ICSV13 - Vienna
The Thirteenth International Congress on Sound and Vibration
Vienna, Austria, July 2-6, 2006

CONTROL OF SUPERSONIC JET NOISE USING A MESH SCREEN

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Abstract
This paper describes an experimental work to control supersonic jet noise using a mesh screen that is placed at the nozzle exit plane. The mesh screen is a wire-gauze screen that is made of long stainless wires with a very small diameter. The nozzle pressure ratio is varied to obtain the supersonic jets which are operated in a wide range of over-expanded to moderately under-expanded jets. In order to perturb mainly the initial jet shear layer, the hole is perforated in the central part of the mesh screen. The hole size is varied to investigate the noise control effectiveness of the mesh screen. A schlieren optical system is used to visualize the flow fields of supersonic jet with and without the mesh screen device. Acoustic measurement is performed to obtain the OASPL and noise spectra. The results obtained show that the present mesh screen device leads to a substantial suppression of jet screen tones. The hole size is an important factor in reducing the supersonic jet noise. For over-expanded jets, the noise control effectiveness of the mesh screen appears more significant, compared to correctly- and under-expanded jets.

INTRODUCTION

Supersonic jet noise consists of three major components [1] : the turbulent mixing noise, the broadband shock-associated noise, and the screech tones. The turbulent mixing noise appears in subsonic jets as well as supersonic jets. 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 turbulence structures and shock-cell structures. With regard to the screech tone, Powell [2] first proposed that the screech tones and its harmonics are generated by a resonant feedback loop between the oscillating shock-cell structures and the nozzle exit. Of major components of the supersonic jet noise, the screech tone has a strong directivity and high intensity, and thus, it can cause sonic fatigue failure of aircraft structures [3, 4].

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, asymmetric nozzles, porous plugs, etc. have been used in these control techniques, which have been successful in suppressing the supersonic jet noise. The effective suppression of the screech tone was obtained by using small tabs installed at the nozzle exit [5]. Norum [6] studied a variety of asymmetric nozzle configurations for screech tone suppression. Kibens and Wlezien [7] investigated the technique for the reduction of jet noise using a porous plug-nozzle, and showed that perforations of plug-nozzle produce a series of weak compression and expansion waves and reduce the jet noise.

Recently, Debiasi and Papamoshou [8] 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. Zoppellari and Juve [9] tried to suppress the jet noise by using water that is injected into the jet stream through the multiple injectors near the nozzle exit.

From practical point of view, it is required that the method 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, noise control has to meet the needs of low cost and a simple structure [10-12].

In the present study, a new technique for the suppression of supersonic jet noise using a mesh screen device is investigated. The mesh screen 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 mesh screen device on the jet structure and acoustic field of supersonic jet.

EXPERIMENTAL FACILITES AND MEASUREMENT

The present work is accomplished in an anechoic test room that is schematically shown in Fig.1. The interior walls of the test room are covered with a sound absorption material of 325mm thickness. Preliminary acoustic tests show that the test room is anechoic for frequency components above approximately 120Hz and a background noise is about 10dB. Compressed dry air is stored in a high-pressure tank that has a capacity of 5m^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. The nozzle has a throat diameter of D_t=20mm, an exit diameter of D= 26mm, and a straight section near the exit of the nozzle (see Fig.2). The pressure inside the plenum chamber is controlled by a pressure regulator value that is located upstream of the plenum chamber. The jet Mach number M_j is varied between 1.05 and 2.53. For the present nozzle with a design Mach number of 2.0, the correct expansion at the nozzle exit is obtained at M_j=2.0. Thus, the jet Mach number applied in the present study covers the range from over-expanded to moderately under-expanded conditions.

The mesh screen device is illustrated in Fig.2. It is placed perpendicular at the nozzle exit plane. The mesh screen is a wire-gauze screen that is made of long stainless wires with a very small diameter of 0.5mm. The mesh size is 1mm×1mm. In order to perturb mainly the initial jet shear layer, the hole is perforated in the central part of the mesh screen. Thus, the jet flow near the axis of the nozzle discharges from the nozzle exit through the perforated hole, without the resistance of the mesh screen. In the present study, the hole size with a diameter of D_m is varied between 0.0D and 0.81D.

