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Supersonic Jet Noise Control via Trailing Edge Modifications

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Various experimental data, including mixing areas, cross correlation factors, surface flow patterns on nozzle walls, and far field noise spectra, was used to draw a noise control mechanism in a supersonic jet. In the underexpanded case, mixing of the jet air with ambient air was significantly enhanced as presented before, and mixing noise was also dramatically reduced. Screech tones, in the overexpanded case, were effectively suppressed by trailing edge modifications, although mixing enhancement was not noticeable. From mixing and noise performance of nozzles with modified trailing edges, enhancing mixing through streamwise vortices seems an effective way to reduce mixing noise in the underexpanded flow regime. However, screech tones in the overexpanded flow regime is well controlled or suppressed by making shock cells and/or spanwise large scale structures irregular and/or less organized by a proper selection of trailing edges. The noise field in the overexpanded flow regime was greatly affected by the symmetricity of the nozzle exit geometry. In the underexpanded flow regime, the effects of the symmetricity of the nozzle exit on mixing were negligible.

Key Words : Noise Control, Supersonic Jet, Screech Tone, Broadband Shock associated Noise, Trailing edge modification

1. Introduction

Extensive researches on mixing enhancement and noise reduction using trailing edge modifications in supersonic rectangular jets have been conducted over the past few years. It was found that the use of trailing edge modifications, in an aspect ratio of 3 rectangular supersonic jet, resulted in significant mixing enhancement at the underexpanded flow regime, moderate enhancement at the overexpanded cases, and no significant mixing enhancement at the ideally expanded case (Samimy et al. 1998; Kim and Samimy 1999). Through a detailed investigation of the physics of the vortex generation mechanism by the trailing edge modification, Kim and Samimy (1999) concluded that the spanwise pressure gradient on the modified surface was the major source of streamwise vorticity. Both shock associated noise and mixing noise was also significantly reduced by trailing edge modifications (Samimy et al. 1998; Kerechanin et al. 2000). The advantage of trailing edge modifications over other techniques such as tabs (Samimy et al. 1993; Zaman et al. 1994) is that they do not cause any thrust loss (Kim and Samimy 1999).

Even with the extensive information regarding the effects of cutouts/modifications on mixing and noise and the mechanism related to the enhanced mixing, what still lacks in the previous experiment is the mechanism related to the noise reduction. One more thing to be investigated further is to find out the relation between the modified flow and noise fields. Thus, the purpose of the manuscript is to investigate and draw the mechanism behind the noise reduction, by using already available noise and flow field data. The experimental results on mixing and noise acquired separately will be compared and analyzed.

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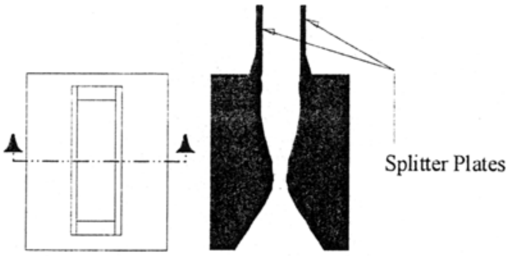
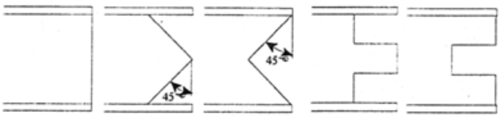
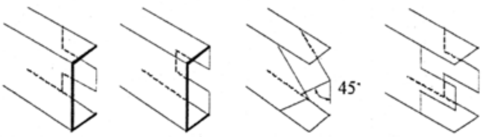


(a) Nozzle and its cross-sectional view



(b) Modifications OS, OC, RS and RC from left to right



(c) Nozzle NS Nozzle NC Nozzle OS-OS Nozzle RS-RS

Fig. 1 Schematics of the nozzles and the modified trailing edges. Letters O and R represent the shape of cutouts; O for oblique and R for rectangular cutouts. Letters C and S represent the position of cutouts; C for central and S for side cutouts in the trailing edge

2. Experimental Facility and Techniques

Since all data used is already published or being published, the experimental facility and techniques are very briefly described here. The air, supplied by two four-stage compressors, is filtered, dried, and stored in two cylindrical tanks with a total capacity of 42.5 m^3 at 16.5 MPa pressure. The compressed air is delivered to the primary stagnation chamber through a 5.08 cm (2 inch) inside diameter flexible hose. Although the jet facility has a secondary stagnation chamber for coflow jet, only the primary jet will be discussed here. The pressure in the primary stagnation chamber is controlled by a pressure regulator actuated pneumatically. The air is expanded from the 5.08 cm line to a 24.1 cm (9.5 inch) diameter pipe that is 91.4 cm (36 inch) long for flow conditioning. The air passes through a perforated plate, two coarse mesh screens of 55.4% opening area, and finally converges to a 5.97 cm (2.35 inch) pipe that is 40.6 cm (16 inch) long. After passing through this pipe, it is throttled down into the ambient air through an rectangular nozzle with aspect ratio of 3. A detailed description is found in Kim and Samimy (1999, 2000).

