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Experimental Studies on the Limiting Tab

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Experiments were carried out to study the effect of the tabs with limiting length, termed Rathakrishnan limit, on controlling the mixing and acoustic characteristics of free jets. The limiting tab is found to be efficient in promoting the jet mixing even in the presence of an adverse pressure gradient. Furthermore, the limiting tab is found to be most efficient in promoting the mixing near the correct expansion rather than at an underexpanded condition, with a favorable pressure gradient at the nozzle exit. The reason behind the working of the limiting tab in the form of a cross wire is discussed for Mach 1.6, 1.79, and 2.0 jets. As high as 50% reduction in the core length is achieved using a cross wire for Mach 1.79 jet operated with nozzle pressure ratio 5.66. The combination of the waves in the jet core and their interaction with the detached shock envelop generated by the wire has a strong influence on the overall jet noise and its spectral content. Even though the wire reduced the overall noise of the jet and the reduction is significant for many cases of the present study, it caused an increase of screech amplitude for some cases. Jet noise reduction was found to be sensitive to the wire orientation.

Nomenclature

D = inner diameter of nozzle exit
M_e = nozzle exit Mach number
P_a = atmospheric or ambient pressure
P_t = pitot pressure
P_0 = stagnation chamber pressure
R = radial direction (primary jet)
X = primary jet axis
Y = direction normal to the cross wire
Z = direction along the cross wire

I. Introduction

DESIGN of large and fast jet-propelled aircraft and large booster rocket engines have focused on noise problems. Difficulties in devising satisfactory solutions stem from the inherent complexities of the phenomena of jet noise generation. Consequently, over the past two decades, extensive theoretical and experimental studies have been conducted in an attempt to understand the basic mechanism of jet noise generation and its abatement. Supersonic jets normally possess complex shock patterns. Therefore, the role of shock waves in noise generation becomes significant. The main sources of high-speed jet noise are the turbulent nature of the flow, shock–turbulence interaction, flow-induced oscillations of shocks, and resonance effects. Noise from such jets is complex and may even be nonlinearly interdependent. Noise prediction for such flows for a wide range of operating conditions is not possible as yet. An intense discrete acoustic emission termed "screech" or "whistle," as a consequence of oscillating shock waves within a supersonic jet, usually dominates the noise emitted by a cold model converging jet operated at slightly above choked flow condition. From literature, it is evident that supersonic jet noise reduction can be achieved by enhancing mixing and eliminating or weakening and/or reducing the effective axial extent of the shock structure. To achieve these goals, many jet controls have been devised and studied. In general, jet control techniques can broadly be divided into passive or active. Passive control techniques may be permanent or deployable, but have no moving parts during operation. They range from alterations of the jet nozzle exit shape to the implementation of toothlike tabs and vortex generators at the nozzle exit. In contrast, active flow controls use energized actuators to dynamically manipulate flow phenomena based on open- or closed-loop algorithms. For example, pulsed jets [1] use piezoelectric actuators for active mixing enhancement. As a simple passive means to enhance jet mixing and reduce jet noise, many studies have focused on the placement of small tabs and vortex generators at the exit of axisymmetric and rectangular nozzles [2]. They introduce streamwise vortices to transport the low-speed fluid entrained at the jet periphery toward the centerline while forcing out higher speed core fluid. The main difference between the two methods is the type of vortex generated. Tabs (which are placed normal to the flow) generate a pair of counter-rotating vortices, but a half-delta-wing vortex generator produces only a simple vortex. A tab is a small protrusion into the flow which produces a counter-rotating streamwise vortex pair that can affect the jet flow development significantly. The streamwise vortices usually have a long life and, once introduced in the flow, tend to persist over tens of jet diameters downstream. This is in contrast to azimuthal, vertical structures that are more energetic but have a shorter life span. The generation mechanism of the streamwise vortex pairs by the tabs and their effect on the entrainment and spreading of free jets have been discussed in literature [3–7]. In the studies carried out so far, various factors have been found to influence the jet decay. Also, the nozzle boundary-layer thickness, turbulence level, and convergence were found to have insignificant influence on the jet development. In contrast, the insertion of small rectangular tabs at the exit was found to have a profound effect on the jet development.

In a continuing effort to increase the mixing in free shear flows, vortex generators in the form of tabs have been investigated by several researchers [3–9]. Bradbury and Khadem [10] were the first to study in detail the effect of tabs on axisymmetric jets. They found that the tabs at the nozzle exit can significantly increase the jet spread. They reported reduction in jet core length from $6D$ to $3D$, where D is the nozzle exit diameter. Zaman et al. [11,12] and Ahuja et al. [13] systematically studied jet mixing enhancement with tabs and found that the tabs not only increase the jet mixing at low-speed conditions but can also enhance the mixing at high-speed and high-temperature conditions. Ahuja [14] studied a Mach 1.12 round jet with a total temperature of 684 K and found that the potential core length could be reduced from $6D$ to less than $2D$ by using two diametrically opposite tabs. He also concluded that the tabs can reduce low-frequency noise up to 5–6 dB. Most of the investigators have focused their attention on the overall mixing enhancement performance of tabs and on the application of tabs to jet noise reduction. However, Zaman [12] carried out an extensive flow visualization study using laser sheet

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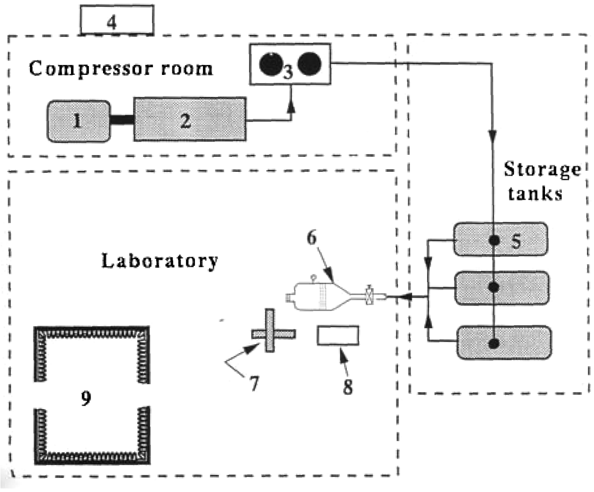
and cigar smoke illumination and pressure measurements to understand the physics of vortex generation by tabs. He conjectured that the jet distortion introduced by a tab is due to the generation of streamwise vortices and postulated the generation of these vortices to the presence of two types of sources. In the study of the effect of a tab on turbulent boundary layer, Gretta and Smith [15] also found that a tab generates a pair of counter-rotating streamwise vortices which stimulate a strong ejection of boundary-layer flow into the high-speed flow, resulting in a rapid cross-stream mixing and a significantly thickened turbulent boundary layer. In particular, it was found that just two tabs produced gross distortions in the jet development compared to four, six, or eight tabs [10]. Also, in another study, Krothapalli and Wishart [16] realized that placing two tabs in symmetry along the exit diameter leads to a more rapid jet development compared to asymmetrical placement. Samimy and Reeder [17] found tabs to be ineffective in overexpanded jet flows. They commented that this ineffectiveness is due to the presence of an adverse pressure gradient that exists near the nozzle exit. Further, for overexpanded flow through the nozzle, tabs have little or no influence at low Mach numbers, whereas, at higher Mach numbers, significant flow discretions were observed. From the preceding discussions, it is evident that tabs are identified as a passive control with potential to enhance mixing and attenuate jet noise. As the jet fluid travels further away from its origin, it slows down due to the mixing with the ambient fluid. The interaction between the jet and the ambient fluid forms the mixing layer or the shear layer. As the primary structures or ring vortices roll up and move downstream, they grow in size due to the entrainment of ambient fluid. The resulting jet decay is proportional to the velocity gradient across the shear layer and is a strong function of the distance downstream of the jet exit. Liepmann and Gharib [18] showed that streamwise vorticity drastically alters the mass entrainment of a jet, and the efficiency of this vorticity in entraining fluid increases relative to that of azimuthal vorticity as the jet evolves downstream. In many systems, mixing enhancement will greatly improve their performance. For example, combustion cycle efficiency can be improved by enhancing the mixing of fuel and oxidizer. Also, by increasing the rate of mixing with the cold ambient air, the infrared radiation of a hot jet plume can be significantly reduced. From the jet noise point of view, alteration of the coherent structures of the jet can produce a significant reduction in far-field noise or can change the directivity or spectral characteristics of the noise field [19]. Further, for an underexpanded flow, the width of the tab was found to have a more profound effect on jet decay for the same blockage area ratios. Also, end shape of the tab has an insignificant effect on the distortion produced as long as the blockage area to the flow was kept constant. A recent study by Singh and Rathakrishnan [2] has shown that the argument given by Zaman et al. [20], “the projection of tabs beyond the boundary-layer thickness is ineffective,” is not true and the tabs can extend up to the radius (for circular nozzles) and serve as effective mixing promoters. Therefore, in the present study, instead of tabs, a cross wire (wire running across a diameter of the nozzle exit) has been used as passive control to enhance the jet mixing. However, it must be noted that the wire causes momentum thrust loss due to area blockage caused by the wire. Also, the drag caused by the wire in a supersonic stream must be accounted for. Hence, the thinnest effective tab has to be identified and used to minimize both the thrust loss and drag caused by the wire.