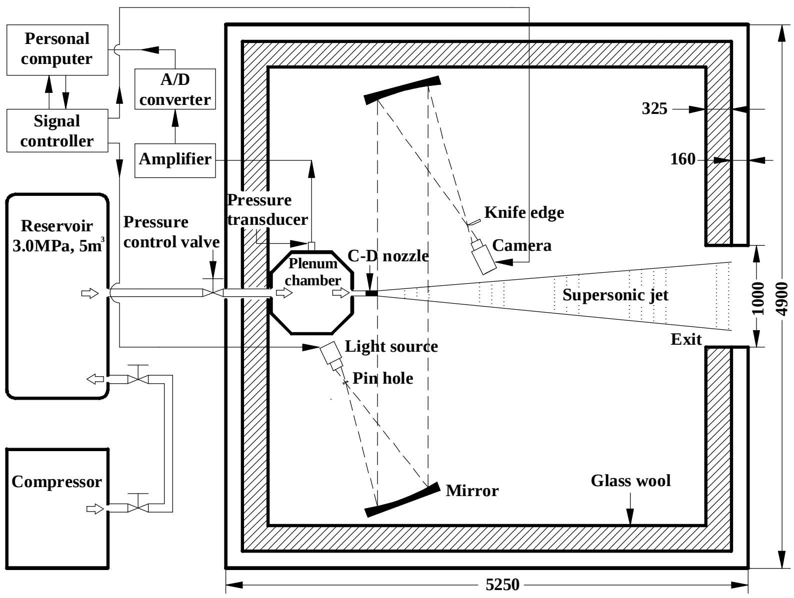

Figure 1 – Schematic diagram of experimental apparatus

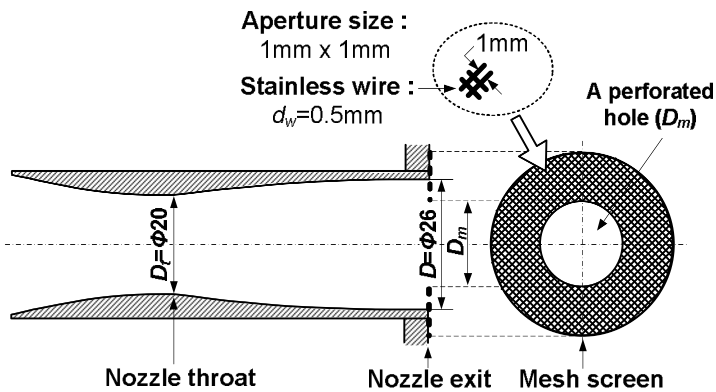

Figure 2 – Arrangement of a mesh screen device

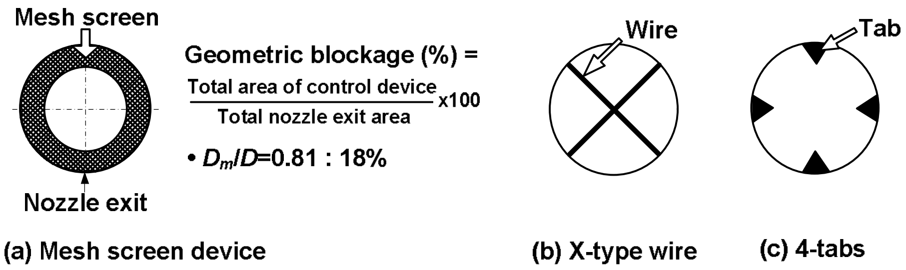

Figure 3 – Three different noise control devices for supersonic jet

The jet noise control technique using the mesh screen device is compared with the control methods by 4-tabs [4] and X-type wire device [9], as shown in Fig.3. The geometric blockage due to the control device is defined as the total area of the control device intruding the jet flow divided by the total nozzle exit area. For the mesh screen device with the perforated hole of D_m/D=0.81, the geometric blockage is 18%. Both the X-type wire and 4-tabs are designed to be the geometric blockage of 18%.

A schlieren optical system is employed to visualize the qualitative structures of supersonic jet. Acoustic measurements are made using a condenser microphone that has a diameter of 6mm. The microphone is located at 98° and the radial distance of r=38D from the exit of the nozzle. The acoustic signals are analyzed by using a FFT analyzer. A FFT analysis provides the noise spectra and overall sound pressure level.

RESULTS AND DISCUSSION

Effect of the Mesh Screen Device on Jet Structure and Noise Spectra

Figures 4 shows flow visualization pictures of supersonic jets with and without the mesh screen device. The perforated hole size is D_m/D=0.81. For an over-expanded jet without the mesh screen at M_j=1.71, 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 mesh screen device is placed at the nozzle exit plane, it seems that the turbulence of the shear layer behind the mesh screen is weakened, compared with the uncontrolled jet, as shown in Fig.4(a). However, the jet structure is very complicated due to the oblique shocks newly generated from the perforated hole's edge of the mesh screen.

