Brief Communication

Twin-Jet Coupling Suppression using Miniature Pins and Cavities

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1. INTRODUCTION

Modern aircraft use nozzles of non-uniform geometry. This includes rectangular nozzles with beveled exits. In addition, some nozzles exhaust on to an adjacent surface on aircraft such as the F-117 and B-2. There is a need to develop devices that can suppress the coupling of jets from nozzles of complex geometry. If left unchecked, the high dynamic pressures caused by the coupling can damage aircraft structures (as in the case of the F-15 E Eagle). Most of the published work on twin jets has focused on jets having circular exit geometry. Berndt[1] performed a series of wind tunnel experiments to measure the dynamic pressure fluctuations on the nozzle surfaces of a twin-jet nacelle and was able to conclude that the pattern of the highest dynamic pressures measured in the wind tunnel matched the pattern of the hardware damage that occurred during the flight test program. Seiner, Manning and Ponton[2] experimentally showed that for closely spaced supersonic jets operating at off design conditions, the dynamic pressures upstream of the jet exits can reach levels that could result in structural damage. Tam and Seiner[3] observed that the twin jet screech frequency was greater than the frequency of two jets that did not interact with each other. Morris[4] showed how an instability wave analysis can provide some insight into the interaction of twin supersonic circular jets. His analysis showed how the growth rates of instability waves or large structures in the initial mixing region of the twin jets are affected by the jet separation. Wlezien[5] showed that the noise produced by the mutual interaction of two supersonic plumes is a strong function of nozzle spacing and the fully expanded jet Mach number. Shaw[6] examined methods to evaluate the effectiveness of several concepts in suppressing the twin-jet screech i.e. tabs, lateral spacing, axial spacing and secondary jets.

Compared to circular jets, there is a very limited amount of data available on jets with rectangular exit geometry. Moreover, of late, the focus has shifted to scarfed[7], asymmetric[8], beveled[9,10], and trailing edge modified[11,12] nozzles. Raman and Taghavi[13] studied the flow and acoustic features of multiple supersonic uniform exit rectangular jets undergoing phase locked screech. Later, Raman and Taghavi[14] conducted a detailed study of the near acoustic field and the coupling mechanism of twin rectangular supersonic jets having uniform exit geometry. They found that there were two modes of coupling that prevailed – the symmetric mode that augmented the screech amplitude and the antisymmetric mode that suppressed it and both these modes were mutually exclusive. A comparison study by Taghavi and Raman[15] on twin jets having straight rectangular exit geometry in various configurations found that the shock spacing did not change significantly when the jets coupled.

The coupling of twin supersonic jets of double beveled exit geometry was studied by Raman[16], and it was found that twin double beveled jets can couple and may lead to either an augmentation or suppression of sound in the inter-nozzle region depending on the fully expanded Mach number at which the jets were operating. Some aspects of individual single beveled nozzles have also been examined in the past[17-20]. A study on the interaction of twin supersonic jets having single beveled exit was conducted by Panickar, Srinivasan and Raman[21] and it was shown that twin, single beveled jets could couple in the spanwise symmetric or spanwise antisymmetric mode. This work also examined the effect of varying nozzle separation while the nozzles were operating. Note that the shocks containing

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rectangular jets exhibit both spanwise and transverse oscillation modes. For high aspect ratio (>5) nozzles, the transverse oscillation mode is predominantly antisymmetric. However in the spanwise direction symmetric, antisymmetric and oblique oscillation modes are possible.

The present work focuses on suppressing the coupling of jets from twin nozzles of complex geometry using miniature pins and cavities. These pins and cavities produce high frequency disturbances relative to the dominant instability frequency of the jets. The noise suppression characteristics of the various configurations will be quantified on the basis of the reduction in the sound pressure level (SPL) amplitudes at the tonal frequencies as well as by the reduction in the overall sound pressure levels (OASPL). The primary aim of this note will be to demonstrate that minimally obtrusive devices can be used to suppress flow induced resonances in complex nozzle geometries used in modern aircraft.