The nozzle has either a cutout on single side or two cutouts on both sides of the minor axis as shown in Fig. 1. The nozzle exit measures 2.86 cm wide and 0.95 cm high, with an equivalent diameter ($D_{eq}=(4A_{exit}/\pi)^{1/2}$) of 1.86 cm, and these dimensions are the same as those used in the previous experiments (Kim and Samimy 1999). The schematic of the baseline nozzle and the types of cutouts on the nozzle block are shown in the figure. Four types of cutouts were used: Oblique Side (OS), Oblique Central (OC), Rectangular Side (RS), and Rectangular Central (RC) type as shown in Fig. 1. The nozzle name bears the type of modifications/cutouts what it has.

The instantaneous cross-sectional images were acquired by the laser sheet illumination technique. A more detailed description of the technique is found in Samimy et al. (1998) and Kim and Samimy (1999, 2000). The visualizations of the jet cross-section were performed at four downstream locations, i. e., $x/D_{eq}=1$, 2,4, and 8. The jet was operated at three fully expanded jet Mach numbers of 1.75 (overexpanded), 2.0 (design Mach number), and 2.5 (underexpanded). Surface flow visualizations were conducted by kerosene Lampblack technique (Settles and Teng 1983). Details on surface flow visualizations are available in Kim and Samimy (1999).

The far-field noise was measured at three downstream locations with three angles of 30, 60, and 90° relative to the jet axis as depicted in Fig. 2. The distance from the jet axis to the tip of each microphone was kept at 40 D_{eq}. Two microphones were placed on the minor axis plane, while one was on the major axis plane. The far-field noise was measured in a fully anechoic chamber with a cutoff frequency of 250 Hz. A more detailed description of the anechoic chamber is found in Kerechanin et al. (2000).

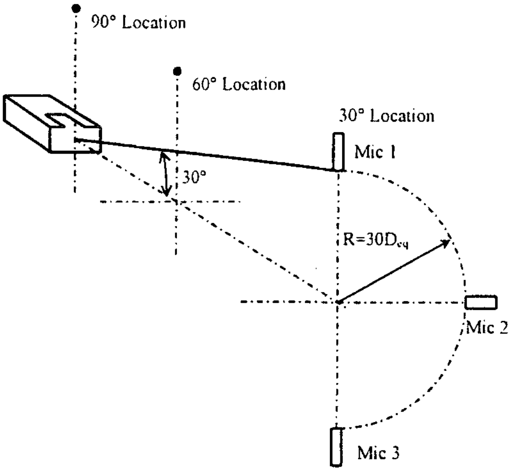


Fig. 2 Location of microphones

3. Results and Discussion

In this research, all available data including cross-sectional images, surface flow patterns, and far-field noise, were used to explore the mechanism of noise reduction by trailing edge modifications. The data for mixing performance of the jet was obtained from Samimy et al. (1998) and Kim and Samimy (1999). Far-field noise data is taken from Kerechanin et al. (2000).

3.1 Underexpanded case

In this flow regime, it was conjectured that the enhanced mixing by trailing edge modifications would result in mixing noise reduction. As presented in Kim and Samimy (1999, 2000), mixing was significantly enhanced by the modified trailing edges in this flow regime. The mixing noise was significantly reduced in the downstream direction at an off-axis angle of 30° relative to the jet axis as shown in Fig. 3. In the figure, each spectrum is an averaged of 100 spectra.

