# New Vortex Generator Design for Nozzle Internal Modification

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## 1. INTRODUCTION

In recent years, numerous active and passive jet noise suppression methods have been proposed. While many of these techniques have been successful in suppressing supersonic jet noise (in particular jet screech and jet impingement noise), these techniques have met with limited success (effect of fan flow deflectors by Papamoschou [3] and effect of chevrons by Bridges and Brown [1] and Rask, Gutmark and Martens [4]) at subsonic conditions. Possible reasons for the lack of effectiveness of some Active Flow Control (AFC) actuators include poor bandwidth and lack of control authority. Moreover, many AFC systems introduce additional noise (e.g., bi-stable fluidic actuators, powered resonance tubes and free stream driven cavities). The additional noise, albeit at higher frequencies, can contribute to the overall sound pressure levels (OASPL) or produce lower frequencies by non-linear interactions. While AFC techniques are clearly promising for the long term they presently result in complex systems that cannot be integrated into aircraft nozzles easily.

The work presented in the current paper describes the results of experiments aimed at jet noise reduction by the introduction of streamwise vorticity into the jet shear layer using passive devices located at the nozzle exit. The current paper describes results from experiments using three separate devices, namely: delta fins, tapered prismoidal humps, and tapered semicircular grooves. A delta fin is defined as one half of a delta wing. While such a wing produces a pair of counter-rotating streamwise vortices, a single stream (as opposed to a pair) of vortices can be produced using a delta fin (half of a delta wing). Thus, a surface mounted half delta-wing shape element is a simple device that can generate a strong leading edge vortex when exposed to the flow from apex side at an angle of incidence.[2, 5, 6] Therefore, it is commonly used in suitable arrangement to introduce streamwise vortices in the flow for a variety of applications. Streamwise vortices in this manner, can also be produced by using tapered prismoidal humps or grooves at the nozzle exit. Our hypothesis is that an array of such fins, humps or grooves within the nozzle, close to the exit, promotes the break up of coherent structures downstream of the nozzle exit and subsequently leads to a reduction in jet noise.

Two separate configurations for the delta fin arrangement will be discussed in this paper. One, where the array of delta fins produced vortices rotating with the same sense (called the co-rotating configuration) and two, where the array of delta fins were such that adjacent fins produced streamwise vortices rotating with opposite sense (called the contra-rotating configuration). The reasoning that motivated the idea of using delta fin vortex generators for noise suppression is that the streamwise vortices produced by such delta fins will help to break up the coherent structures downstream of the nozzle exit.

The following discussion describes an investigation of streamwise vortex generators such as delta fins, tapered prismoidal humps and tapered grooves, and their potential benefit for jet noise suppression. Geometric and configurational details of these devices will be provided in the forthcoming sections of this paper.

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## 2. EXPERIMENTAL SETUP AND INSTRUMENTATION

### 2.1. Facility and instrumentation

This experimental investigation was conducted in the High Speed Jet Facility (HSJF) 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 reducing the system pressure drop 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 based on a nozzle exit diameter of $5.4 \times 10^6$ 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. Acoustic measurements were made using Brüel & Kjær (B & K) 0.635 cm (0.25 inch) microphones that were calibrated using a B & K pistonphone calibrator which provided a constant 124 dB sound source at 250 Hz. All sound pressure levels are reported in dB relative to 20 $\mu$Pa.

Previous experimental evidence has shown that jet noise peaks at an angle of 30° to the nozzle exit axis. For this reason, acoustic data was acquired by placing microphones at a distance 25 equivalent nozzle diameters downstream of the nozzle exit at an angle of 30° to the nozzle exit axis.

Spectral data was acquired using a PC based National Instruments data acquisition board capable of acquiring 1.6 Megasamples/second. The programming interface used for data acquisition was Lab VIEW 6*i*. The data reported here were taken at a sampling rate of 100 kHz for 1.024 seconds, and plotted after dividing the acquired time series into 50 records and taking FFT blocks of 2048 data points each. The frequency resolution of the resulting spectra was close to 50 Hz.

### 2.2. Nozzle design

The jet noise suppression experiments discussed in this report were conducted on a converging nozzle whose inner profile follows a 6th order polynomial curve to converge from a diameter of 95.25 mm