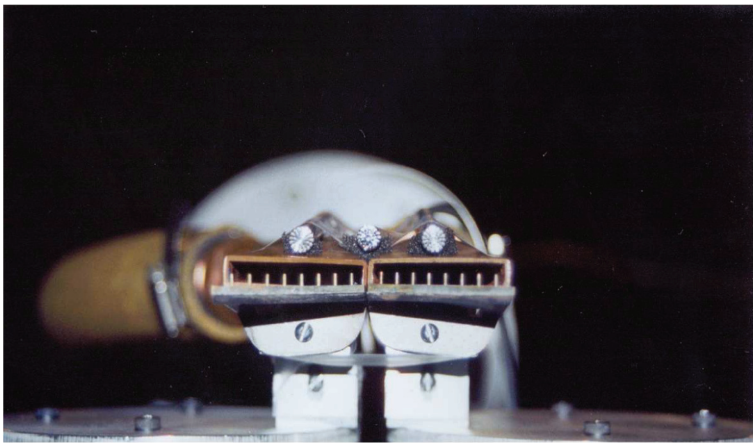
2. EXPERIMENTAL APPARATUS AND PROCEDURE

The experiments were carried out in the high speed jet facility at the Fluid Dynamics Research Center, Illinois Institute of Technology, Chicago. This facility receives compressed air at a maximum initial pressure of approximately 1.54 MPa from storage tanks that have a total volume of approximately 198 m^3. The compressor bank is made of three compressors and serves not only to charge the storage tanks before a run but also to extend the life of each run by supplementing their flow incrementally as the pressure falls during blow down. The settling chamber has walls covered with acoustic foam in order to reduce flow borne acoustic disturbances. Furthermore, honeycomb sections and screens provide additional flow conditioning. The compressed air system can provide a maximum momentary exit pressure ratio of 15.3 resulting in a fully expanded Mach number of 2.4 and a Reynolds number of 5.4×10^6 based on an exit diameter of 25.4 mm. The jet exhausts into an anechoic chamber, equipped with multiple access panels including a set of optical windows. The jet nozzles are connected to the stagnation chamber by means of reinforced flexible tubing to facilitate positioning of the nozzles. The nozzle axes are kept parallel to each other for all the experiments described in this study. While this does not necessarily depict actual aircraft operating conditions, it provided a baseline where the coupling studies could begin. The spanwise width of each nozzle was 33.58 mm and the transverse dimension was 5.08 mm, which meant that the nozzles used had an aspect ratio of 6.6. Zilz and Wlezien[18] showed that for low aspect ratio jets it was possible to have oscillation modes in the spanwise as well as the transverse directions. For large aspect ratio jets, such as the ones used in this study, the transverse oscillation modes are predominantly antisymmetric and the spanwise modes can vary. The lip thickness of the nozzles was 2.0 mm which meant that at the closest location the internozzle separation parameter $s/h = 7.4$, where s is the separation between the two nozzles measured between their respective centerlines, and h is the smaller dimension of the nozzle. The nozzles were tested in the fully expanded jet Mach number range from 1.24 to 1.51. The Mach number range studied is narrow since the jets did not screech in the twin jet configuration beyond this range.

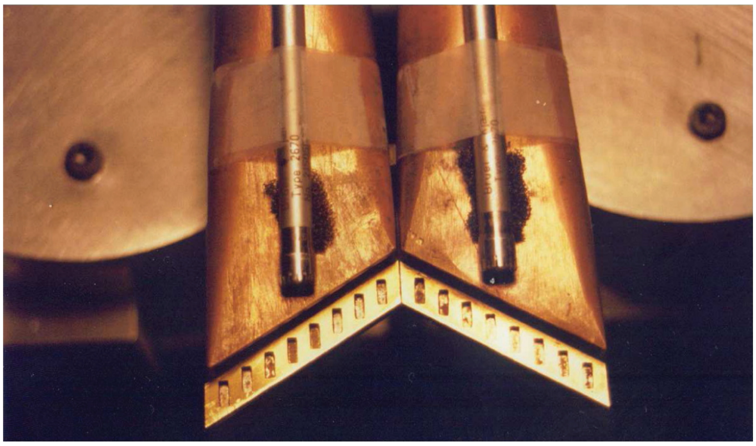
All acoustic measurements were made using 6.35 mm diameter Brüel & Kjær microphones. Data was acquired by using three such microphones, one each located at the span-wise centers of the nozzles and the third located between the two nozzles as shown in figure 1. The microphones were calibrated using a Brüel & Kjær pistonphone calibrator. The sound pressure levels reported are in dB relative to 20 μPa. All the data acquisition was achieved using a PC based National Instruments data acquisition board capable of acquiring 1.6 Megasamples/second, using LabVIEW 6i. Spectra were obtained by sampling at 200 kHz, dividing the time series into 50 records and taking FFT blocks of 4096 data points each. Phase data was processed using the Matlab software.