From the preceding review, it is evident that, in the contemporary studies on supersonic jets, jet decay holds a distinct priority because of its widespread applications. The tabs in the limit length have been found to be effective in promoting the mixing. But the physical reason for the effectiveness of the limiting control and its effect on the jet noise has not been studied so far. To fill this gap, the present study aims at investigating the effect of the passive control termed Rathakrishnan limit [21–28], which is the limiting case of a tab running across a diameter of the nozzle, referred to as a cross wire, on the mixing and acoustic characteristics of correctly, under- and overexpanded axisymmetric supersonic jets, without going into the details of thrust loss caused by the wire blockage and the wire drag.

II. Experimental Details

A. Test Facility and Experimental Models

The experiments were conducted in the jet facility at the High-Speed Aerodynamics Laboratory, Indian Institute of Technology, Kanpur [29]. A schematic diagram of the experimental facility used for this study is shown in Fig. 1. Three convergent–divergent (C-D) nozzles of design Mach numbers 1.6, 1.8, and 2.0 made of brass were used in the study. The calibrated Mach numbers for these nozzles were 1.6, 1.79, and 2.0, respectively. The throat diameter of all the C-D nozzles was 10 mm. Copper wires of diameters 0.5 and 0.7 mm were used as cross wires in the present study. The geometric blockage due to cross wire is defined as the ratio of the projected area of the wire normal to the nozzle axis, intruding the flow to the nozzle exit area. For 0.5 mm cross wire, the blockage area ratios (projected area of wire/nozzle exit area) were 5.69, 5.32, and 4.9% for Mach 1.6, 1.79, and 2.0 nozzles, respectively. The corresponding values for a 0.7 mm wire were 7.97, 7.45, and 6.86%. The cross-wire diameter was decided keeping the blockage limit less than 10%. To have an idea about the effect of cross-wire diameter on aerodynamic characteristics of the jet, two wires of diameters 0.7 and 0.5 mm were tested for the Mach 1.6 jet. Excepting for nozzle pressure ratio (NPR) 2, the 0.7 mm wire was found to be more effective in reducing the jet core length and weakening the shocks. Therefore, for the rest of the investigation at Mach numbers 1.79 and 2, only 0.7 mm wire was used for control. A view of a nozzle with the limiting tab (cross wire) at its exit and the coordinate system used is shown in Fig. 2. One of the serious shortcomings of this kind of control is the momentum thrust loss suffered by the nozzle due to the blockage offered by the wire. Also, it should be noted that the nozzle exit area spoiled is not just the wire projection, but the extent of area occupied by the detached shock envelope due to the wire presence, in the supersonic stream. This area is much higher than the projected area of the wire. Fortunately, in a supersonic flow, any decrease of flow velocity caused by area reduction is accompanied by a large increase of density (to satisfy the mass conservation [30]), making the thrust loss suffered due to the blockage less severe than what it appears to be. Recently, Lovaraju et al. [21] showed that the momentum thrust loss suffered due to a cross wire is approximately equal to the projected area of the wire. Also, it is essential to realize that, in addition to momentum thrust loss, there is a penalty in the form of increased base drag. The cross wire is also found to be efficient in promoting the mixing of subsonic jets [24].



1. 150 hp induction motor
2. Ingersoll Rand 2-stage reciprocating compressor
3. Activated charcoal filter and silica gel dryer units
4. Water cooling unit
5. Storage tanks
6. Jet test facility
7. Traversing system
8. Instrumentation desk
9. Movable anechoic chamber

Fig. 1 Schematic diagram of experimental setup.

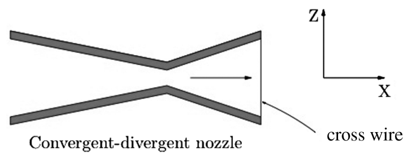


Fig. 2 Convergent–divergent nozzle with cross wire.

B. Instrumentation

Pressures were measured with a 16 channel Pressure Systems, Inc. 9010 transducer with a range of 0–300 psi. The software provided by the manufacturer was used to interface the transducer with a computer. The user-friendly menu-driven software acquires data and shows the pressure reading from all 16 channels simultaneously in a window-type display on the computer screen. The software can be used to choose the units of pressure from a list of available units, perform a rezero/full calibration, etc. The transducer also has a facility to choose the number of samples to be averaged by means of dip-switch settings. The accuracy of the transducer (after rezero calibration) is specified to be $\pm 0.15\%$ full scale. The pitot pressure in the jets were measured using a pitot tube of 0.4 mm inner diameter and 0.6 mm outer diameter mounted on a rigid three-dimensional traverse with a resolution of 0.1 mm in linear translation. In all measurements, the sensing probe stem was kept normal to the jet axis with its sensing hole facing the flow. The pitot pressures measured were accurate within $\pm 2\%$.

In jet noise experiments, free-field conditions become very essential for scaling laws to be derived, which would enable a comparison of results obtained at different power settings (e.g., model and full-scale jets). The anechoic chambers used for experiments in jet acoustics are different from those used for purely acoustic or electronics experiments like, for example, calibration of a microphone. Jet experiments involve mass flow through the chamber, and because jets entrain ambient fluid, it is necessary to provide ventilation for mass entrainment. Similarly, ventilation should be provided for the passage of jet mass outside the enclosure.

The present construction is a highly simplified arrangement for producing a near free-field condition to carry out jet noise studies, taking advantage of the flexibility of allowing a larger cutoff frequency for high-speed jet noise studies [31]. This is because high-speed jets contain most of their energy in the higher frequencies. Corrugated foam was mounted on an iron mesh, to which they were stitched. An air gap space was maintained between the wire mesh and the outer wall of the chamber. The inner surface of the outer wall was covered with a foam layer. This three-layered arrangement was done on all walls of the anechoic chamber except the floor. Corrugated foam blocks were used to cover the floor area. The chamber has two openings: one to accommodate a small portion of the stagnation chamber and the traversing system, and another to permit mass flow outside the chamber. During the noise measurements, all reflecting surfaces inside the chamber (e.g., face of settling chamber, traverse, etc.) were covered with a 15-mm-thick polyurethane foam to minimize sound reflection.