Since this direction with an off-axis angle of 30° is the principal direction of mixing noise, the amount of mixing noise reduction in this direction was most significant as expected. The mixing noise level reduction in this direction is more than 9 dB at the peak frequency of the baseline nozzle BB. As shown in Fig. 2, the microphone head of Mic 1 is facing the modified trailing edge. The spectra obtained from microphone 3 placed on the opposite side of nozzle did not show any significant mixing noise reduction. This is most probably related to the less enhanced mixing since the mixing at this side was not affected by the cutout as observed in Fig. 4. When the amount of noise reduction by two types of cutout is compared, trailing edges with central cutouts performed better in mixing noise reduction at a frequency higher than 7 kHz. As discussed in Kim and Samimy (1999, 2000), this type of cutout generated a kidney type pair of streamwise vortices and showed better mixing at a far downstream location. These experimental evidences suggest that the mixing noise reduction is most likely due to the enhanced mixing by the trailing edge modifications.

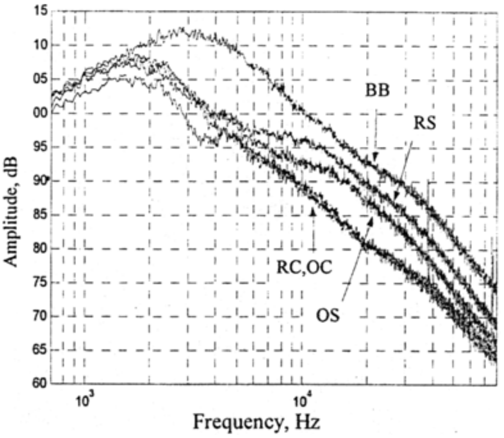


Fig. 3 Noise spectra for nozzles with single-sided trailing edge modifications at 30°. Relative 10 dB downshift in each spectrum

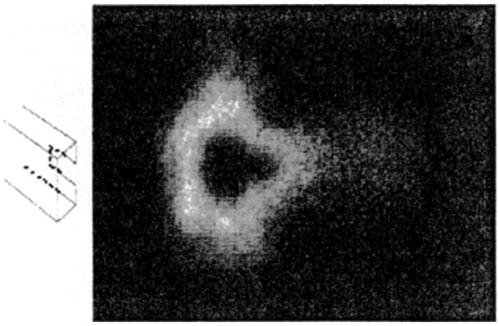


Fig. 4 An averaged image of the jet cross section at $8D_{eq}$ downstream location for nozzle RC

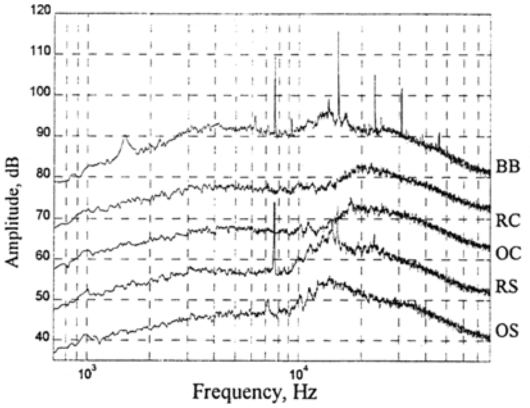


Fig. 5 Far-field noise spectra for nozzles with single-sided modification at 90°. Relative 10 dB downshift in each spectrum

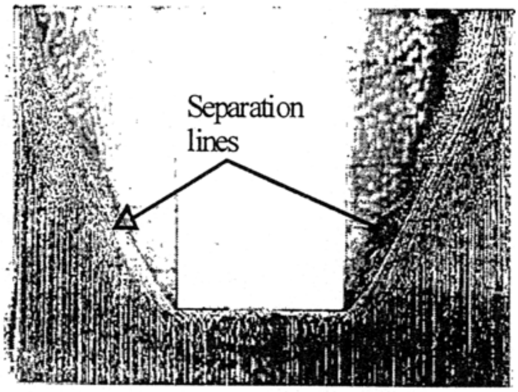


Fig. 6 Surface flow pattern on modification RC at $M_j = 1.75$

However, the spectra acquired at an off-axis angle of 90° showed no remarkable reduction in amplitudes of broadband shock associated noise. As in the experiments for tabbed nozzles and beveled nozzles (Zaman et al. 1994; Raman 1997), it appeared that broadband shock associated noise is less controllable compared to screech tones. As will be shown later, this seems true for both in the underexpanded and overexpanded cases of nozzles with trailing edge modifications.

Since the mixing noise is not dominant over the other components of the jet noise in the other directions of 60 and 90°, the mixing noise reduction was not noticeable. A further mixing noise reduction by using cutouts on both sides of the wider trailing edge was not significant. Contrary to the case of overexpanded flow regime, mixing and noise characteristics were not strongly affected by the symmetricity of the nozzle exit.