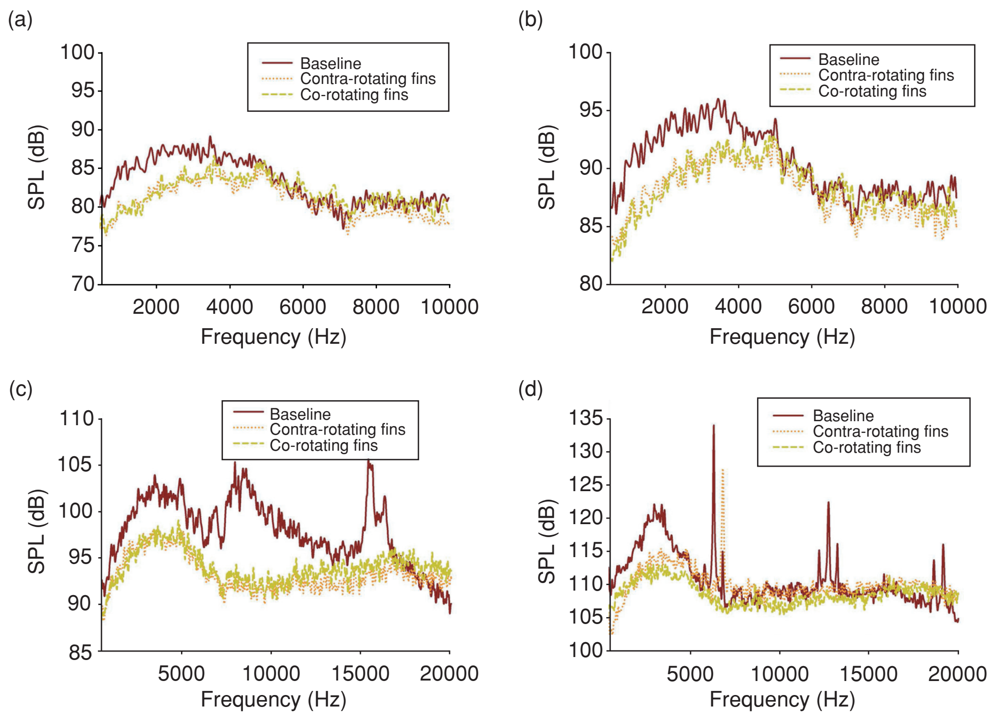


Figure 1. Sample spectra showing efficacy of jet noise suppression using delta fins. (a). $M_j = 0.77$, (b). $M_j = 0.93$, (a). $M_j = 1.11$, (a). $M_j = 1.53$.

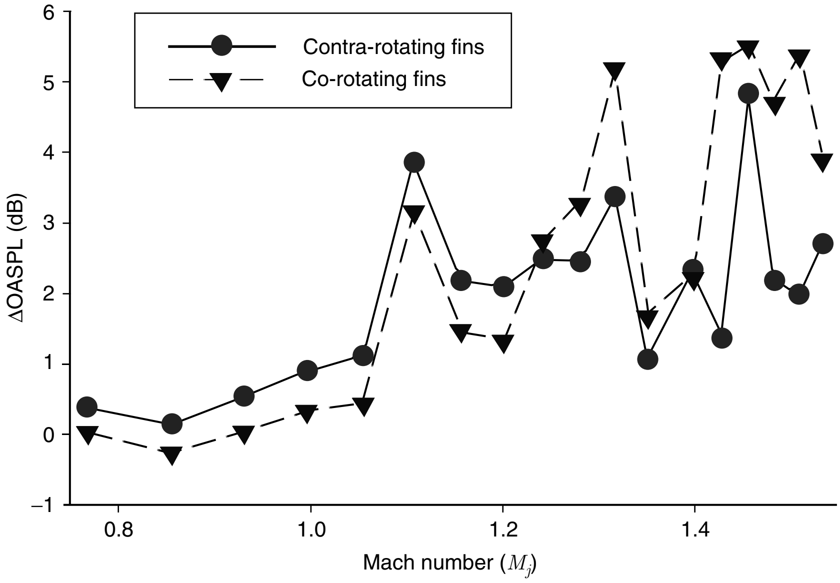


Figure 2. OASPL reduction characteristics of co-rotating and contra-rotating delta fin configurations for rectangular nozzle.

(3.75 inches) to 30.48 mm (1.2 inches) over a length of 152.4 mm (6 inches). Upstream of the nozzle, there is a constant diameter section (diameter = 95.25 mm (3.75 inches)) for a length of 101.6 mm (4 inches) that acts as an extension to a pre-existing plenum. There is a pressure tap in the plenum extension that provides a measure of the inlet stagnation pressure. The 3-D model shown in figure 3 depicts the inner contour of the nozzle. In order to facilitate easy testing of each control technique, a plug type device is manufactured that slips on and off the exit portion of the nozzle shown above. These devices were secured to the main nozzle with the help of set-screws located at the upstream portion of the plug. Each plug type device has a separate control strategy mounted at the exit. For the baseline case, a plug with no control device was used. Initial testing was conducted using a baseline with a straight exit. The devices that showed the best suppression characteristics were then transitioned for further testing on nozzles that had conical convergent exits. Figure 4 shows a photograph of the two types of baselines tested. For the conical convergent exit nozzle, we conducted tests for two convergence angles of 11° and 5°. The set-screw holes are visible in figure 4.

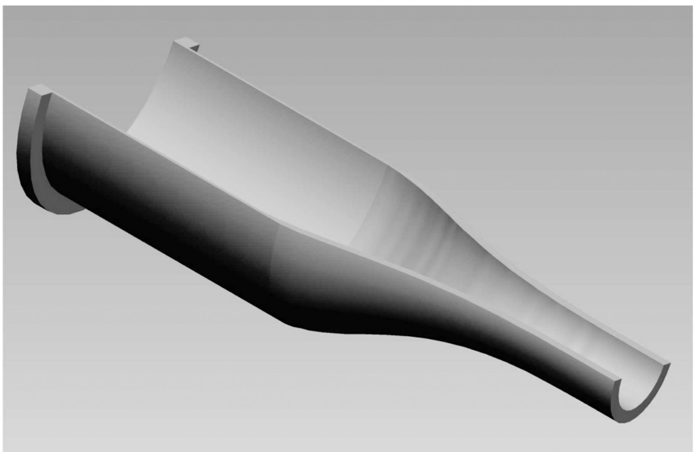

Figure 3. 3D rendering of axisymmetric nozzle showing the interior contour and 6th order polynomial type convergence.