In the present study, the jet noise was measured using a Larson Davis model 800B precision integrating sound level meter with a $\frac{1}{8}$ in. B & K type 4138 condenser microphone [29]. This microphone is certified to have a flat response in the range of 10–50 Hz within $1 \pm$ dB, and 6.5 Hz–140 kHz within ± 2 dB. The microphone was calibrated using a CA 250 precision acoustic calibrator. This acoustic calibrator gives a uniform monotone of 250 Hz at 114 dB (reference $20 \pm$ Pa). The accuracy of the noise measurement, according to the manufacturer's specification, is 0.3 dB. The sound level meter has an amplitude range from -10 to 140 dB, in five user-selectable ranges of 60 dB dynamic range. Three standard weighting networks, A, C, and linear weightings, are available. Throughout the present work, C weighting was used [29]. The instrument gives an output signal in both ac and dc form. The ac output follows all signal-conditioning circuits, including the band pass filters. The ac output can be used to drive the inputs of external signal analyzers such as fast Fourier transforms. Full-scale output is approximately 1.0 V ac. The dc output voltage is 50 mV/dB and the full-scale output is 3.2 V dc. The sound pressure was measured in fast mode. All sound pressure levels are referred to 20 Pa.

C. Experimental Procedure

Compressed air from storage tanks was ducted through a gate valve and a pressure-regulating valve to a settling chamber where it was brought to an equilibrium stagnation condition. This stagnant air from the settling chamber was expanded through the C-D nozzle at five different settling chamber pressures. The pitot pressure along the jet centerline was measured at intervals of 1 mm up to approximately $6D$ and then in intervals of 4 mm up to $30D$. This was done to capture the details of the shock-structure immediately downstream of the nozzle exit. The pitot probe mounted on a rigid traverse measured the pressures along the jet axis X, the direction normal to the cross wire Y, and along the cross wire Z at 1 mm intervals, with the origin at the center of the nozzle exit plane. Detailed pressure measurements were made in only one quadrant of the jet at various axial locations downstream of the nozzle, ensuring a reasonable degree of symmetry in the other quadrants by measuring pressures at selected locations of symmetry in the opposite quadrants [24].

The acoustic measurements were made at two locations: in the nozzle exit plane and far field. In the nozzle exit plane, the microphone was positioned at $30D$ radial distance. For the far-field case, acoustic data were acquired at a radial distance of $100D$ in the azimuthal plane, with the microphone tip positioned at 30 deg orientation to the jet axis. For both cases, acoustic data were acquired in two planes, namely along the wire and normal to the wire. The measurement location and orientation used here are similar to that used by Vishnu and Rathakrishnan [29]. For both cases, acoustic data were acquired in two planes, namely along and normal to the wire.

D. Data Accuracy

The pitot pressure measurements were accurate within $\pm 2\%$. The noise measurements had an accuracy of ± 0.3 dB, with the $\frac{1}{8}$ in. microphone having a flat response of 10–50 Hz within ± 1 dB and 6.5–140 Hz $\pm$ 2 dB for the sound level meter of amplitude range 10–140 dB, in five ranges of 60 dB dynamic range. The sound pressures measured were referred to 20 μPa. The repeatability of noise and pressure measurements were $\pm 2\%$ and $\pm 3\%$, respectively.

III. Results and Discussion

A pitot probe was used to measure the pressure along the jet centerline at various operating conditions. In the supersonic flow region, the measured pitot pressure P_t corresponds to the stagnation pressure behind the bow shock in front of the pitot probe. It is important to note that, in a supersonic jet core, what the probe measures is the total pressure behind the bow shock that stands ahead of the probe. Thus, it is not the actual total pressure. If the actual total pressure is required, one has to correct the measured pressure for the pressure loss across the shock. But the jet core is wave dominated and the Mach number in the core varies from point to point, and also the shocks in different shock cells are of different strength. Therefore, it is difficult to correct the measured total pressure for shock loss. Furthermore, in supersonic regions, there is some measurement error due to probe interference with shock structure. Hence, the results in supersonic regions should be considered only as qualitative and are good enough for comparative purposes [29]. The pressure oscillations in the core region of the flow are due to the shock cells in the jet. Because of the probe interference with the shock structure, there could be some measurement error and hence the results represent the qualitative nature of the flow. Nevertheless, the data are accurate enough to capture the overall features, such as the number of shock cells and the spacing between them, etc. In a steady supersonic flow with a single normal shock ahead of the pitot tube, a sharp drop in total pressure followed by a rise signifies the presence of a strong shock wave. The measured data consist of settling chamber pressure, pitot pressure along the jet centerline, and stagnation temperature.

The primary objective of this investigation is to examine the feasibility of using a cross wire at the nozzle exit as a passive control to achieve mixing enhancement and noise reduction. In other words, the aim here is to refix the passive control extent by stretching it up to the maximum limit, namely equal to the nozzle radius. To understand and authenticate the aforementioned objectives, the results are presented in the form of jet centerline pressure decay, percentage reduction of core length as a function of nozzle pressure ratio, defined as the ratio of the settling chamber stagnation pressure P_0 to the ambient atmospheric pressure P_a, isopitot pressure contours, overall sound pressure levels (OASPLs), and the frequency spectra. The NPRs covered in the present investigation is such that the jets are correctly under- and overexpanded.

The Mach numbers 1.6, 1.79, and 2 were specifically chosen to study the cross-wire effect on jets which are screech prone (Mach 1.6 and 1.79 jets) and jets without screech (Mach 2 jet). Even though the Mach 2 jet without control is free from screech, when the wire is introduced, the Mach number downstream of the wire may be such to fall in the range of 1.6–2.0 to become screech prone. Another aspect of interest in jet control is the control effectiveness in the presence of adverse pressure gradient. To achieve this goal, the nozzle pressure ratios considered were such that the jets generated were underexpanded, correctly expanded, and overexpanded, exhibiting favorable pressure gradient and adverse pressure gradient under underexpanded and overexpanded conditions, respectively. Mach 1.6 and 1.79 jets were tested at NPRs 2, 4, 6, and 8. In addition to these NPRs, they were also tested at correct expansion. The tested NPRs for Mach 2 were 4, 7.82, and 9.

A. Centerline Decay

The jet centerline pitot pressure decay is a measure of jet mixing, indicating the mixing of the ambient fluid mass entrained at the jet boundary with the mass of the fluid inside the jet. Therefore, to investigate the effect of a cross wire on jet mixing, the measured pitot pressure P_t along the jet axis (X direction) is nondimensionalized with the settling chamber pressure P_0 and plotted as a function of nondimensionalized axial distance, X/D (where D is the nozzle exit diameter) in Figs. 2–6. Centerline pressure decay for the Mach 1.6 jet operated at NPR 2, with and without cross wire, are compared in Fig. 3. For the uncontrolled jet, the core is the axial extent up to which supersonic flow prevails. But when the cross wire is introduced, the core can be taken as the axial extent from the nozzle exit, at which the characteristic decay begins [24]. The cross wire essentially divides the jet into two smaller jets. Because of this bifurcation and the associated initiation of enhanced transverse momentum exchange, the flow along the centerline behind the wire gains momentum rapidly and attains a peak followed by characteristic decay, typical of a free jet. Therefore, the axial extent at which characteristic decay begins can be justifiably taken as the core length for a jet from a nozzle with cross wire [24]. It is seen that the uncontrolled jet core has only mild oscillations in the centerline pitot pressure. This implies that the shocks prevailing in the jet core are very weak. But the jet from the nozzle with wire does not exhibit any pitot pressure oscillation. This reveals that there are no waves of significant strength along the jet centerline downstream of the wire. After the core, the jet without wire experiences a faster decay compared to the jet with wire. It should be noted that, all the aforementioned differences in the jet behavior are taking place within $10D$ axial distance. Beyond $10D$, jets from nozzles with wire and without wire behave almost similar. It is well established that weakening the shocks in the jet core will result in reduction of shock-associated noise, hence reduction in the overall jet noise [29]. Therefore, weakening of the mild shocks in the core by the presence of wire can be expected to result in jet noise reduction. The faster decay of the jet from the plain nozzle (without wire) is because the jet passes through a number of mild shocks before the core ends, thereby resulting in a lower subsonic Mach number compared to the wired jet for which the core does not posses any shock of significant strength. It is seen that the jet with wire has a marginally shorter core than the plain nozzle jet. It is essential to have a word of caution here about the arguments given for the larger pressure loss at the nozzle exit when the wire is introduced. Because of the wire, there is a detached shock generated. This shock is positioned upstream of the wire. Therefore, the pitot pressure just behind the wire is the pressure in the subsonic wake of the wire. Hence, what is measured is essentially the pressure in the wake of the wire. Thus, the magnitude assumes significantly lower values than the plain nozzle jet.