At M_j=2.0, the jet is correctly-expanded condition at the nozzle exit, and the pressure at the exit of the nozzle is matched to the ambient back pressure. In this case, the jet boundary is nearly parallel to the jet axis, and no shock-cell structure is found in the jet flow. The correctly-expanded jet is modified by placing the mesh screen device, as shown in Fig.4(b). At M_j=2.46, the jet is under-expanded, as shown in Fig.4(c). The jet boundary is expanded because the expansion waves are generated at the exit of the nozzle. It is observed that for under-expanded condition, the mesh screen device somewhat increases the spreading rate of the jet behind the mesh screen.

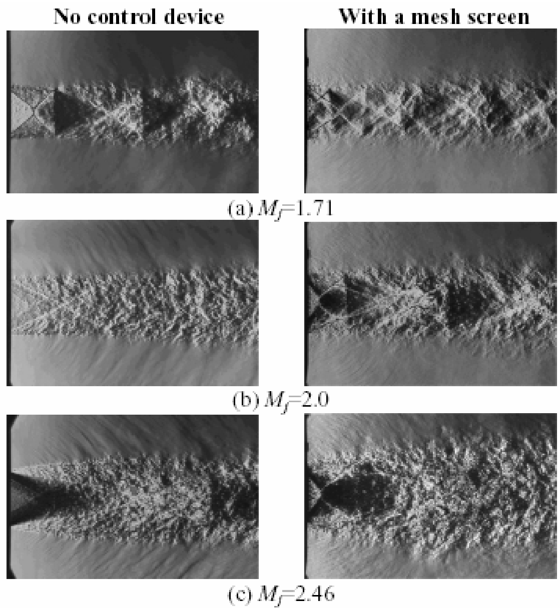

Figure 4 – Schlieren pictures of supersonic jets without (left) and with (right) a mesh screen device (D_m/D=0.81)

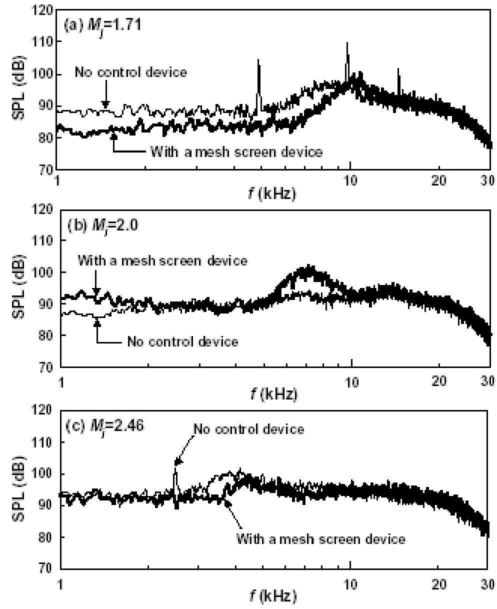

Figure 5 – Far-field noise spectra of supersonic jets (D_m/D=0.81)

Figure 5 shows the far-field noise spectra of supersonic jets with and without the mesh screen device. In Fig.5(a), for uncontrolled over-expanded jet, there are three discrete peaks, referred to as the screech tone. It is interesting to note that the mesh screen eliminates the screech tone and considerately suppresses the jet noise in the frequency range below f=10kHz. For correctly-expanded jet, there are no discrete tones in the noise spectra. As can be seen in Fig.5(b), the mesh screen device is not effective for suppressing the correctly-expanded jet noise. The noise spectra of under-expanded jets with and without the mesh screen are shown in Fig.5(c). For uncontrolled jet, there is a screech tone at a frequency of about f=2.6kHz. However, the screen tone and the broadband shock-associated noise are reduced by placing the mesh screen device at the nozzle exit plane.

The effect of the hole size (D_m/D) on the jet structure is shown in Fig.6. In Fig.6, the case of D_m/D=0.0 indicates that the nozzle exit is completely covered by the mesh screen. When the hole size perforated in the central part of the mesh screen decreases, the intensity of the large-scale turbulence in the jet shear layer is more significantly suppressed. Behind the mesh screen, the Mach disk is formed, as shown in Fig.6(c) and (d). It seems that the shock-cell strength decreases with a decrease in D_m/D, compared with the shock-cell structure of uncontrolled jet (i.e., D_m/D=1.0).