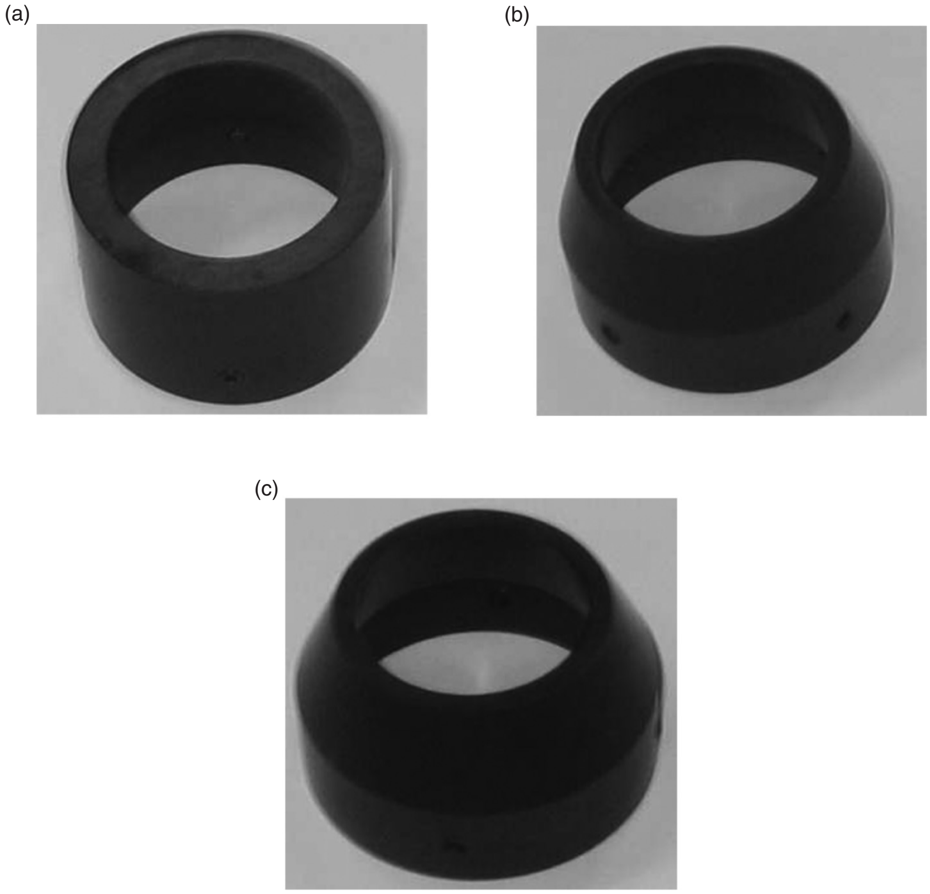


Figure 4. Photograph of the baseline nozzle exit attachments used in the present study, (a). Straight exit, (b). Convergent conical exit, semi-cone angle = 5°, (c). Convergent conical exit, semi-cone angle = 11°.

## 2.3. Streamwise vorticity generation mechanisms

A knowledge of the details of the boundary layer at the exit of the nozzle is necessary before designing target devices that can produce effective jet noise suppression. These devices are located at the nozzle exit plane protruding inwards towards the nozzle and separated equal azimuthal distances apart. In order for a target device to produce minimal blockage at the nozzle exit, an effective noise control strategy would be to produce disturbances from within the boundary layer. Based on our initial calculations, the boundary layer thickness at the exit is approximately 2.5 mm. This would mean that any passive control device would have to have a length less than 2.5 mm protruding into the flow. These devices are located at the nozzle exit plane protruding inwards towards the nozzle and separated equal azimuthal distances apart. Keeping these requirements in mind, our test matrix for noise suppression devices consisted of the following three types of devices:

- Delta fins in co-rotating and contra-rotating configuration, oriented at an angle of attack of 30° to the nozzle exhaust.
- Tapered prismoidal humps oriented at a zero angle of attack to the incoming flow.
- Tapered semicircular grooves oriented at a zero angle of attack to the incoming flow.

For all the above devices, the length of insertion into the flow at the nozzle exit was 1.59 mm (0.063 inches; less than the boundary layer thickness) for the configuration using delta fins and the prismoidal humps. For the semicircular grooves, in order to maintain consistency with the configurations using delta fins and prismoidal humps, the radius of the semicircular arc at the exit of the nozzle was 1.59 mm (0.063 inches). For the delta fin configurations, we also tested an additional immersion length into the flow of 3.18 mm (0.125 inches; greater than the boundary layer thickness). For all the configurations tested, the effective area of the nozzle at the exit was maintained constant.

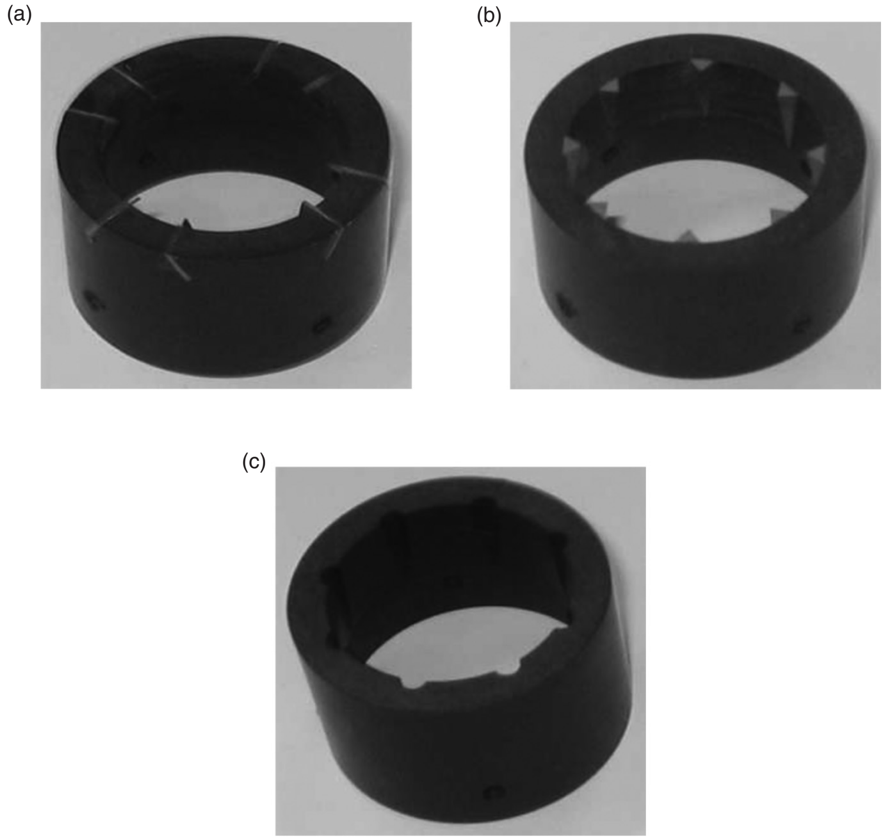


Figure 5. Photographs showing samples of various control devices used in this study, (a). Delta fins (in this figure shown in the contra-rotating orientation), (b). Tapered prismoidal humps, (c). Tapered semicircular grooves.