The centerline decay for NPR 4 is given in Fig. 4. This is again an overexpanded jet. It is seen that the shocks in the jet core become significantly weaker when the wire is introduced. Also, the core length is reduced considerably with the introduction of wire. It should be noted that, even though both NPR 2 and NPR 4 generate overexpanded jets, the level of overexpansion comes down with

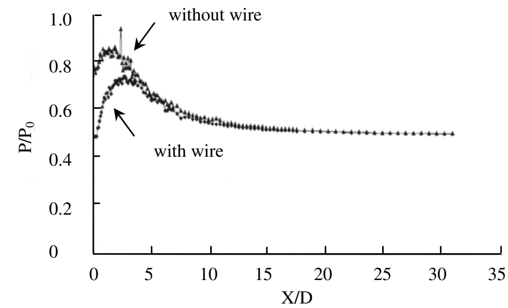


Fig. 3 Centerline decay for Mach 1.6 jet at NPR 2 (overexpanded).

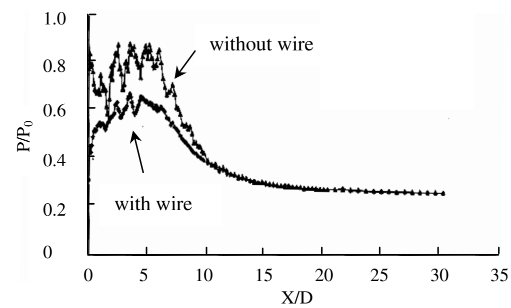


Fig. 4 Centerline decay for Mach 1.6 jet at NPR 4 (overexpanded).

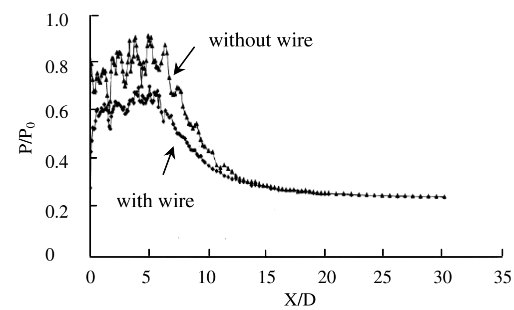


Fig. 5 Centerline decay for Mach 1.6 jet at NPR 4.24 (correctly expanded).

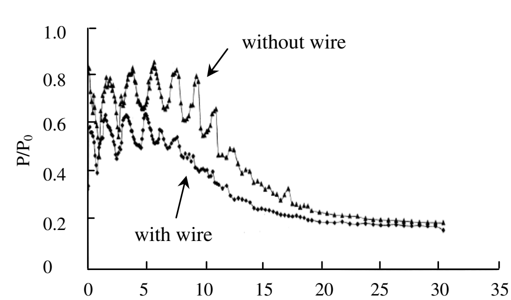


Fig. 6 Centerline decay for Mach 1.6 jet at NPR 6 (underexpanded).

increase of NPR, that is, with NPR increase, the adverse pressure gradient comes down and the cross wire becomes more effective in reducing the core length and weakening the shocks. These results agree well with the observation made by Samimy and Reeder [17] that passive control will be effective in the presence of favorable pressure gradient. Even though the preceding NPR increase from 2 to 4 does not establish a favorable pressure gradient, the adverse pressure gradient level comes down when the NPR is increased from 2 to 4, and hence the passive control becomes more effective. This may be because the mixing action of the streamwise vortices shed by the cross wire depends on its vorticity and the interaction time available for it. With increase of NPR, even though the inertia of the jet goes up, in the direction normal to wire (y direction), the potential core is undisturbed at the nozzle exit. But because of the low momentum in the wake of the wire, the surrounding fluid at higher momentum is deflected toward the lower momentum zone. This results in an active transverse exchange of momentum, because the flowfield is turbulent [24]. It is essential to note that, because of the circular cross section of the cross wire, the vortices shed will cause production of entropy. Therefore, the vortex size and the associated entropy production will be strongly influenced by the wire diameter. Also, the detached shock ahead of the wire in a supersonic jet will result in entropy generation. Thus, there are two mechanisms for entropy production, namely the vortices shed by the wire and the detached shock ahead of the wire. Though no quantitative estimates are made in this work, both these mechanisms should be equally responsible for mixing enhancement by the cross wire. For NPR 4, the core has come down from $7.2D$ (plain nozzle) to $4.6D$ (nozzle with wire), that is, presence of the wire causes a reduction of about 36% in core length.

The centerline decay for NPR 4.24 (correctly expanded jet) is shown in Fig. 5. For the plain nozzle, the core exhibits shocks of significant strength, even though at the nozzle exit there is no shock present for the correct expansion. This is because, even though the nozzle is correctly expanded, the flow exiting the nozzle finds a larger area to relax. This would cause the flow to encounter an associated expansion fan. Because of this expansion fan at the nozzle exit, the flow accelerates to a higher Mach number downstream of the nozzle exit and the expansion waves getting reflected as compression waves from the jet boundary coalesce to form shock at the jet axis, and the shock gets reflected as an expansion fan and the cycle repeats. Because of this, in the uncontrolled jet, the initial shocks are weaker compared to some of the downstream shocks. But when the wire is introduced, the shock envelope in front of the wire results in significant reduction in total pressure and hence a much lower pressure at $X/D = 0$ compared to the plain nozzle jet. The shocks were found to be very weak for the wired case and the core comes down from $9.2D$ to $6.3D$. Here, again, the wire does not influence the jet propagation beyond $13D$. The centerline decay for the underexpanded jet with and without wire, at NPR 6, is compared in Fig. 6. This is the case with a favorable pressure gradient, because the jet is underexpanded. As reported by Zaman et al. [4,11,12], Samimy and Reeder [17], and Singh and Rathakrishnan [2], the passive control causes significant core reduction. For the plain nozzle, large numbers of strong shocks are present in the core and the core extends up to about $17D$. Whereas, when the wire is introduced, the core length comes down to around $12D$. Further, the number of shock cells is reduced and shocks become significantly weaker. Also, the effect of wire results in different decay than the plain nozzle, even beyond $13D$.

When the underexpansion level increases, the favorable pressure gradient also increases and the shocks in the core for the plain nozzle become stronger, as seen in Fig. 7, for NPR 8. At this level of underexpansion, the cross wire also causes the shocks to become considerably weaker. However, the core length reduction achieved is only marginal for this case. For both with wire and without wire, the jet decay retains its identity as far as $30D$.