Figure 7 shows the effect of D_m/D on the far-field noise spectra. When D_m/D decreases, the noise control effect of the mesh screen device is more significant. For example, for D_m/D=0.81, the mesh screen device reduces the noise spectra by about 7dB in the frequency range below f=10kHz. However, for D_m/D=0.5, the noise suppression of about 13dB is observed in the frequency range below f=13kHz. The broadband shock-associated noise decreases with a decrease in D_m/D, because the shock cell strength decreases, strongly depending on the hole size, as shown in Fig.6.

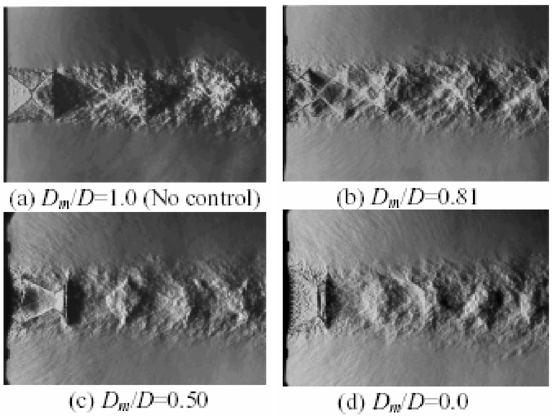

Figure 6– Over-expanded jets with a mesh screen device (M_j=1.71)

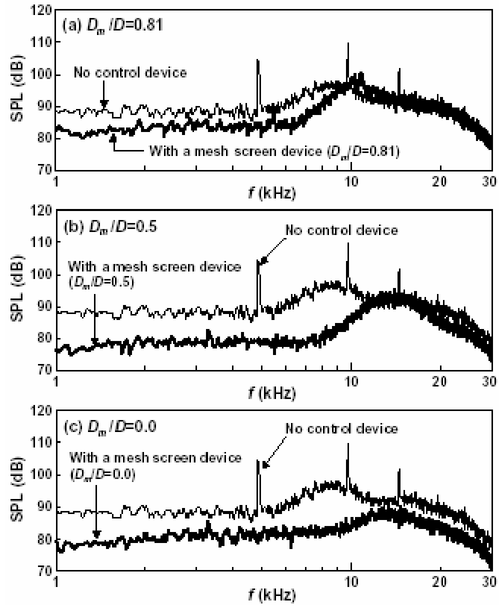

Figure 7 – Effect of D_m/D on far-field noise spectra (M_j=1.71)

Comparison with X-Type Wire Device and 4-Tabs

The noise control technique using the mesh screen is compared with the X-type wire device and 4-tabs. The effects of three different control devices on the jet structure are shown in Fig.8. In Fig.8(b), although the jet structure is modified by placing the mesh screen device at the nozzle exit plane, the shock-cells are still observed in the jet flow. However, when the X-type wire device and 4-tabs are placed at the nozzle exit plane,

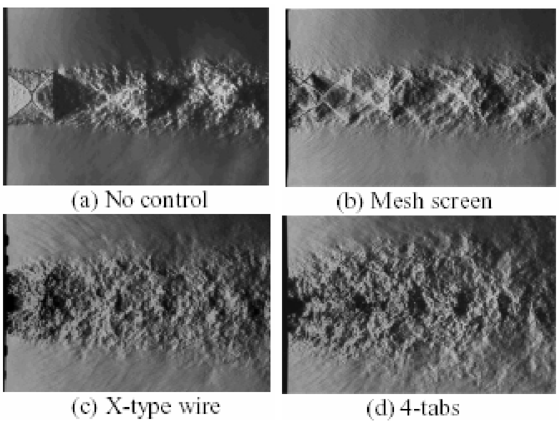

Figure 8– Effects of three different noise control devices on jet structures (M_j=1.71)

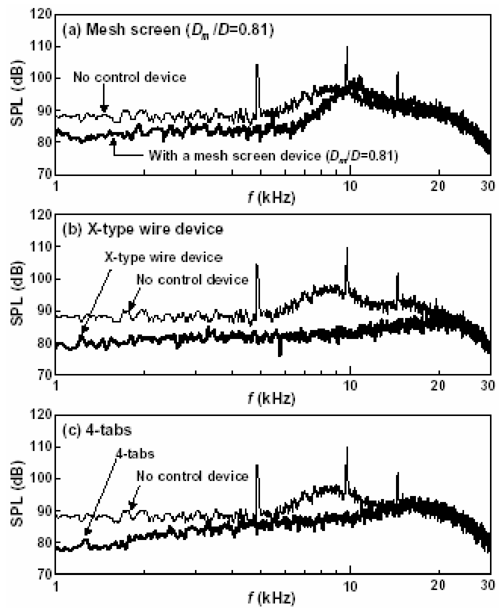

Figure 9 – Far-field noise spectra for three different noise control devices (M_j=1.71)