The thickness of the material used to manufacture the delta fin was assumed to be negligible which meant that the exit diameter of the configurations using delta fins was the same as the exit diameter of the baseline nozzle. However, for the configurations using prismoidal humps, the exit diameter of the nozzle was larger than that of the baseline in order to compensate for the blockage due to these humps at the nozzle exit. Similarly, for the configurations using semicircular grooves, the exit diameter of the nozzle was smaller than that of the baseline, taking into account the increase in effective area due to the grooves. Figure 5 shows photographs of the control devices that were used in this study. The noise suppression characteristics of the configurations with the humps grooves were studied by varying the number of these devices around the nozzle exit. For the delta fin configuration, 8 fins arranged azimuthally around the periphery of the nozzle were used for all the experiments.

## 3. RESULTS AND DISCUSSION

In order to test our hypothesis, we first considered a convergent rectangular nozzle with aspect ratio of 16. An array of delta fin vortex generators were first installed in the co-rotating configuration and then in the contra-rotating configuration to study their noise suppression characteristics for a wide range of subsonic and fully expanded supersonic jet Mach numbers, $M_j$. Using estimates of the boundary layer thickness at the nozzle exit, the height of the fin was appropriately selected such that it lay within the nozzle exit boundary layer. Figure 1(a–d) show spectra at Mach numbers 0.77, 0.93, 1.11(fully expanded) and 1.53(fully expanded) respectively, comparing the effectiveness of the noise suppression using the co-rotating delta fins and the contra-rotating delta fins configurations. It was found that the co-rotating configuration completely eliminated the screech tone that was present in the baseline at supersonic fully expanded Mach numbers (see figures 1(c) and 1(d)). However, it was found that at the higher fully expanded Mach numbers (see figure l(d)) the contra-rotating configuration lowered the amplitude at the screech frequency, but did not eliminate it completely. However, the contra-rotating configuration did eliminate all higher harmonics of the screech tone observed in the baseline spectra. Figure 2 shows the reduction in the OASPL values compared to the baseline for the co- and contra-rotating configurations as a function of the Mach number. As seen from this figure, at the subsonic and low supersonic Mach numbers, the contra-rotating configuration shows a greater reduction in the OASPL compared to the co-rotating configuration. At Mach numbers higher than $M_j = 1.24$, the trend switches and it is the co-rotating configuration that shows a greater OASPL reduction as compared to the contra-rotating configuration. This is because while the co-rotating configuration completely eliminates the screech tone and its harmonics, the contra-rotating configuration merely reduces the screech tone amplitude while eliminating only its harmonics.

Baseline measurements were obtained by using the attachment with the simple axial exit with no vortex generating device on the inside. The first round of experiments involved a wide test matrix that aimed at arriving at an optimal configuration of each vortex generation device with regard to immersion length, in the case of the delta fins, or the number of vortex generators in the case of the humps and the grooves, that provided the best suppression characteristics in jets from nozzles with a straight exit. The optimal device in each category was the one that gave the maximum overall sound pressure level (OASPL) reduction. The OASPL reduction in this case is defined as:

$$\Delta\text{OASPL} = 20\log_{10}\left(\frac{p_{rms,b}}{p_{rms,d}}\right), \tag{1}$$

where $p_{rms,b}$ is the RMS of the fluctuating pressure for the baseline configuration and $p_{rms,d}$ is the RMS of the fluctuating pressure for the suppression device being tested. Once the optimal configuration was reached, these devices were tested on conical converging nozzles. Two semi-conical angles, 11° and 5°, were chosen for this purpose. Experiments were conducted and the suppression characteristics were compared at five subsonic Mach numbers, $M_j = 0.70$, 0.80, 0.85, 0.90, and 0.95 and two fully expanded supersonic Mach numbers, $M_j = 1.10$, and 1.20.

### 3.1. Experiments on jets from nozzles with straight exits

As mentioned earlier, experiments on nozzles with a straight exit were conducted in order to arrive at optimal configurations for each vortex generating device. We started off by testing the suppression characteristics of delta fins in the co-rotating and contra-rotating configurations at two immersion lengths: one larger and one smaller than the estimated boundary layer thickness at the nozzle exit. Figure 6 shows the OASPL reduction characteristics of each configuration at the various Mach numbers tested. The (L) and (S) shown in the legend caption indicate large and small immersion lengths respectively. As seen from this figure, the contra-rotating fins with the small immersion show suppression characteristics comparable to of the co-rotating fins with the large immersion. For the two configurations with small immersion, the contra-rotating fins produce a greater OASPL reduction than the co-rotating fins. This trend is similar to the OASPL reduction trend seen in figure 2 for the jet from the rectangular nozzle where the contra-rotating fins showed superior noise reduction characteristics at the subsonic and low supersonic Mach numbers. For the fully expanded supersonic Mach numbers tested in the axisymmetric jet, it was found that all the delta fin configurations eliminated the baseline screech tone. OASPL reduction levels of up to 2–3 dB at the subsonic Mach numbers and up to 5.8 dB at the fully expanded supersonic Mach numbers were obtained using the contra-rotating configuration with small immersion length. Hence, this configuration was chosen for further study on jets from nozzles with a conical convergent exit.