From the preceding discussions on centerline pressure decay, it is can be inferred that the wire is effective in promoting jet mixing at all levels of expansion. However, the expansion level significantly influences the degree of wire effectiveness in promoting mixing. The

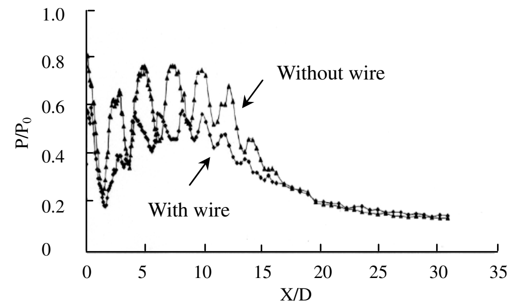


Fig. 7 Centerline decay for Mach 1.6 jet at NPR 8 (underexpanded).

physical reason for the wire performance may be summarized as follows. The azimuthal radius of curvature of plain nozzle exit is uniform. Therefore, azimuthal vortices of uniform size are shed at the nozzle exit. Because of this, the vortices would be able to promote the mixing only from a downstream station where they interact with the mass entraining vortices at the jet periphery. But the cross wire, as reported by Lovaraju et al. [25], to begin with, introduces four sharp corners with the nozzle exit, at their root ends, thus spoiling the uniformity of the azimuthal radius of curvature of the nozzle exit. These four corners would shed vortices of a smaller size than the azimuthal vortices. Thus, vortices of varying size are generated right at the nozzle exit. It is well known that large vortices are efficient entrainers, but are highly unstable and get easily fragmented into small vortices. In other words, large structures comparatively have a short life span and cannot travel long distances [25]. In contrast, small vortices are efficient mixing promoters and are capable of traveling longer distances before losing their identity, even though they are poor entrainers. Therefore, the mass entraining large structures and mass transporting small structures should exist in proper proportion for efficient mixing of the jet mass with the ambient fluid. However, identifying an optimum combination of large and small vortices is highly difficult because the vortices are extremely sensitive to both flow and geometrical parameters, and, in a jet, the flow parameters vary at a rapid rate, which cannot be predicted explicitly. Owing to the complex nature of the vortex dynamics, it is a usual practice to quantify the mixing by measuring flow parameters such as pitot pressure, which is amenable for physical measurements, as in the present study. In addition to introducing the sharp corners, the wire in a supersonic stream positions a detached shock all along its length. The flow over the wire assumes reduced velocity after passing through the shock envelop. Because of this flow, the wire sheds a row of spanwise vortices (rotational axis along the wire length) on its either side. Even though these vortices are spanwise while shedding, they become streamwise soon after shedding, due to the inertia of the jet flow. These spanwise vortices being small and shed right up to the jet centerline could be able to promote mixing significantly.

Another aspect of the control with cross wire is that the geometry of the nozzle is essentially rendered asymmetrical, as reported by Lovaraju and Rathakrishnan [24]. Because of this, even though the flow encounters greatly reduced velocity due to the shock envelop at the wire and due to the wire wake, on either side of the wire, the flow is with large inertia. The low-momentum fluid behind the wire receives momentum from the neighboring high-momentum streams on either side of the wire through the active momentum exchange process associated with the turbulent jet flow. All these favorable mixing promotion aspects make the controlled jet decay faster than its uncontrolled counterpart. To quantify the aforementioned results on core length reduction, a parameter, namely the percentage reduction of core length, defined as

$$\text{percentage reduction} = (\text{core length without wire} - \text{core length with wire})/(\text{core length without wire}) \times 100 \quad (1)$$

has been used. The variation of percentage reduction in core length as a function of NPR for the Mach 1.6 jet is shown in Fig. 8. It is seen

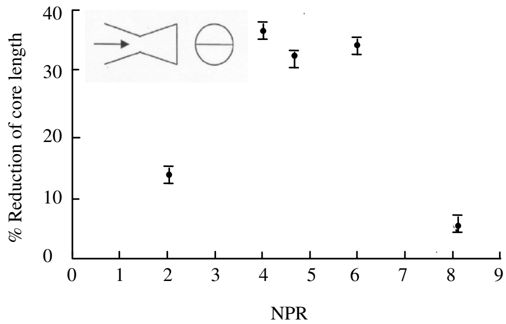


Fig. 8 Percentage reduction in core length with NPR for Mach 1.6 jet.

that the cross wire is highly effective in reducing the core length in the range of NPR from about 4 to 6. It is interesting to note that this range of NPR covers overexpanded, correctly expanded, and underexpanded conditions for the jet. Hence, the literature information, namely that passive control will not be efficient under adverse pressure gradient and will be very efficient under favorable pressure gradient, should be looked into further. From the preceding results, it is seen that the passive control in the form of cross wire extending up to the nozzle centerline can reduce the core length and weaken the shocks in the core very efficiently for some combinations of Mach number and level of expansion. A closer look into the physical phenomenon taking place in the jet when the wire is present may explain the reason for this control achieved with cross wire. Basically, when a cylinder is placed in a subsonic stream it will shed vortices alternately. But these vortices are essentially normal (z vortices; because a vortex is named after the axis about which it rotates, while leaving the tab edge, it rotates about the z direction). As reported by Lovaraju et al. [25], these vortices become streamwise in nature soon after shedding because of the inertia of the jet flow. These streamwise vortices can travel longer distances compared to spanwise or azimuthal vortices. Therefore, the streamwise vortices can efficiently serve as a mixing enhancement mechanism for jets [25]. This aspect is exploited for faster decay with passive control in subsonic jets. But in supersonic jets, the core consists of a mixture of subsonic and supersonic Mach number zones. Further, when a passive control in the form of a cylindrical cross wire, as in the present study, is introduced at the nozzle exit, a detached shock is positioned ahead of the wire. This makes the flow behind the shock subsonic, thereby rendering the wire to shed streamwise vortices as in the case of subsonic flow. However, these streamwise vortices shed by the cross wire have to pass through different Mach number zones in the jet flowfield before losing their identity. This process results in mixing enhancement. The mixing level would vary from place to place in the supersonic jet because of the presence of mixed subsonic and supersonic zones. Nevertheless, the mixing initiated by these streamwise vortices will result in significantly enhanced mixing of the supersonic jet, especially in the core region. This is the main cause for the shocks in the core to become weaker compared to the plain nozzle jet. The effectiveness of the cross wire is strongly influenced by the level of expansion because the Mach number zones in the jet core strongly depend on the expansion level, that is, the level of NPR.

B. Flow Development

To get an insight into the physics of streamwise vortices generation and their effect on jet mixing, the pitot pressures measured at different planes normal to the jet axis were studied by constructing isobars using the measured pressures. The isobaric contours for the Mach 1.6 jet, with and without wire, $X/D = 0$ and 1 for NPR 4, 4.24, and 6 are shown in Figs. 9a–9c. The outermost isobaric contour in these figures is with $P_t/P_0 = 0.2$, with intermediate contours uniformly stepped up by a value of $P_t/P_0 = 0.1$.

The isobars for NPR 2 at different axial distances from $X/D = 0$ to 6 exhibited that, at $X/D = 0$, the introduction of the wire introduces a relatively low-speed zone across the jet. As the jet moves

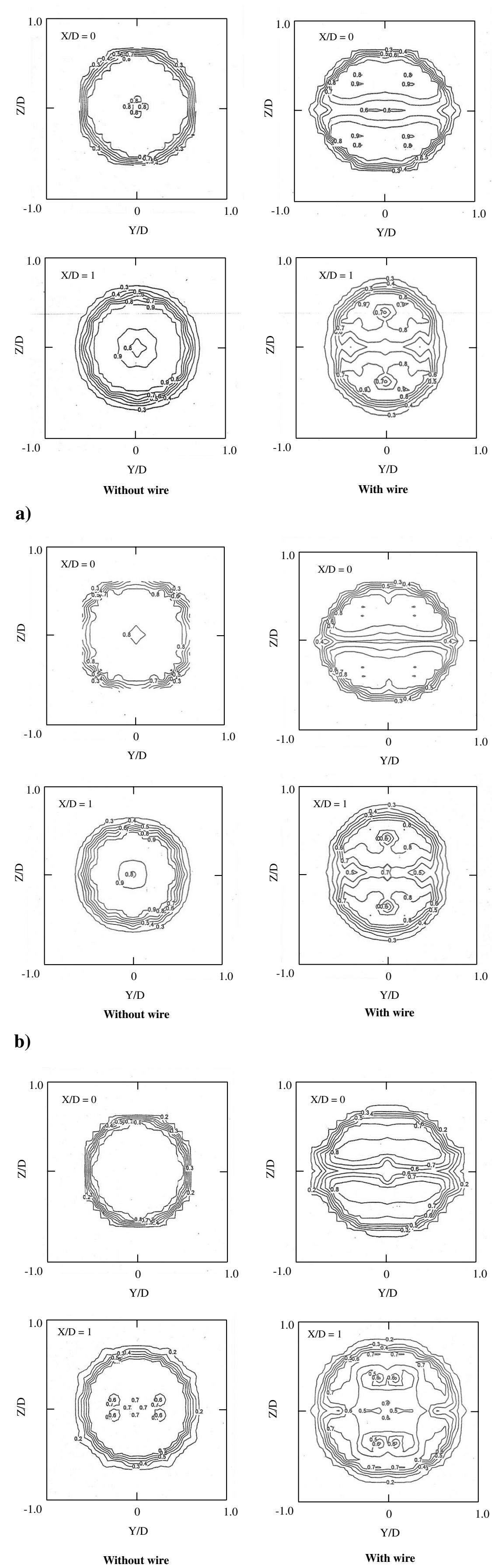


Fig. 9 Isopitot pressure contours for a) $M = 1.6$ at NPR 4, b) $M = 1.6$ at NPR 4.24, and c) $M = 1.6$ at NPR 6.