3. NOZZLE CONFIGURATION AND DESCRIPTION OF SUPPRESSION DEVICES

The nozzle axes were kept parallel to each other with the beveled edges facing each other (a co-directed configuration) for all the experiments described in this study. The bevel angle of the beveled nozzle was 30°. Experiments were conducted in the fully expanded Mach number range from 1.24 to 1.51. Lip extensions (one for each nozzle) that were flush with the bottom lips of the nozzles, extending 9 mm in the axial direction were used to attach various suppression techniques. The axial length of these extension pieces were chosen such that they accommodated the length of the miniature cavities; extension pieces of the same length were used for studying subsequent control configurations in order to maintain a consistent basis for comparison. The addition of these extension pieces will lead to an asymmetric expansion of the jet downstream of the nozzle exit. For this reason, the baseline for comparison of the acoustic suppression performance corresponds to a configuration that uses a blank lip extension. The boundary layer thickness calculation suggested the fully developed condition for the entire Mach number range at the exit of the nozzle. Figure 1 shows the twin nozzle arrangement and the miniature pins and cavities used for noise suppression. The various configurations used in the current study, viz. the miniature pins, the miniature cavities and the mixed configurations, are shown in figures 1(a), (b) and (c) respectively. The microphones



(a)



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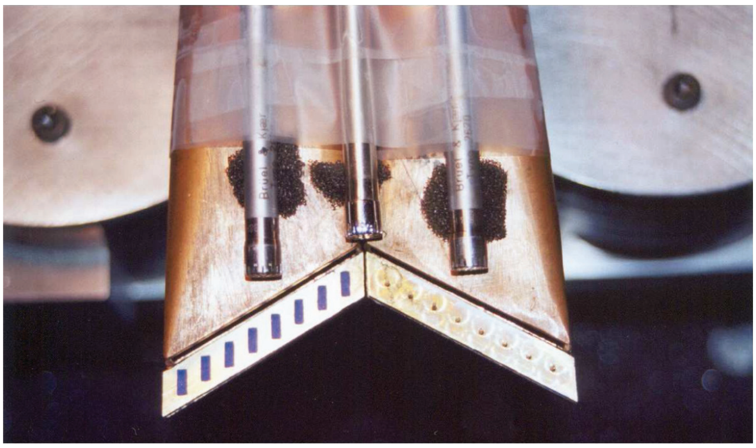


(c)

Figure 1. Photographs of the experimental setup showing the various devices used and the microphone locations. (a). Configuration using miniature pins, (b). Configuration using miniature cavities, (c). Mixed configuration with miniature pins on the right nozzle and miniature cavities on the left nozzle.

that detected the coupling and the noise suppression are also shown in these photographs. All the noise suppression spectra presented in the current paper correspond to those acquired using the microphone located at the spanwise center of the left nozzle. The instability frequencies dominant in the unsuppressed jet ranged from 15 to 25 kHz for the range of fully expanded Mach numbers examined. The vertical pins used were 0.79 mm (1/32 inch) in diameter and had heights of 1, 2 and 3 mm resulting in the corresponding aspect ratios of 1.26, 2.53 and 3.8, respectively. As can be seen from the figures, 8 pins and cavities, equally spaced, were used along the oblique spanwise dimension of the nozzle. The miniature cavities used had a length-to-depth ratio, L/D = 3, with a width, W = 2.38 mm (3/32 inch) and W = D. The miniature cavities were designed based on the considerations of high frequency excitation[22,23]. The frequencies produced by the miniature cavities ranged from 20 to 22.5 kHz for the primary Rossiter mode and 46.5–52.5 kHz for the second Rossiter mode. The frequency of vortex shedding from the pins was estimated to be in the range of about 60 to 70 kHz for a constant Strouhal number of St = 0.2 assuming the inviscid and subsonic flow over the pins behind the shock waves.

4. RESULTS AND DISCUSSION

As mentioned in the Introduction, the coupling characteristics of twin, single beveled nozzles were studied in the work by Panickar, Srinivasan and Raman[21]. It was shown that jets from closely spaced nozzles with a single beveled exit could couple such that the coupling instability mode was spanwise symmetric at the lower fully expanded Mach numbers and spanwise antisymmetric at the higher fully expanded Mach numbers. In the current study, the experimental setup was modified by adding lip extensions to the lower lip of both the single beveled nozzles. This modification of the nozzle geometry lead to a change in the coupling mechanism of the twin jets emanating from these nozzles. In particular, it was found that adding the lip changed the spanwise coupling instability mode in such a way that it was spanwise oblique over the entire range of fully expanded Mach numbers. This change can be explained by recognizing that the lower lip of both the nozzles were extended due to the presence of the lip extension; this created an asymmetry in the transverse direction which was manifested in the spanwise oblique mode. However, the jets still underwent spanwise coupled oscillations.