Next, various configurations using tapered prismoidal humps as vortex generation devices were tested in order to determine their noise suppression characteristics. The configurations differed from one another in terms of the number of humps located around the inner periphery of the nozzle; specifically configurations using 6, 8, 10 and 12 humps were used. Figure 7 shows the OASPL reduction characteristics of the humps as a function of the jet Mach number. As seen from this figure configuration with 8 and 10 humps show comparable performance at the subsonic Mach numbers. However, at the low supersonic Mach numbers, the 8-hump configuration shows superior characteristics compared to all other configurations. For this reason, the configuration with 8 tapered prismoidal humps was selected for study.

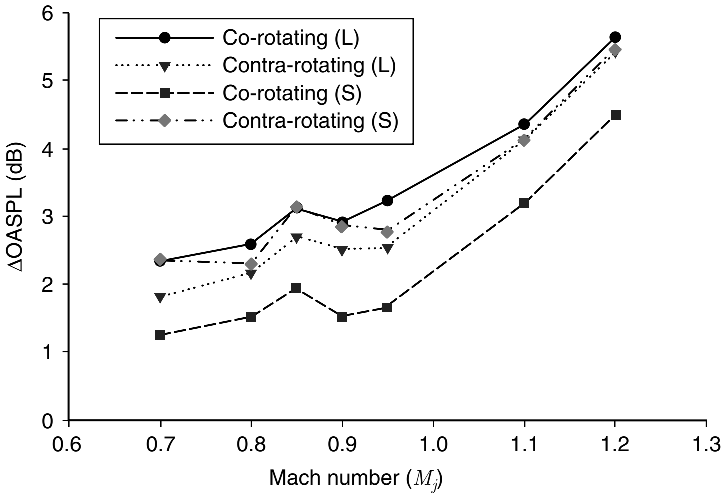


Figure 6. OASPL reduction characteristics of co-rotating and contra-rotating delta fin configurations for jets from nozzles with a straight exit.

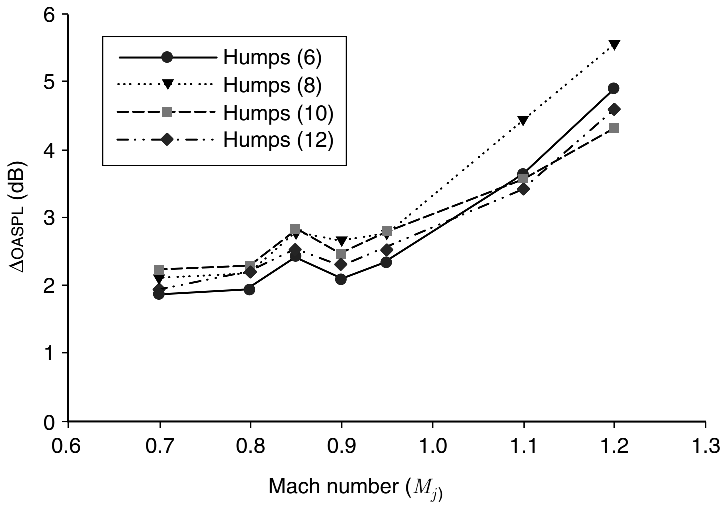


Figure 7. OASPL reduction characteristics of various tapered prismoidal hump configurations for jets from nozzles with a straight exit.

Finally, the suppression characteristics of configurations using semicircular tapering grooves were investigated. Configurations using 6, 8 and 12 grooves were studied. Figure 8 shows the OASPL reduction levels of these configurations. From this figure it appears as though the configuration with 12 grooves is superior to the configurations with 6 and 8 grooves. The spectra revealed that at the supersonic Mach numbers tested, while all three configurations eliminated the screech tone present in the baseline at the supersonic Mach numbers tested. However, the 12-groove configuration introduced a tonal component at a higher frequency. For this reason, and in order to main consistency with the optimal configurations selected for the delta fins and humps, we selected the 8-groove configuration for further testing.

Figure 9 shows a comparison of the OASPL reduction characteristics of the optimal configurations selected for jets from nozzles with a straight exit - namely, the 8 contra-rotating delta fins, the 8 tapered prismoidal humps and the 8 tapered semicircular grooves. As seen from this figure, the delta fins and the humps show superior suppression characteristics as compared to the grooves. Amongst the humps and the delta fins, the latter shows superior suppression characteristics at the subsonic Mach numbers and the former is marginally superior at the fully expanded supersonic Mach numbers. Figure 10(a) and (b) show sample spectra comparing the suppression characteristics of the optimal

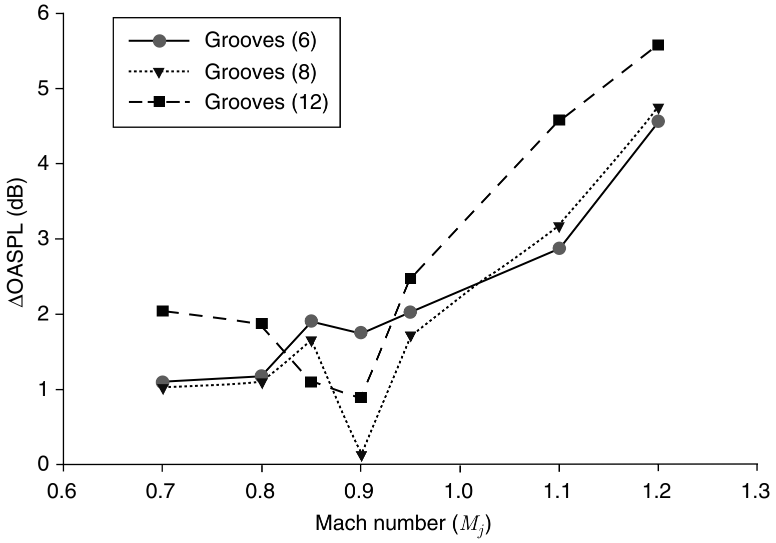


Figure 8. OASPL reduction characteristics of various tapered semicircular groove configurations for jets from nozzles with a straight exit.