downstream, the low-speed zone introduced gets bifurcated and forms two counter-rotating zones toward the jet periphery. Because of this, the jet with cross wire behaves like a noncircular jet, showing a tendency of axis switching, which is a well-known phenomenon in jet mixing. An earlier axis switching implies a faster mixing. For NPR 2, the axis switching with wire was at about $6D$, whereas, for the plain nozzle case, there was no tendency of axis switching. This validates the discussion for Fig. 3, indicating almost no shocks in the core.

The isobars for NPR 4 (Fig. 9a) show axis switching at X/D less than 1. This implies a greater enhancement in mixing compared to NPR 2. This is reflected as a drastically reduced core length and significantly weakened shocks in the core, as seen in Fig. 4. The slower jet decay compared to the plain nozzle case was also evident from the larger jet width of the plain nozzle compared to the wired nozzle at X/D 5 and 6. The bifurcation of the jet by the cross wire is evident from these isobars. Similar effect of cross-wire bifurcating jet into two parts with high Mach number cores on either side of the wire was reported by Lovaraju and Rathakrishnan [24]. For the correctly expanded case at NPR 4.24 (Fig. 9b), the axis switching is taking place at X/D less than 1. The observation of considerable reduction in core length and decrease of shock strength due to wire control are supported by these isobars. The faster decay of the jet after the core for the plain nozzle compared to the controlled nozzle was evident from the isobars.

The isobars at the underexpanded condition with NPR 6 (Fig. 9c) show that the jet core for the plain nozzle contains no low-speed zones, but low-speed zones are introduced at the centerline when the wire is introduced. However, because of the favorable pressure gradient, the jet travels faster and the axis switching takes place at about $3D$ compared to less than $1D$ for the lower NPR cases. The streamwise vortices could not weaken the shock to the extent they could be able to do for the lower NPR cases. However, the effect of the vortices introduced by the wire on core length reduction and shock weakening became better after the fourth cell, that is, beyond $5D$. For NPR 8, the axis switching takes place at $3D$. The streamwise vortices introduced by the wire could be able to have only a marginal control over the shock strength and jet mixing in the near field.

From these isobaric contours, it is seen that, basically, the circular geometry of the nozzle is made noncircular by the wire. As discussed earlier, the wire introduces four sharp corners to the nozzle exit. This makes the uniform azimuthal radius of curvature at the nozzle exit become asymmetric. This leads to the formation of vortices of mixed sizes. This mixed size of vortices initiates mixing right at the nozzle exit. In addition to this, unlike tabs, the wire sheds streamwise vortices all along the diameter of the nozzle exit. Also, the vortices shed by the wire encounter a low-momentum zone in the wake of the wire, thus finding more residential time for their interaction to promote mixing. The combined influence of the noncircular effect introduced, introduction of vortices right up to the nozzle centerline, and providing the vortices with more time for interaction leads to enhanced mixing. The effect of mixing enhancement is clearly seen from the isobaric contours as axis switching (the phenomenon that causes the major axis of the jet cross section to switch over to become the minor axis and vice versa [32,33]).

The centerline decay of Mach number 1.79 jet at different levels of expansion (the plots are not shown here) shows that, at NPR 2, there is no significant reduction in the core length excepting that the pressure level with wire is always lower than that without wire. This is because the presence of the wire generates a detached shock and the flow experiences considerable pressure loss due to the detached shock. At NPR 4, the shocks in the jet core have been made very weak by the wire. This reduction of shock strength can result in significant reduction of jet noise, because the shock-associated noise forms a significant portion of the jet noise for supersonic jets. The core length reduction achieved is not significant in this case even though the shocks get weakened. The results for NPR 5.66, that is, the correctly expanded case, reveal that the wire is effective in weakening the shocks in the core. Also, the core length comes down from $20D$ to $10D$, as seen in Fig. 10. Supersonic flow prevails up to about $20D$ for the plain nozzle, as it has been brought down to just about $10D$ when wire is introduced. This may be considered as a very good aerodynamic advantage in terms of mixing. For NPR 6, which is an underexpanded case, the strong shocks in the plain nozzle core have been made significantly weaker with the introduction of the wire. The core comes down from $13.2D$ to $9.8D$. For NPR 8, which is again an underexpanded condition, the results show that the strong shocks in the jet core have been significantly diffused by the wire and the core length has come down from nearly $11.2D$ to $10.2D$.

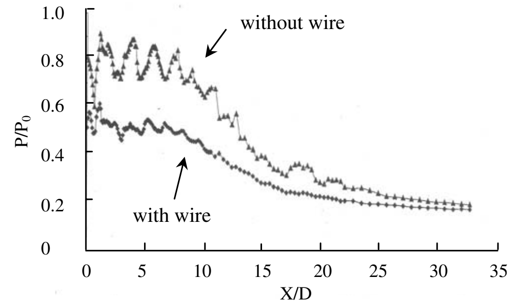


Fig. 10 Centerline decay for Mach 1.79 jet at NPR 5.66 (correct expansion).

The percentage reduction of core length with NPR is shown in Fig. 11. It is interesting to note that, for the overexpanded case, the core length reduction is only marginally influenced by NPR. The maximum core length reduction is around the correct expansion, namely around NPR 4.25 for the Mach 1.6 jet (Fig. 8) and NPR 5.66 for the Mach 1.79 jet (Fig. 11). For the underexpanded condition, the core length reduction comes down with an increase of NPR.

C. Acoustic Characteristics of Mach 1.6 Jet

As summarized by Tam [34], except for jets operating at the correctly expanded condition, the noise of a supersonic jet comprises three basic components: the turbulent mixing noise, the broadband shock-associated noise, and the screech tones. The appearance of screech tone is usually accompanied by its harmonics. Sometimes, even the fourth or fifth harmonics can be detected. The relative magnitude of this noise intensity is a strong function of the direction of observation. In the downstream direction of the jet, turbulent mixing noise is the most dominant noise component. In the upstream direction, the broadband shock-associated noise is more intense. For circular jets, the screech tones radiate primarily in the upstream direction.

As mentioned in the literature review, screech tones from supersonic jets were first observed by Powel [35,36]. Since then, the phenomenon has been studied experimentally by a large number of investigators. It is found that the fundamental screech tones radiate primarily in the upstream direction, whereas the principal direction of radiation of first harmonics is at 90 deg to the jet flow [37].

The turbulent mixing noise is from both large-scale turbulence structures and fine-scale turbulence of the jet flow. The large-scale turbulence structures generate the dominant part of the turbulent mixing noise. The fine-scale turbulence is responsible for the background noise.

