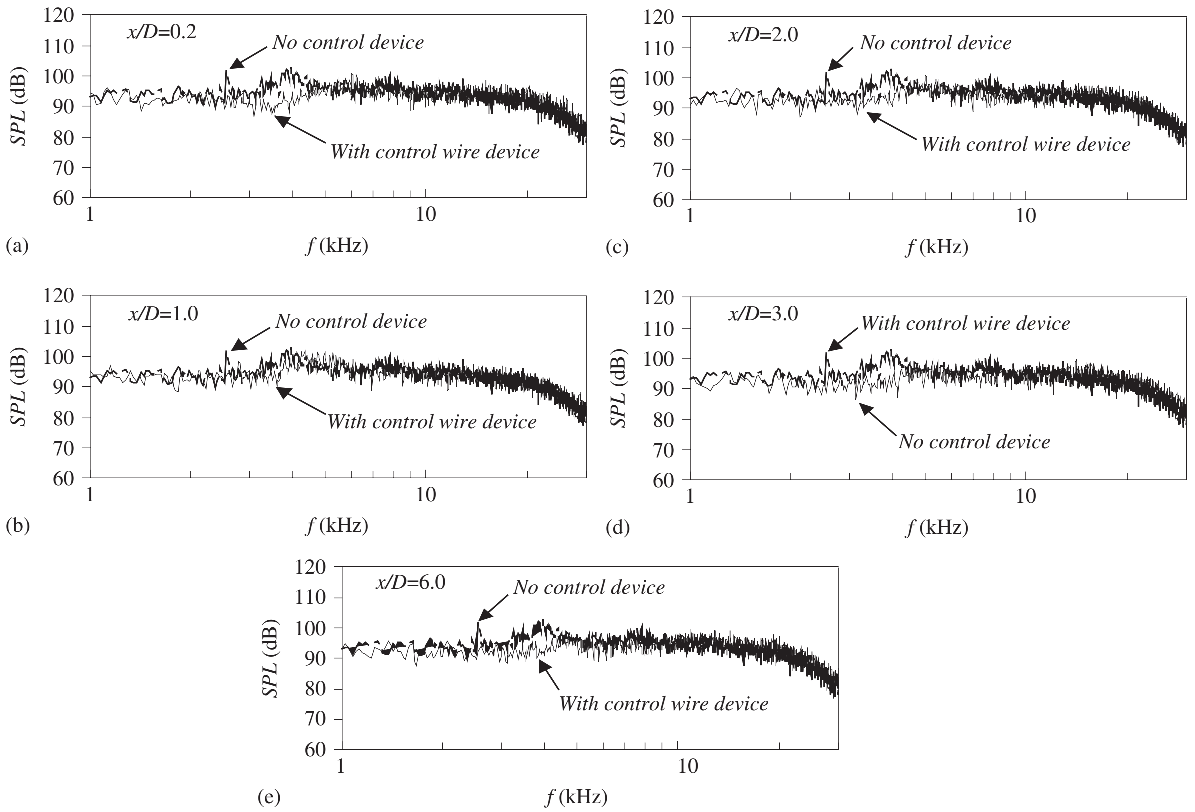
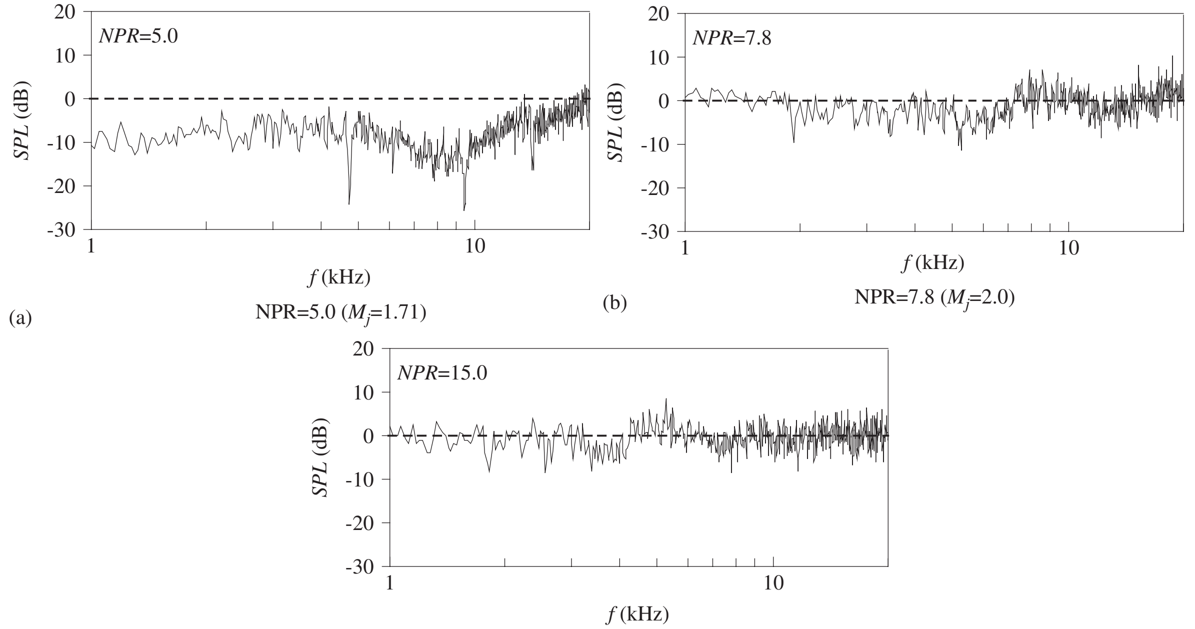