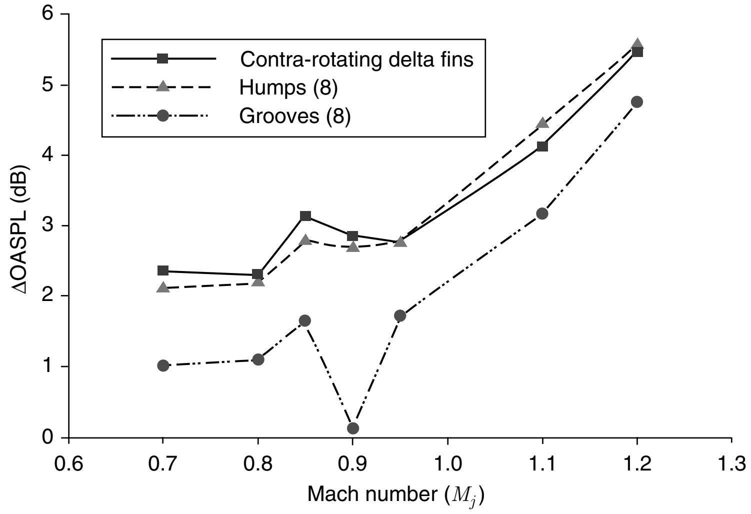


Figure 9. OASPL reduction characteristics of configurations that showed the best suppression characteristics for jets from nozzles with a straight exit.

cases at $M_j = 0.8$ and $M_j = 1.2$ respectively. This spectra is zoomed in to show the acoustic content up to a frequency of 20 kHz. At subsonic Mach numbers (figure 10(a)), the acoustic content of the control cases drops marginally as compared to the baseline. At the supersonic Mach number (figure 10(b)), the control cases eliminate the screech tone completely in addition to reducing the amplitudes of the broadband noise.

### 3.2. Experiments on jets from nozzles with conical convergent exits

The second round of experiments consisted of testing the control cases that showed the best suppression characteristics on jets from straight nozzles, viz. the contra-rotating delta fins, the 8 tapered prismoidal humps and the 8 tapering semicircular grooves, on jets from nozzles that have a convergent conical exit. These tests were conducted on conical nozzles having semi-conical angles of 5° and 11°. Before the results are presented, it is necessary to understand why testing on conical convergent nozzles are important. We know that the flow leaves with constant velocity from nozzles having both, rectangular exits or constant diameter circular exits. However, in practice, nozzles have some convergence towards

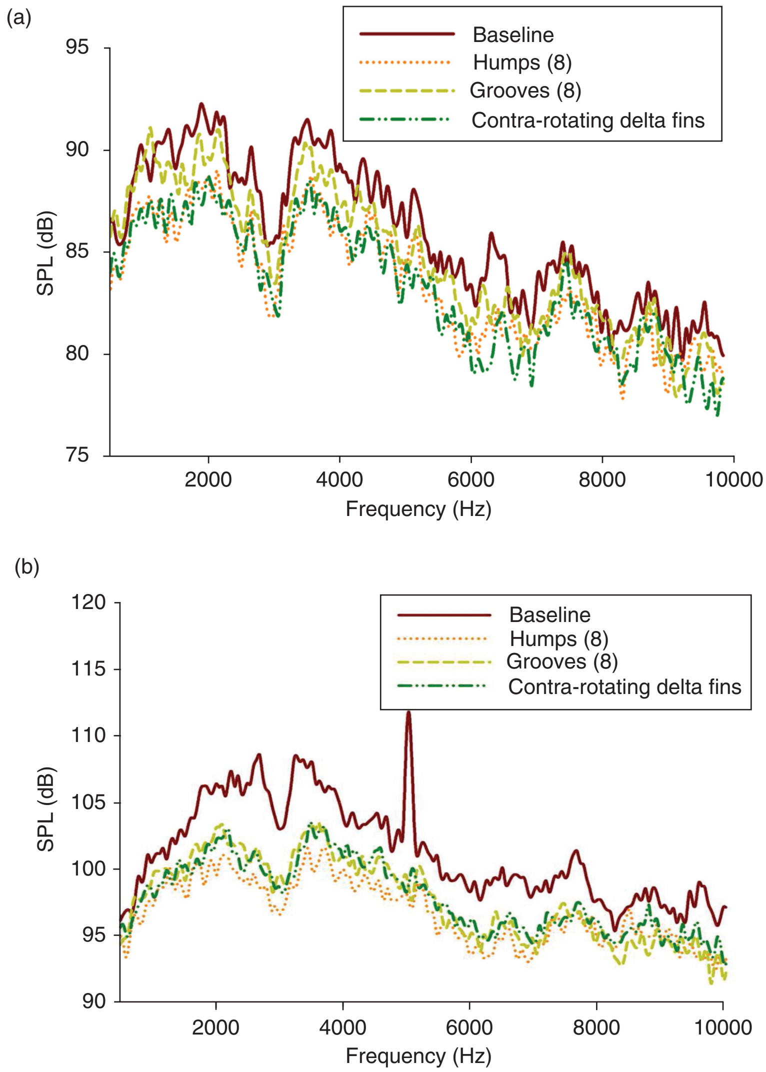


Figure 10. Comparative spectra showing acoustic suppression characteristics of the various devices for jets from nozzles with a straight exit. (a). $M_j = 0.8$, (b). $M_j = 1.2$.

the exit and hence the flow accelerates while exiting these nozzles. Considering the fact that the dynamics of the jets from nozzles, having constant exit areas or converging exit areas, may be affected differently, it was deemed necessary to test the vortex generators on nozzles with conical convergent exits.