these control devices disperse the kinetic energy of the jet flow to radial direction with respect to the jet axis. This can lead to both weakening the shock cell structure and enhancing the mixing of the jet. As shown in Fig.8(c) and (d), the jet structures are considerably changed by the X-type wire and 4-tabs, compared with that of the mesh screen device.

Figure 9 shows the far-field noise spectra for three different control devices. All of three control devices applied in the present study are very effective for suppressing the screech tones. In Fig.9(a), the peak of the broadband shock-associated noise is observed at a frequency of f=10kHz. However, the X-type wire device and 4-tabs completely eliminate the broadband shock-associated noise, because they break the shock-cell structures, as readier shown in Fig.8.

The effects of jet noise control devices on the overall sound pressure level are shown in Fig.10. For uncontrolled supersonic jets, the OASPL increases gradually with an increase in M_j, decreases in the vicinity of M_j=2.0, and then is nearly constant with a further increase in M_j. 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. In the cases with noise control device, the OASPL increases with M_j. The OASPL in the over-expanded condition is reduced by the mesh screen device, while the mesh screen device becomes less effective in reducing the OASPL for the correctly- and under-expanded jets. The maximum reduction in the OASPL by the mesh screen is about 4dB at M_j=1.56. Of three different control devices, the X-type wire device is the most effective for reducing the OASPL.

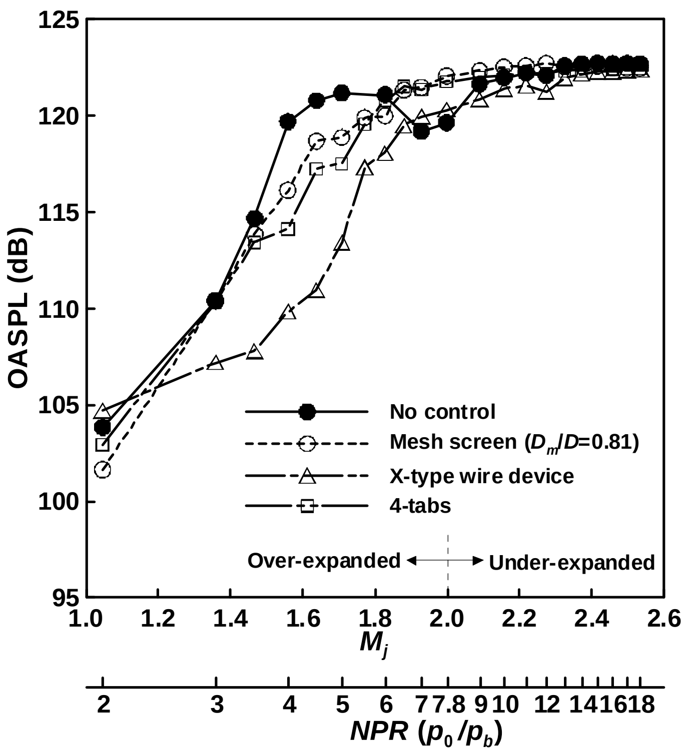

Figure 10– Effects of jet noise control devices on the overall sound pressure level (OASPL)

CONCLUSIONS

The present study describes an experimental work to control supersonic jet noise using a mesh screen that is placed at the nozzle exit plane. The mesh screen is a wire-gauze screen that is made of long stainless wires with a very small diameter. The nozzle pressure ratio is varied to obtain the supersonic jets which are operated in a wide range of over-expanded to moderately under-expanded conditions. In order to perturb mainly the initial jet shear layer, the hole is perforated in the central part of the mesh screen. The size of a perforated hole is varied to investigate the control effectiveness of supersonic jet noise. A high-quality schlieren optical system is used to visualize the flow fields of supersonic jet with and without the mesh screen device. Acoustic measurement is performed to obtain the overall sound pressure level and noise spectra. The results obtained show that the mesh screen device leads to a substantial suppression of jet screen tones and the OASPL. The hole size is an important factor in reducing the supersonic jet noise. For over-expanded jets, the noise control effectiveness of the mesh screen device is more significant, compared to correctly- and under-expanded jets.

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