Fig. 10. Noise spectra of under-expanded jets without and with the control wire device (NPR = 15.0, $\theta = 98°$).



NPR=5.0 (M_j=1.71)

NPR=7.8 (M_j=2.0)

NPR=15.0 (M_j=2.42)

Fig. 11. Sound pressure level ΔSPL relative to no control wire device ($x/D = 1.0$, $\theta = 98°$).

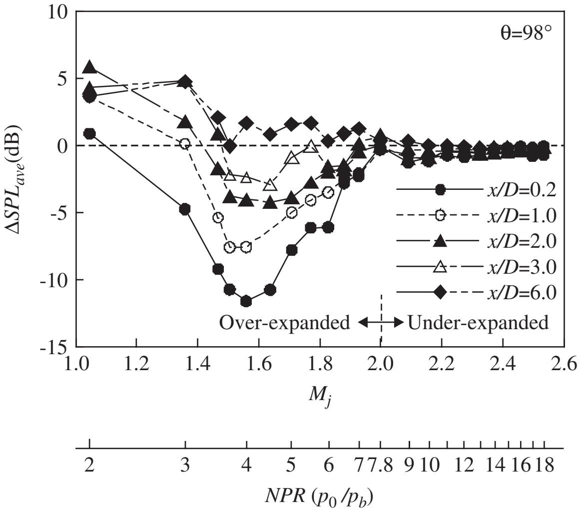


Fig. 12. Relationship between $\Delta\mathrm{SPL}_{\mathrm{ave}}$ and M_j.

In incompressible jet streams, the presence of a cylinder with a small diameter can become, in general, an important noise source since a cylinder in a jet stream generates a number of turbulent eddies. The resulting impinging tones are produced by these turbulent eddies impinging on the cylinder. Krothapalli [30] and Umeda et al. [31] have experimentally investigated the impinging tones which are generated from both subsonic jets and supersonic jets impinging on a circular cylinder. They reported that the impinging tones are generated when the cylinder is located at a distances less than eight times the exit diameter of nozzle, and these tones are due to the strong interactions between the eddies convected downstream and the cylinder. In under-expanded jets, they argued that the screech tones are radiated with nearly the same frequencies in the supersonic jet both with and without a cylinder, and the screech tones are replaced by the impingement tones.

The relationship between the fundamental frequency of screech tone and the jet Mach number (or jet pressure ratio) is shown in Fig. 13. Closed and open symbols represent the screech tone and impingement tone frequencies, respectively. For supersonic jets without the noise control device, the fundamental frequency of screech tone decreases with an increase in the jet Mach number. For $x/D = 0.2$, no screech tone is generated because the shock-cell structure is completely eliminated by the wire device. In the cases of $x/D > 1.0$, impingement tones are generated and their frequencies are nearly constant with an increase in the jet Mach number. When the wire device is placed at a location greater than $x/D = 3.0$, both the screech tones and the impingement tones are generated, as indicated by the closed and open symbols. The screech tones are generated with nearly the same frequencies, regardless of the presence of the wire device [31].