Figure 11 shows a comparison of the OASPL reduction levels achieved by the different control methods at the various Mach numbers. This figure shows that the performance of the contra-rotating configuration of delta fins and the tapered semicircular grooves are comparable since they show similar levels of OASPL suppression. However, the tapered prismoidal humps show negligible OASPL suppression over the entire range of Mach numbers. The real difference between the three suppression devices is revealed upon comparing the spectrum for each control case to the baseline spectrum, especially at the supersonic Mach numbers. Whereas all the control cases reduce subsonic acoustic levels in the baseline spectrum (12(a)), the configuration with the humps and the grooves introduce narrowband tonal content at frequencies that are distinct from the screech frequencies observed in the baseline. The contra-rotating delta fin configuration, on the other hand, eliminates the screech tone altogether without introducing tones at other frequencies (see figure 12(b)).

For conical convergent nozzles with a semi-conical angle of 11°, the reduction in OASPL levels of the contra-rotating delta fins are found to be the greatest compared to the prismoidal humps or the semicircular grooves. This can be seen in figure 13 where the OASPL reduction for the 11° convergent nozzle ranges between 1–2 dB at the subsonic Mach numbers and from 3-5 dB at the supersonic Mach

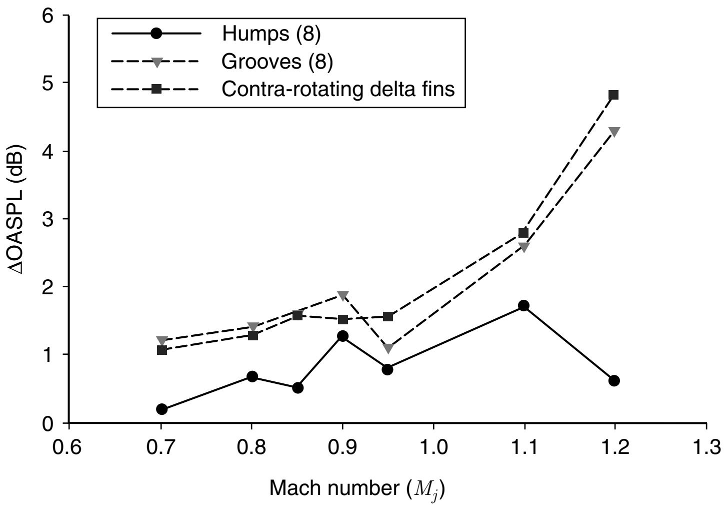


Figure 11. OASPL reduction characteristics of of various devices for jets from nozzles with a convergent conical (semi-cone angle = 5°) exit.

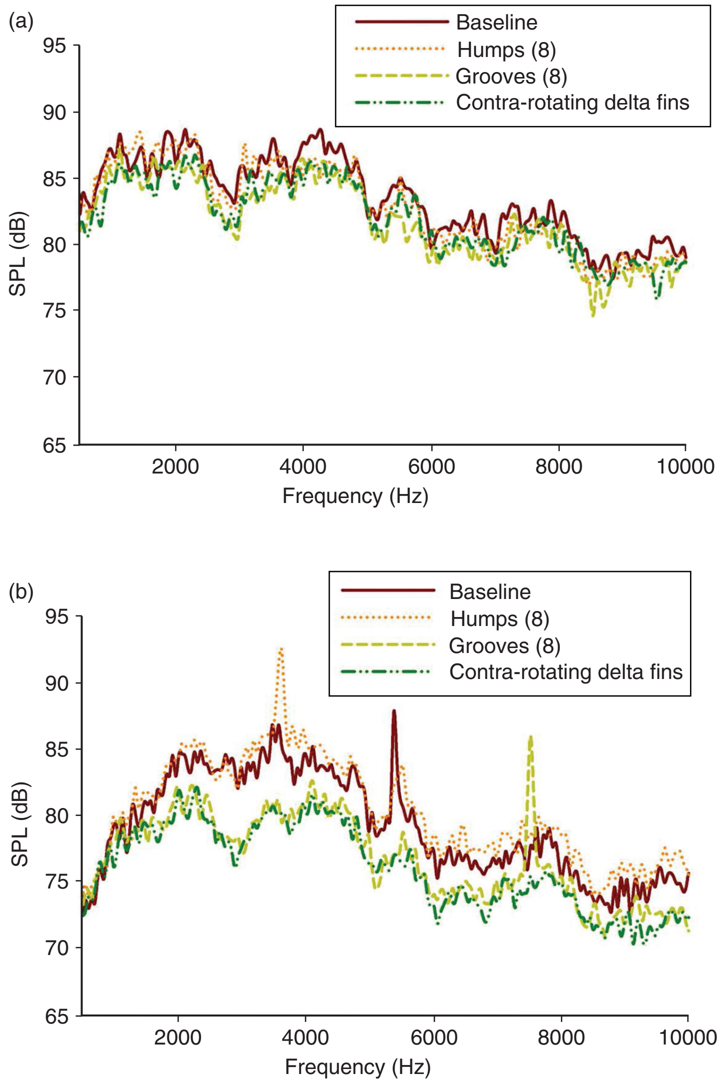


Figure 12. Comparative spectra showing acoustic suppression characteristics of the various devices for jets from nozzles with a convergent conical (semi-cone angle = 5°) exit. (a). $M_j = 0.8$, (b). $M_j = 1.2$.