Figure 2 shows sample spectra at various Mach numbers which compare the noise suppression characteristics of the various configurations using miniature pins. For the baseline flow, shock-associated noise components such as jet screech and broadband shock-associated noise are seen in the 20–45 kHz frequency range. In the Mach number range of 1.24 to 1.38 as seen from figure 2(a–d), the fundamental screech tone frequency is around 20 kHz and, as expected, an increase in the Mach number leads to a decrease in the screech frequency. On the other hand, an increase in the Mach number initially leads to a rise in the peak amplitude. Further increasing the Mach number leads to a reduction in the tonal amplitudes and finally at $M_j = 1.51$, the screech tones are extremely weak. This could be a result of screech cessation as explained in Raman[24]. These features in the baseline configuration are indicative of complex interaction between such the twin jets that influences the scale of flow structures in a peculiar way with increasing Mach number.

The spectra in figure 2 show that although the pins having immersions of 1 mm and 2 mm reduce the tonal amplitudes at most of the operating conditions, it is the 3 mm pins that shows the maximum reduction of tonal amplitudes at all the operating conditions. According to our calculations, the pins were expected to produce tonal peaks associated with the vortex shedding at frequencies in the range of 60 to 70 kHz. However, the spectra show no such peaks. Instead, a distinct peak in the case of 3 mm pins is observed which shifts progressively from 43 to 48 kHz with increase in the Mach number from 1.24 to 1.51. We believe that the pins having 1 mm and 2 mm immersions, due to small aspect ratio, fail to result in coherent vortex shedding, which is a two-dimensional phenomenon. It is also conceivable that the 1 mm pins, due to their small aspect ratio, do not seem to affect the coherent structures and hence the flow noise at lower Mach number as suggested by the spectrum in figure 2(a) which very closely follows that of the baseline configuration. However, the induced perturbations affect the shock-cells as evidenced from the reduced frequency of screech tone and its harmonic. The reason for lower frequency of vortex shedding by 3 mm pins seems to be reduction in the flow speed due to the viscous effects within the boundary layer and a complex flow field resulting from the interaction between bow shocks generated by the pins. In addition to a system of bow shocks, the supersonic wall-bounded flow around finite aspect ratio miniature pins is also expected to be laden with a complexities due to formation of