Fig. 14 shows the effect of the wire device on the amplitude of fundamental screech tone. In the case of no control device, the amplitude of fundamental screech tone has peak values for both the over- and under-expanded jets, while there is no screech tone for correctly expanded jet. When the wire device is placed at $x/D \leqslant 3.0$, the screech tone amplitude is significantly decreased, compared to the case of no control device. It is noted here that when the wire device is located at $x/D = 0.2$, the screech tones are completely eliminated. However, as the wire device is moved further downstream, the wire device is located at downstream rather than the sound sources of shock-associated noise (i.e., the third and fourth shock-cells). The sound sources of shock-associated noise remain to exist ahead of the wire device, without weakening or diffusing the shock cells. Moreover, there also exists the vortex shedding behind the wire device that interacts with the supersonic jet structure. Accordingly, it can have noise enhancement effect, depending on the location of the wire device. For instance, when the wire device is located at $x/D = 6.0$, the screech tone amplitude is much higher than that of no control device in the over-expanded conditions. The amplitude has peak values at $M_j = 1.64$, 1.88 and 2.09, respectively [32].

The effect of the present wire device on the OASPL is presented in Fig. 15. For the supersonic jets without the control device, the OASPL increases gradually with an increase in M_j, decreases in the vicinity of $M_j = 2.0$,

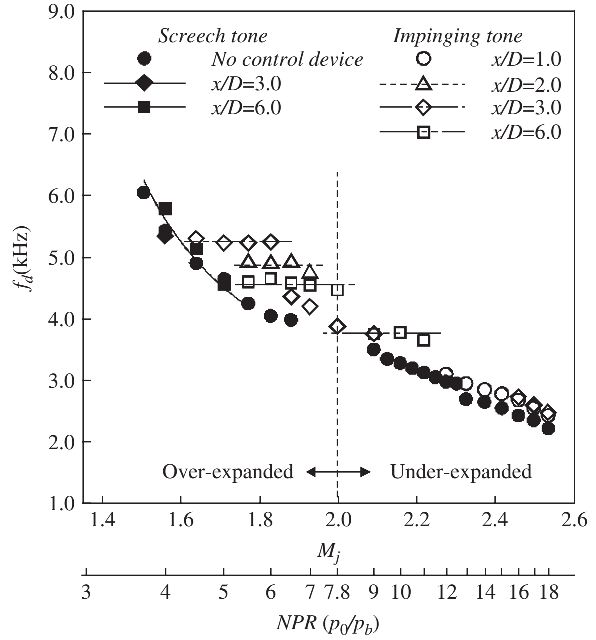


Fig. 13. Fundamental screech tone frequency vs. M_j.

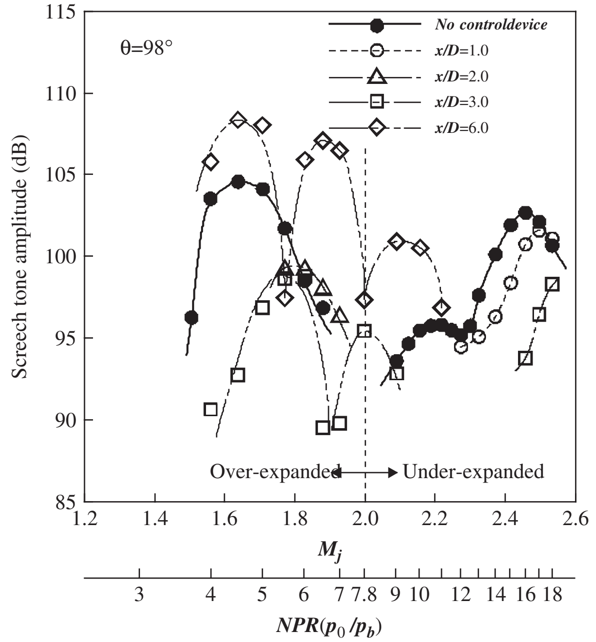


Fig. 14. Fundamental screech tone amplitude vs. M_j.

and then is nearly constant with a further increase in M_j. Similar qualitative tendencies are also found in the cases with the wire device. However, when the wire device is located at $x/D = 0.2$, the OASPL in the over-expanded condition is considerably reduced by the wire device. The maximum reduction in the OASPL is about 11 dB at $M_j = 1.56$. As the wire device is moved downstream, the wire device becomes less effective in reducing the OASPL.