3.2 Ideally expanded case

When the splitter plate or nozzle extension was modified, there were no significant effects of cutouts on the mixing and noise at all (Samimy et al. 1998; Kim and Samimy 1999). However, there was quite enhanced mixing when the contoured nozzle block was modified rather than the splitter plate being modified (Kim and Samimy 2000). For these nozzles, the jet development at downstream locations was similar to that in a slightly underexpanded case for a nozzle with cutouts on a splitter plate. Thus, it is expected that mixing noise would be reduced in this flow regime because of the enhanced mixing as the same way in the underexpanded case. Since the noise measurement was not performed, a quantitative information on noise reduction is not available.

3.3 Overexpanded case

In this flow regime, a significant reduction in shock noise, especially in screech tones, was observed for nozzle with single-sided trailing edge as shown in Fig. 5. Screech tones were suppressed by the cutouts except for modification RS. However, the broadband shock associated noise level was not significantly reduced. As was found by Samimy et al. (1998) and Kim and Samimy (1999), mixing enhancement in this flow regime was not so dramatic as in the underexpanded case. This suggests that the reduction/suppression in screech tone level is probably not related to mixing in a significant fashion. Thus, the focus was directed on the deformation of shock cells and large-scale structures by the modifications, which is considered to be responsible for the reduced screech tones.

By visualizing surface flow patterns on the nozzle walls, the effects of cutouts on the shock cell structures were investigated. As shown in Fig. 6 for cutout RC, separation lines due to oblique shock waves are marked on the surface flow pattern along with streaklines in a slightly

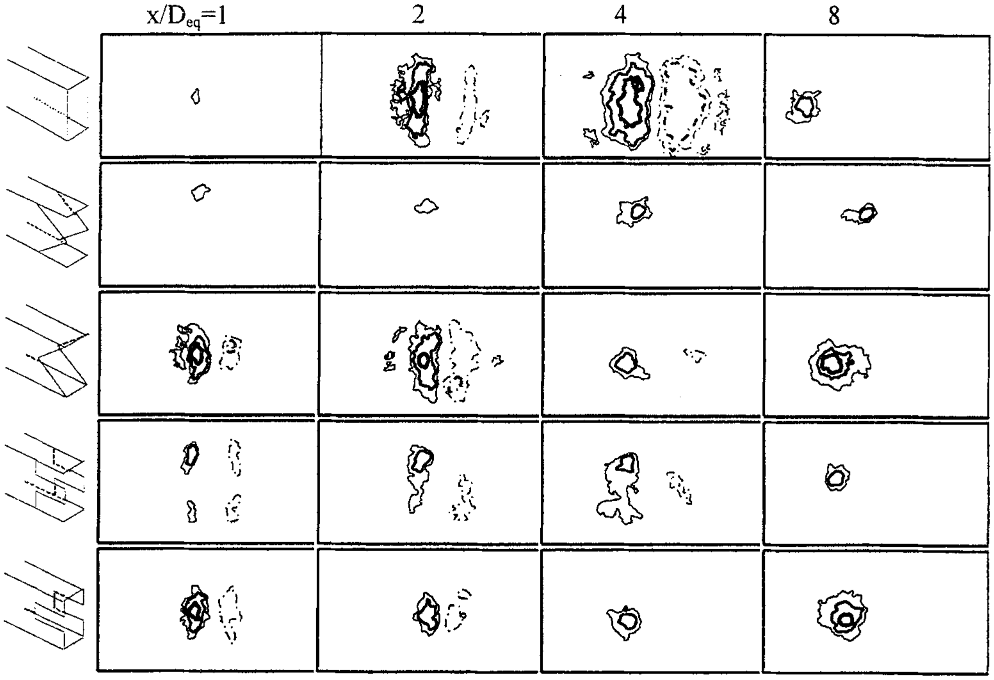


Fig. 7 Cross correlation factors at four downstream locations at $Mj=1.75$. The contours on the right hand side with dash-dot lines has negative signs. A point which has a local rms maximum is used as a reference point

overexpanded condition of $M_j=1.75$. Just above these separation lines, shock waves are formed. If there are no cutouts on the splitter plate, quasi two-dimensional oblique shock waves would be generated at the edge of the splitter plate. Because of these oblique shock waves, large-scale structures would be also deformed and thus less organized. These combined effects of cutout on the shock cell and large-scale structures are most probably responsible for the screech tone reduction or suppression in the overexpanded flow regime.