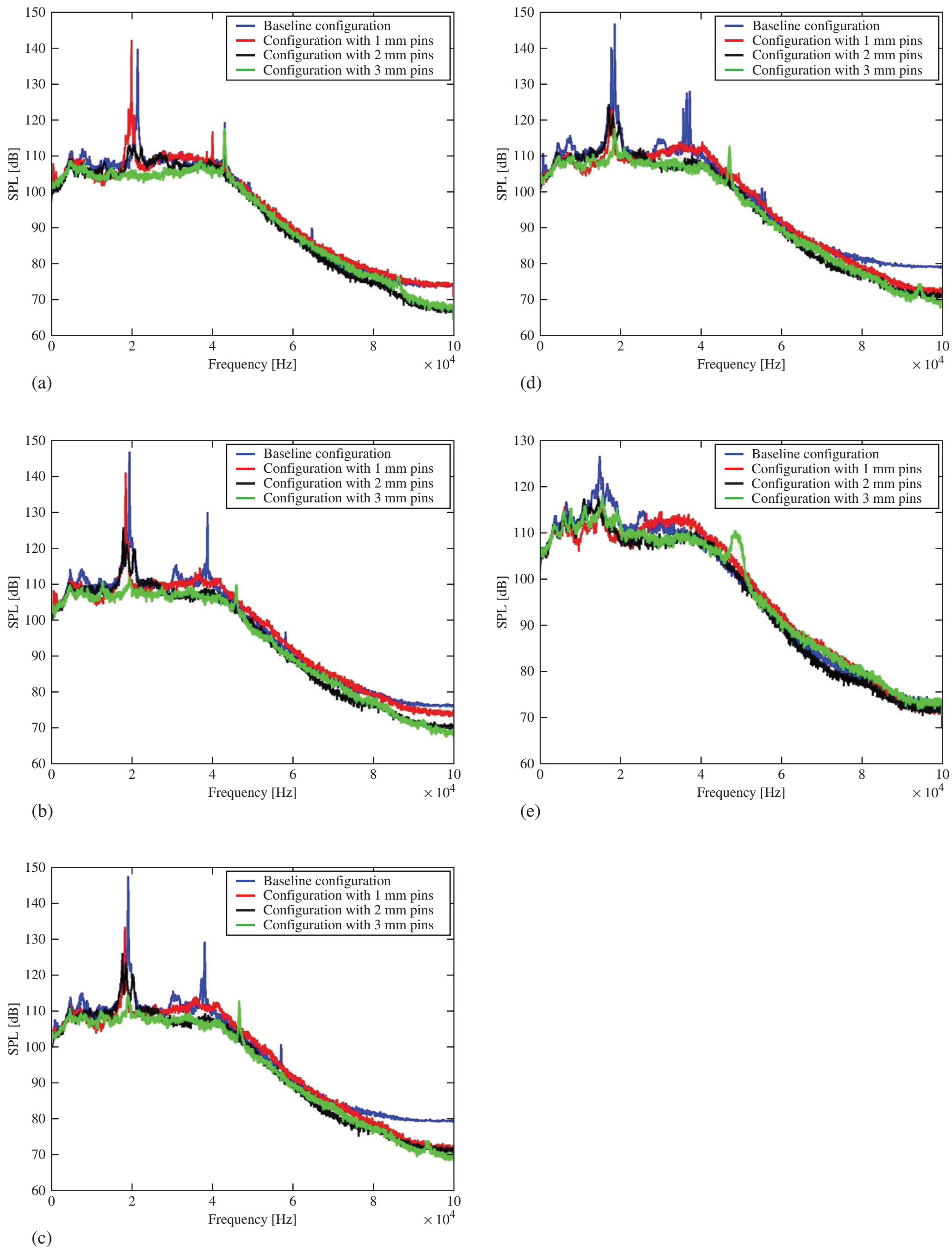


Figure 2. Spectra showing noise suppression characteristics of the configuration using miniature pins at various fully expanded Mach numbers. (a). M_j = 1.28, (b). M_j = 1.35, (c). M_j = 1.37, (d). M_j = 1.38, (e). M_j = 1.51.

horse-shoe vortices, vortex shedding (for the pin aspect ratio greater than 3) and the flow around the free end of the pin. Introduction of small scale streamwise vortices in a jet flow are known to disintegrate the large scale primary vortices and enhance entrainment thereby promoting mixing. From the observation of the spectra it is surmised that the pairs of contra-rotating streamwise vortices, which are part of the horse-shoe vortices, play a similar role and result in subdued high frequency components with suppression of flow noise by 5 to 8 dB in the range of 80–100 kHz at $M_j < 1.4$ (figure 2).

For the spectra shown in figure 3, comparing the suppression performance of the miniature cavities, it is seen that although the miniature cavities suppress the tonal component in the baseline, it does not effectively suppress the broadband components. Finally, as shown in the spectra of