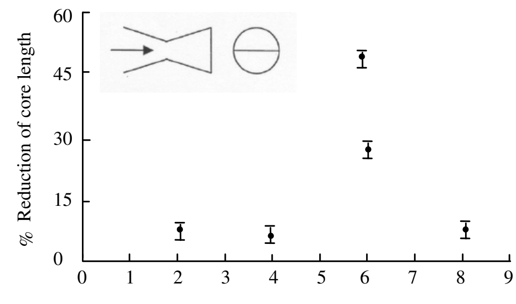


Fig. 11 Percentage reduction in core length with NPR for Mach 1.79 jet.

Broadband shock-associated noise and screech tones are generated only when a quasi-periodic shock cell structure is present in the jet core. The quasi periodicity of the shock cells plays a crucial role in defining the characteristics of both the broadband and discrete frequency shock noises. The shock cell structure in an imperfectly expanded supersonic jet is formed by oblique/normal shock and expansion fans. These shocks or expansion fans are generated at the nozzle lip because of the mismatch of the static pressures inside and outside of the nozzle exit. For an underexpanded jet, an expansion fan is positioned at the nozzle lip. The expansion fan or shock, once formed, propagates across the jet flow until it impinges on the mixing layer on the other side. Because the flow outside the jet is stationary, either a shock or an expansion fan is not allowed to that zone. The impinging shock or expansion fan is, therefore, reflected back into the jet field. The reflection process gets repeated many times downstream until the shock/expansion fan is dissipated by turbulence. These repeated reflections of the shock/expansion fans by the mixing layer of the jet give rise to quasi-periodic shock cells. From this point of view, the disturbances get trapped inside the jet by the mixing layer surrounding the jet core zone. In other words, one may consider the jet flow as behaving like a wave guide for the disturbances that form the shock cell.

The frequency spectra for the Mach number 1.6 jet at NPR 2 and $X/D = 0$ are presented in Fig. 12, for the cases without wire and with wire, along the wire and normal to the wire. It is seen that introduction of the wire results in reduction of shock-associated noise as seen at frequency 5 kHz for these cases. Also, the fact that the jet noise is sensitive to the direction of measurement is evident from lines b and c in Fig. 12.

The jet noise (OASPL) measured at $R/D = 100$ is presented in Fig. 13 for Mach 1.6, 1.79, and 2.0 jets of the present study as a function of NPR. The frequency spectra at $R/D = 100$ and NPR 2 are shown in Fig. 14. (In the frequency spectra plots shown in Figs. 14–20, there are three spectra corresponding to without wire, along the wire, and normal to the wire, referred to as a, b, and c, respectively. The datum used for plotting a, b, and c are marked on the

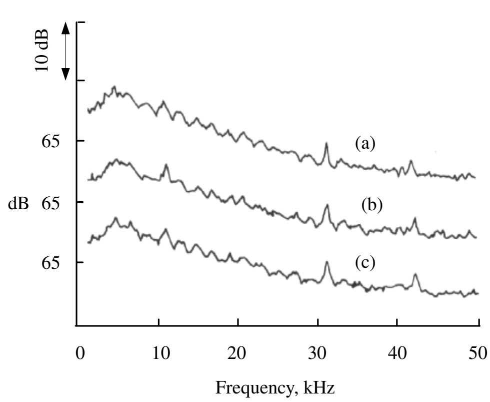


Fig. 12 Frequency spectrum for $M = 1.6$, NPR 2, $X/D = 0$, $R/D = 30$: a) without wire, b) along the wire, and c) normal to the wire.

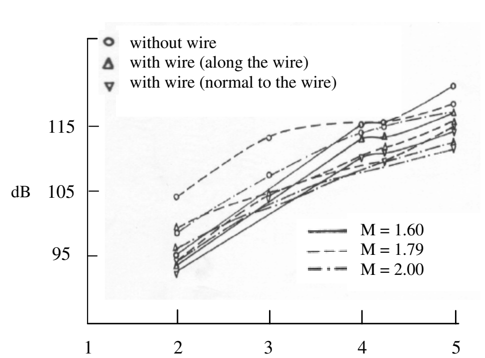


Fig. 13 Overall sound pressure level variation with NPR.

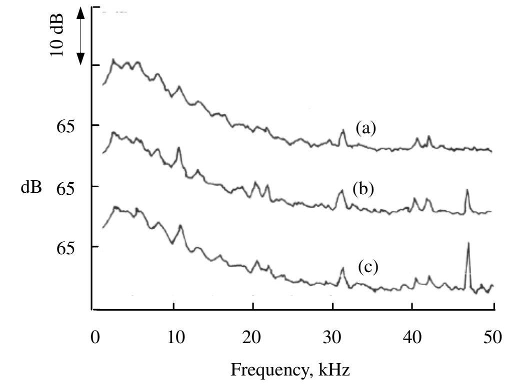


Fig. 14 Frequency spectrum for $M = 1.6$, NPR 2, $R/D = 100$, $\theta = 30$ deg: a) without wire, b) along the wire, and c) normal to the wire.

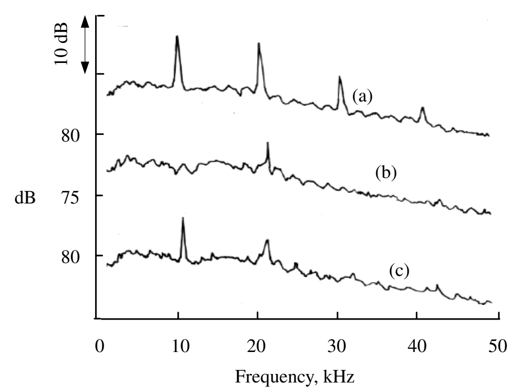


Fig. 15 Frequency spectrum for $M = 1.6$, NPR 4, $X/D = 0$, $R/D = 30$: a) without wire, b) along the wire, and c) normal to the wire.

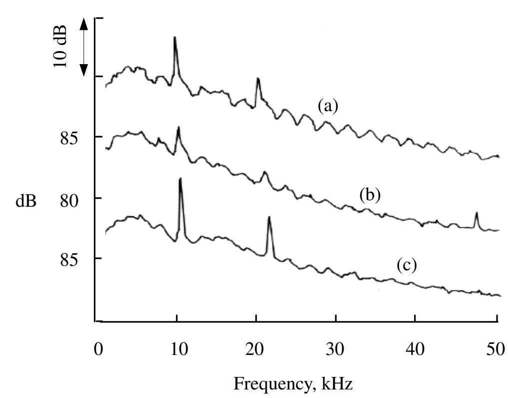


Fig. 16 Frequency spectrum for $M = 1.6$, NPR 4, $R/D = 100$, $\theta = 30$ deg: a) without wire, b) along the wire, and c) normal to the wire.

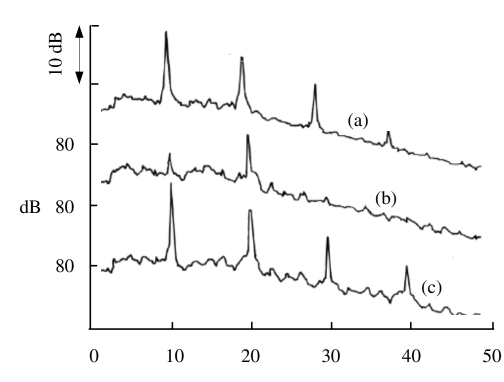


Fig. 17 Frequency spectrum for $M = 1.6$, NPR 4.24, $X/D = 0$, $R/D = 30$: a) without wire, b) along the wire, and c) normal to the wire.

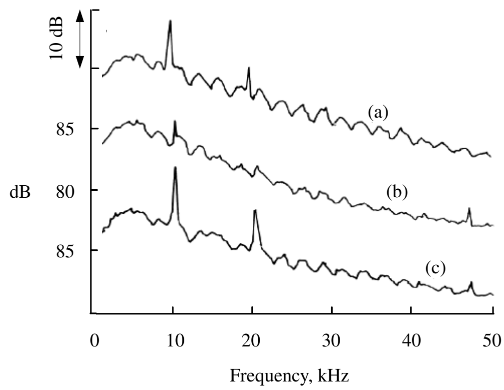


Fig. 18 Frequency spectrum for $M = 1.6$, NPR 4.24, $R/D = 100$, $\theta = 30$ deg: a) without wire, b) along the wire, and c) normal to the wire.