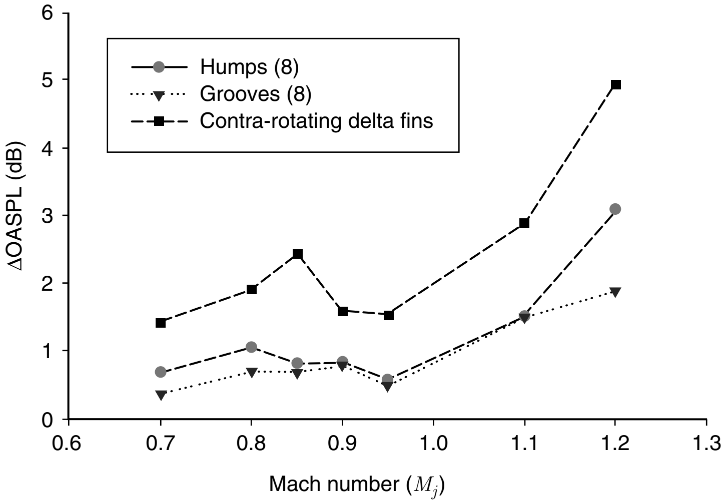


Figure 13. OASPL reduction characteristics of of various devices for jets from nozzles with a convergent conical (semi-cone angle = 11°) exit.

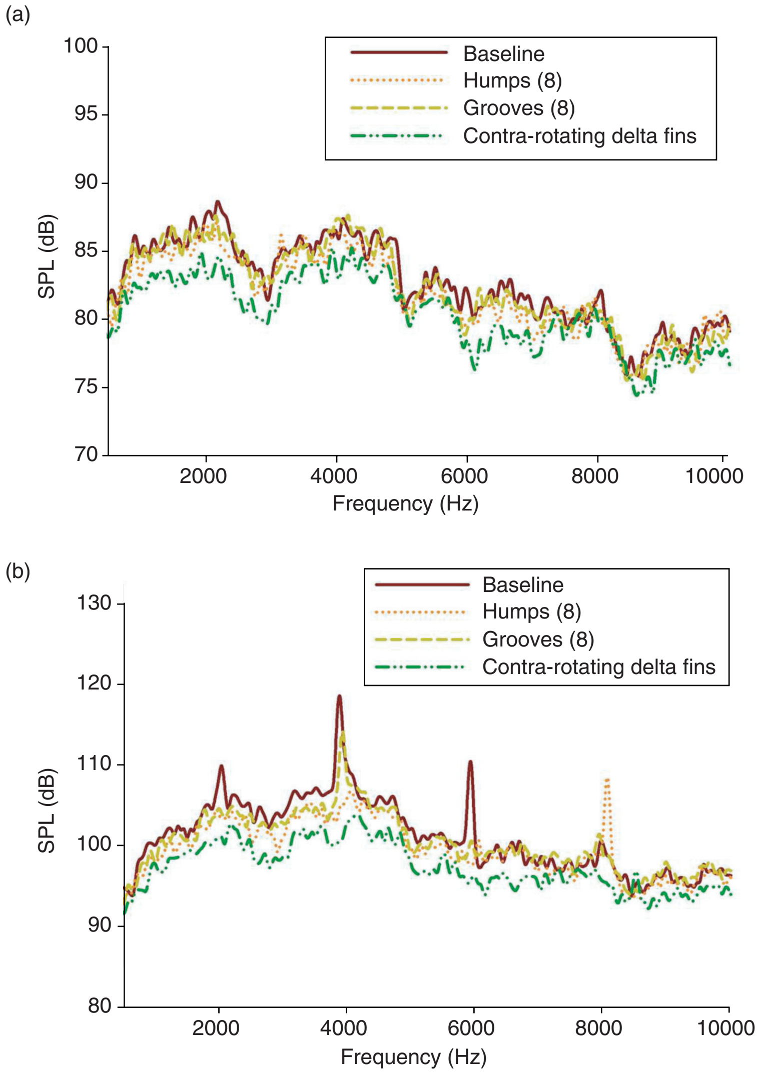


Figure 14. Comparative spectra showing acoustic suppression characteristics of the various devices for jets from nozzles with a convergent conical (semi-cone angle = 11°) exit. (a). $M_j = 0.8$, (b). $M_j = 1.2$.

numbers. Considering the spectra (figures 14(a) and 14(b)) reveals that while all the various control methods reduce the acoustic levels compared to the baseline at the subsonic Mach numbers, the configuration with the contra-rotating delta fins is the only one that, at supersonic Mach numbers, completely eliminates the screech tone without causing narrowband components at other unrelated frequencies.

## 4. CONCLUSIONS

A study of jet noise suppression techniques using passive devices that generate streamwise vortices was undertaken. . In addition to the delta fin type vortex generators, devices such as tapered prismoidal humps and tapered semicircular grooves were also explored as methods of introducing streamwise vorticity into the base flow. On the other hand, it was found that these devices provide marginal benefits at subsonic Mach numbers but are liable to introduce non-screech related tonal components at supersonic fully expanded Mach numbers. It was found that using vortex generators shaped in the form of contra-rotating delta fins oriented at an angle of attack to the flow was extremely effective in reducing jet noise at subsonic Mach numbers and suppressing screech tones at supersonic Mach numbers. On an average, an OASPL reduction in the range of up to 2 dB at the subsonic Mach numbers and close to 6 dB at supersonic fully expanded Mach numbers was obtained.

## ACKNOWLEDGEMENT

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