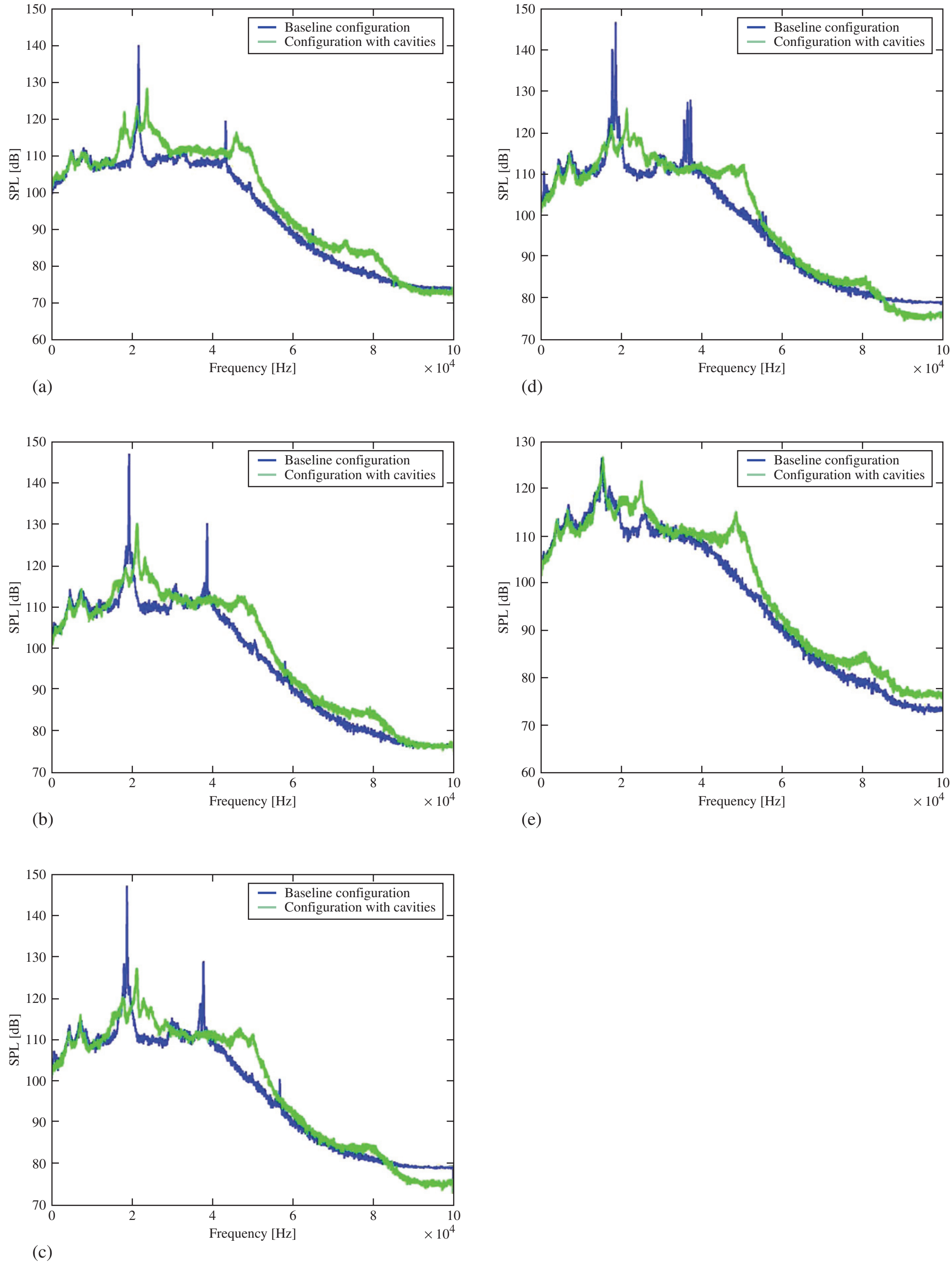


Figure 3. Spectra showing noise suppression characteristics of the configuration using miniature cavities at various fully expanded Mach numbers. (a). $M_j = 1.28$, (b). $M_j = 1.35$, (c). $M_j = 1.37$, (d). $M_j = 1.38$, (e). $M_j = 1.51$.

figure 4, which compares the suppression characteristics of the mixed configuration and the configuration using 3 mm pins to the baseline configuration, it can be seen that the mixed configuration further reduces some of the high frequency tonal components that remain when using the configuration with 3 mm pins. In the mixed configuration, the tonal peak associated with the vortex shedding from the pins having 3 mm immersion, as seen in figure 2, is not present. We believe that combination of one nozzle with pins and the other with cavities present a geometrical asymmetry which could be a key to prevent the coupling between the adjoining jets from beveled nozzles.