It is also expected that the jet flow field is significantly altered by the cutout. To investigate the effects of cutout on the flow field, especially on the flapping motion, a statistical based analysis was adopted at the overexpanded case of $M_j=1.75$. When a jet is flapping, the relatively thick mixing layer was mutually exclusive as shown in Kim (1998). The size of flow structure and orientation was extracted from the two-dimensional spatial correlation field by the same way as Messersmith and Dutton (1996) and Gruber and Nerjad (1997) used. In the present case, a pixel whose rms is a local maximum is used as a reference point.

As shown in Fig. 7 for nozzles with double-sided trailing edges, right and left side mixing layers are not in phase: their signs are exclusive. Most probably, this is due to flapping motion of the jet column. The flapping motion of the jet column was greatly reduced by the cutouts, for nozzles with double-sided trailing edge modifications. For nozzle OS-OS, which has OS type cutouts on both side of the nozzle, screech tones are almost suppressed (as shown in Fig. 8) and the flapping motion of the jet plume is not noticeable (as shown in the second row in Fig. 7). On the other hand, all nozzles that have strong screech tones show flapping motion. From these observations, a possible mechanism responsible for the screech tone reduction is a three dimensional deformation of shock cells and/or large-scale structures by the cutout/modification.

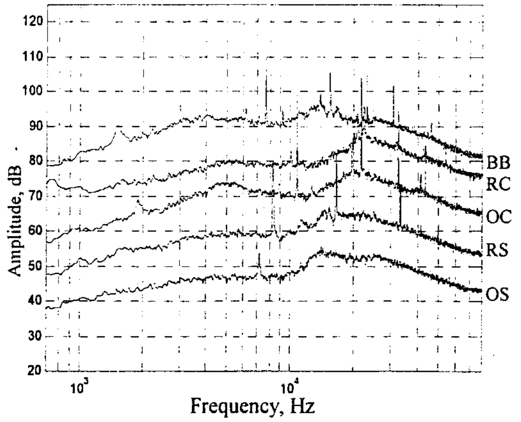


Fig. 8 Far-field noise spectra for nozzles with single-sided modification at 90°. Relative 10 dB downshift in each spectrum

By this three-dimensional deformation, flapping motion is probably reduced and thus the jet is less effective to generate screech tones.

For the nozzles with single-sided trailing edge modification, screech tones are suppressed except for cutout RS as seen in Fig. 5. Thus, it is better to use cutouts on a single side rather than on both sides of the nozzle, since the use of the same types of cutouts on both sides of the nozzle provides a favorable condition for symmetric formations of shock cells and/or large-scale structures about the major axis of the nozzle.

Another issue to be considered is the influence of cutouts on the broadband shock associated noise. Although the peak frequency of the broadband shock associated noise was significantly altered as shown in Fig. 8, the level was not so much reduced. It seems that the use of trailing edge modifications is not an effective way to suppress/reduce broadband shock associated noise as mentioned before. This result on broadband shock associated noise agrees with Zaman et al. 's (1994) findings.

4. Conclusions

From mixing characteristic, surface flow patterns, and noise data of a rectangular jet with trailing edge modifications, an attempt to draw/infer a noise control mechanism was made. In the underexpanded case, mixing noise was significantly reduced in the principal direction of mixing noise at an off-axis angle of 30°. This reduction is most likely due to remarkably enhanced mixing by cutouts. In this flow regime, nozzle with symmetric and asymmetric exits showed no differences in noise and mixing performance of the jet. As in overexpanded case, broadband shock associated noise was barely controlled or suppressed by the cutouts.

From surface flow patterns and cross correlation factors, it was found that shock cells and large scale spanwise structures were significantly deformed by the cutouts/modifications in the overexpanded case. Since two-dimensional shock cells and spanwise large-scale structures provides a favorable condition for shock noise, three-dimensional or irregular deformation of these would result in reduced screech tones and broadband shock associated noise. In fact, the far-field noise data showed that controlled or removed flapping, through three-dimensional deformation of shock cells and/or large-scale structures, is closely related to the screech tones suppression. Although nozzles with symmetric and asymmetric nozzle exits did not show any difference in noise and mixing performance in the underexpanded case, screech tones were better suppressed by asymmetric nozzle trailing edges than symmetric ones in the overexpanded regime.

Two different noise control mechanisms for each flow regime can be inferred/drawn. In the underexpanded, enhancing mixing through streamwise vortices seems an effective way to reduce jet mixing noise. However, screech tones are well suppressed simply through deforming shock cells and/or large scale structures by asymmetric trailing edges in the overexpanded regime.

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