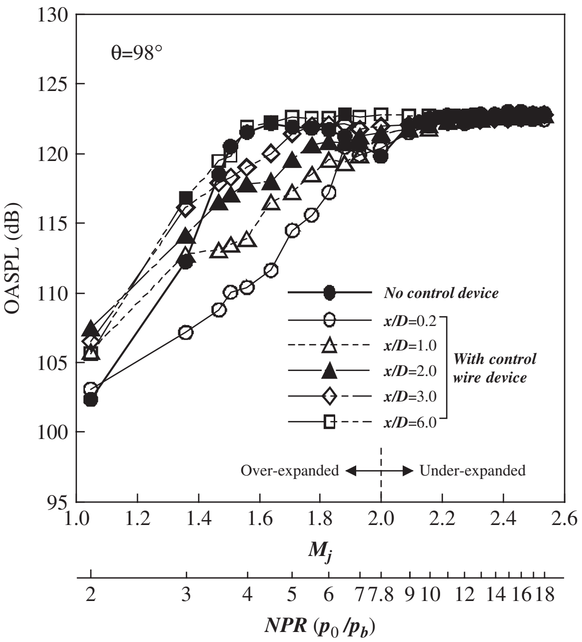


Fig. 15. Variation of OASPL with M_j.

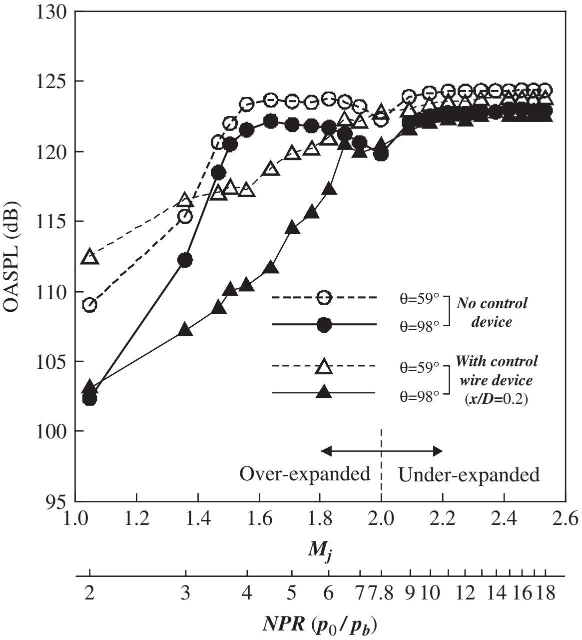


Fig. 16. Relationship between OASPL and a measurement angle θ.

The relationship between the OASPL and a measurement angle θ is shown in Fig. 16. For the case of no control device, the OASPL at $\theta = 59^\circ$ is higher by about 2–5 dB than that of $\theta = 98^\circ$, depending on M_j. This tendency results from the far-field directivity pattern of jet noise. For over-expanded jets, the difference between the OASPLs of $\theta = 59^\circ$ and 98° is increased by the placement of the wire device into the jet stream.

This result may be due to increased spreading rate of a jet in the downstream of the wire device. However, for under-expanded jets, the difference in the OASPL seems to be relatively small.

4. Conclusion

The present study describes a new control technique for the supersonic jet noise reduction using a wire device, which has a simple structure and is easy to implement. The control wire device is placed perpendicularly to the supersonic jet stream, and its location is varied to investigate the noise control effects. From flow visualization, pressure and acoustic measurements, several useful conclusions are obtained. The wire device significantly affects the jet structure and acoustic field, depending on its location and the jet pressure ratio. By introducing the wire device to the jet stream, the shock-cell structure is destroyed and its strength is reduced, while the jet spreading rate downstream of the wire device somewhat increases. The present wire device suppresses the screech tones and the broadband shock-associated noise as well as the OASPL, when it is suitably placed at a location close to the exit of nozzle. The noise control effects significantly increase in over-expanded jets, compared with under-expanded jets.

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