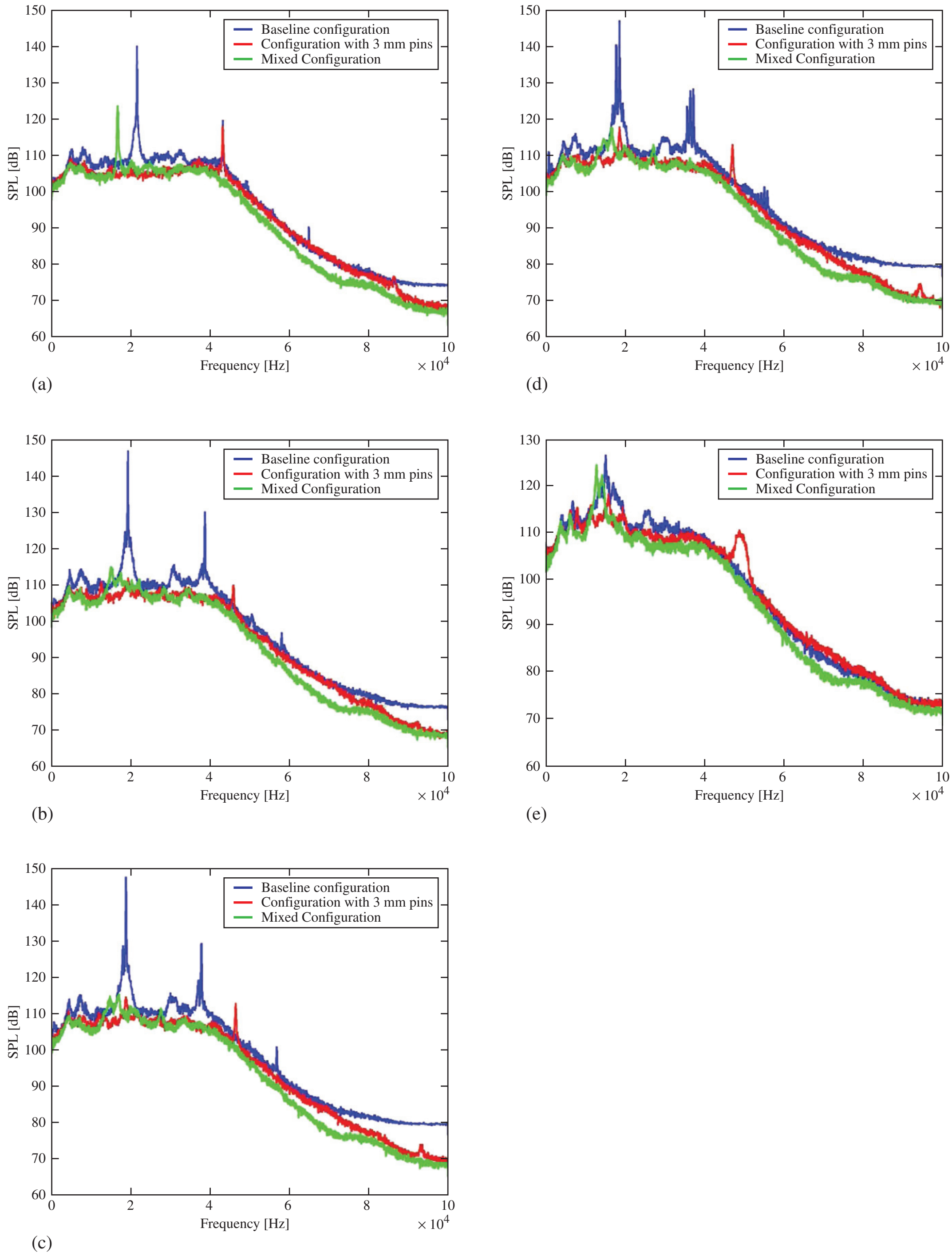


Figure 4. Spectra showing noise suppression characteristics of the mixed configuration using both miniature pins and cavities at various fully expanded Mach numbers. (a). M_j = 1.28, (b). M_j = 1.35, (c). M_j = 1.37, (d). M_j = 1.38, (e). M_j = 1.51.

The tonal frequencies and sound pressure level amplitudes of the baseline and various noise suppression configurations are shown in figure 5. For the configuration using the 3mm pins this figure 5(a) shows that at the low Mach number range M_j = 1.28–1.34, the peak tonal amplitude lies at frequencies greater than 40 kHz. This is indicative of the fact that this configuration effectively eliminates the tonal component at the fundamental screech frequency at these Mach numbers. For all other configurations, the peak tonal frequency lies close to the screech frequency of the baseline configuration. Figure 5(b) shows that at the strongly screeching operating conditions in the baseline,

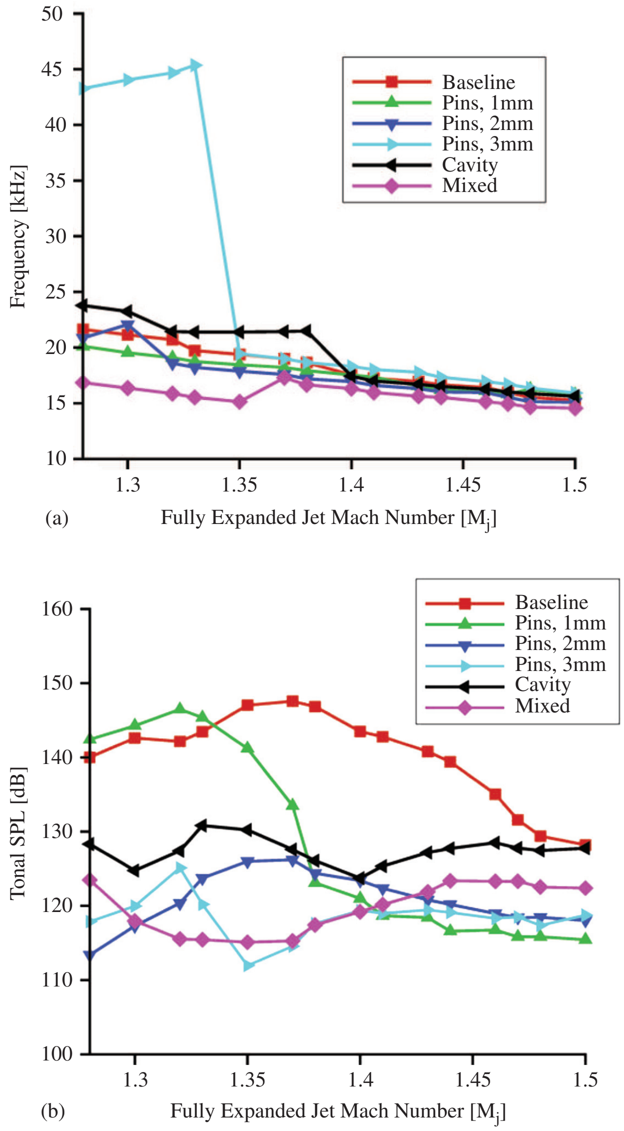
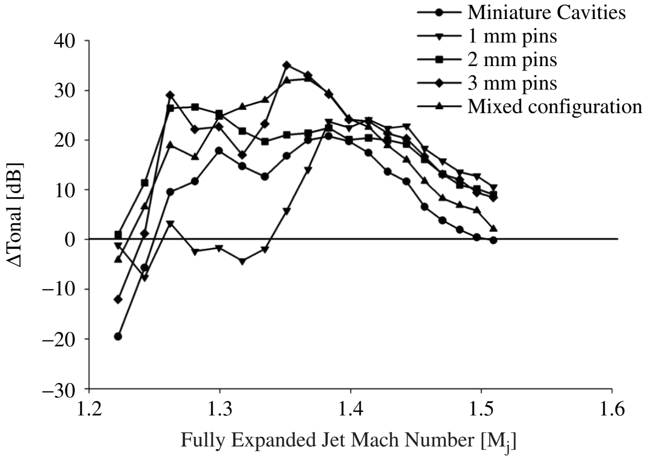
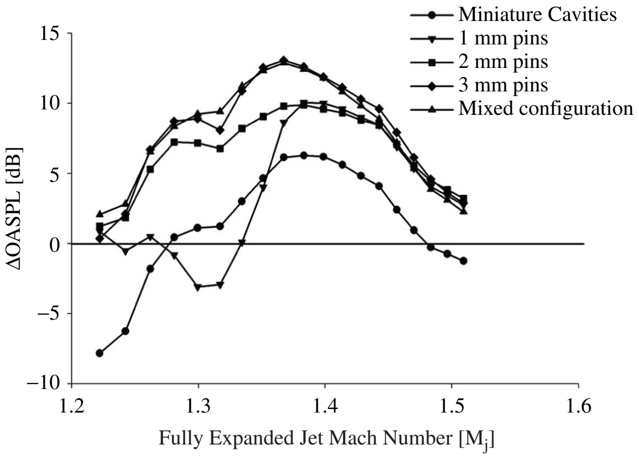


Figure 5. (a). Tonal frequency, and (b). Tonal SPL characteristics of the configurations at various fully expanded Mach numbers.

the tonal SPL amplitudes are well above 140 dB. At the lower Mach numbers, the peak tonal amplitude of the configuration using 1mm pins is close to those seen in the baseline; this however drops off as the fully expanded Mach number exceeds $M_j = 1.37$, which is indicative of the effectiveness of this configuration at higher Mach numbers. This amplitude is reduced to below 120 dB by the use of the devices described in the current study. Tonal and overall suppression levels of the various configurations relative to the baseline are shown in figures 6(a) and 6(b) respectively. In the fully expanded Mach number range from 1.3 to 1.4 where the screech tones in the baseline configuration have the strongest amplitude, it is found that the mixed configuration and the configuration using 3 mm pins provide the best tonal suppression characteristics (figure 6(a)). At fully expanded Mach numbers greater than 1.4, the tonal suppression characteristics of all the configurations deteriorate; but this can be attributed to the reduced screech intensities in the baseline. The OASPL suppression characteristics in figure 6(b) show that all the configurations except the one using miniature cavities provide similar OASPL suppression at the higher fully expanded jet Mach numbers. The configuration using 3 mm pins and the mixed configuration showed similar overall suppression characteristics over the entire range of Mach numbers. To summarize, the 3 mm high pins and the combined use of the 3 mm pins and the miniature cavities (one applied to each nozzle) provided the best results, both in terms of suppressing the peak tonal component as well as the overall levels. It has thus been demonstrated that minimally



(a)



(b)

Figure 6. (a). Tonal, and (b). OASPL suppression characteristics of the configurations at various fully expanded Mach numbers.

obtrusive devices can be used to suppress flow induced resonances in complex nozzle geometries used in modern aircraft.

5. CONCLUDING REMARKS

Experiments in the present study have demonstrated that miniature pins and cavities and their combination have great potential for suppressing the noise generated by the interacting supersonic jets produced by two adjoining rectangular beveled nozzles. Small scale perturbations produced by these devices, at frequencies much higher than the instability frequency in the jet, presumably interfere with the shock-cells and disintegrate the large scale coherent structures thereby resulting in suppression of the screech tones as well as the flow noise. Consequently, tonal suppression levels by up to 33 dB and OASPL suppression up to 13 dB were obtained in the Mach number range of 1.24 to 1.51.

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