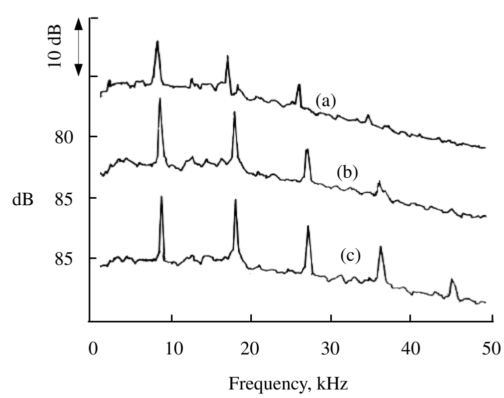


Fig. 19 Frequency spectrum for $M = 1.6$, NPR 5, $X/D = 0$, $R/D = 30$: a) without wire, b) along the wire, and c) normal to the wire.

ordinate and are not always the same, as seen from Figs. 14–20.) From these results, it is seen that the jet noise comes down by nearly 2 dB when wire is introduced. This is mainly due to the reduction of shock-associated noise owing to weakening of the shocks by the cross wire as seen from the centerline pitot pressure distribution shown in Fig. 3.

The frequency spectra at $X/D = 0$ for NPR 4 are shown in Fig. 15. For the plain nozzle, screech tones with four harmonics are seen in the spectrum. When the cross wire is introduced, in the direction along the wire, the screech is suppressed to a large extent and, at low frequencies, it is totally eliminated. In the direction normal to the wire, the screech is reduced to a single peak screech, and its amplitude has also come down by 8 dB (from 98 dB to about 90 dB). This is mainly due to the weakening of the shocks by the cross wire, as seen from Fig. 3.

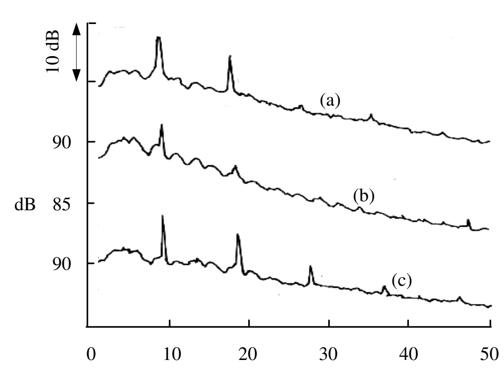


Fig. 20 Frequency spectrum for $M = 1.6$, NPR 5, $R/D = 100$, $\theta = 30$ deg: a) without wire, b) along the wire, and c) normal to the wire.

The far-field ($R/D = 100$) spectra for NPR 4 are shown in Fig. 16. In this case, the OASPL comes down by 5 dB along the wire and 2.1 dB normal to the wire. For the plain nozzle, screech tones with two frequencies are present. It reduces to screech with a single frequency in the wire plane, resulting in nearly 5 dB reduction in jet noise. However, in the direction normal to the wire, there is no screech suppression; both the harmonics are prevailing with a slight reduction in their amplitudes.

For the correctly expanded jet (NPR 4.24, $X/D = 0$), as seen from Fig. 17, the spectra for the plain nozzle as well as the wired nozzle exhibit screech tones. For the plain nozzle, four screech harmonics are seen. But along the wire, the harmonics are reduced to two and the amplitude of the screech tones also comes down significantly. However, normal to the wire, even though the screech amplitudes have come down, the four harmonics present in the plain nozzle case are also seen for this case.

The far-field ($R/D = 100$) spectra for correct expansion (NPR 4.24) are given in Fig. 18. For the plain nozzle, two screech tones are present. The screech is suppressed to a large extent along the wire, but normal to the wire, though the shock-associated noise is reduced marginally, the screech amplitude remains unaffected. For this case, an OASPL reduction of 4.5 dB along the wire and 2.1 dB normal to the wire are achieved, as seen from Fig. 13.

The frequency spectra for NPR 5, which corresponds to an underexpanded condition, is shown for $X/D = 0$ in Fig. 19. The behavior for this NPR is slightly different from the correctly expanded and overexpanded cases. For the plain nozzle, three prominent screech frequencies are seen, but when the wire is introduced, the screech amplitude increases along the wire as well as normal to the wire, as seen from Fig. 19. However, at low frequencies, the noise (in decibels) content comes down. Further, at high frequencies, the noise level shows some increase when the wire is introduced.

The far-field ($R/D = 100$) spectra for NPR 5 are shown in Fig. 20. For the plain nozzle, two screech tones are present, also the shock-associated noise content is significant. The introduction of wire brings down the screech amplitude from 109 to 98 dB along the wire. Also, the shock-associated and mixing noise is reduced significantly when the wire is introduced. This results in an OASPL reduction of 6.9 dB along the wire. Normal to the wire, the screech frequencies are unaffected for the first two harmonics and a third harmonic is also seen, but the shock-associated noise and mixing noise get reduced in this plane also. This results in an OASPL reduction of about 4 dB.

As reported by Vishnu and Rathakrishnan [29], when the jet Mach number is supersonic, the jet field is dominated by shock waves and expansion fans for both correctly and incorrectly expanded jets. The entrainment is taking place at the jet periphery where there is a zone of subsonic flow. That is, the supersonic zone in the jet central portion is submerged in the subsonic layer surrounding that. The axial extent of the supersonic regime is termed the core. Therefore, the aim in the case of supersonic jet control is twofold: the control should result in core length reduction, and shocks in the core should be made weaker or eliminated. The former will result in an aerodynamic advantage, namely, enhanced mixing, and the latter will result in acoustic advantage, namely, reduction in the jet noise. In accordance with this, it is seen from Figs. 4–7 that weakening of shocks in the core of the jet, operated at different levels of expansions corresponding to NPR 4, 5, 6, and 7, results in significant reduction of jet noise.

D. Acoustic Characteristics of Mach 1.79 Jet

The frequency spectra for the plain nozzle and along the wire and normal to the wire at $X/D = 0$ and NPR 2 reveal that introduction of the wire results in an increase of the amplitude of shock-associated noise both along and normal to the wire compared to the plain nozzle. A probable reason for this may be that the detached shock generated by the wire also contributes to the shock-associated noise. However, from the spectral content, it is seen that introduction of wire results in reduction of overall sound pressure level.

The frequency spectra for NPR 2 at $R/D = 100$ show that, for the plain nozzle, there is a screech at around 6 kHz frequency. Introduction of wire reduces the screech amplitude from 90 to about

82 dB along the wire. The spectrum normal to the wire shows that the screech is completely suppressed in this direction, but the shock-associated noise takes a wider band of frequency. From these spectra, it is evident that the introduction of wire results in an OASPL reduction of 4.8 dB along the wire and 8.9 dB normal to the wire, which is a substantial reduction.

Similar results for NPR 3 at $X/D = 0$ show that the screech present for the plain nozzle is completely suppressed by the wire introduction. Also, there is a significant reduction in the amplitude at all frequencies. At $R/D = 100$, for the plain nozzle, there are two screech harmonics and significant broadband shock noise. Introduction of wire completely eliminates the screech and even the shock-associated noise amplitude comes down significantly. Because of these effects, an OASPL reduction of 8.9 dB along the wire and 9 dB normal to the wire is achieved.

The frequency spectra for $X/D = 0$ and NPR 4 exhibits screech tones with four harmonics for the plain nozzle. When the wire is introduced, the screech tone amplitude is reduced significantly along the wire and to some extent normal to the wire. This reduction in screech tone amplitude is reflected as a reduction in OASPL in the far field. The spectra of far-field noise at $R/D = 100$ and NPR 4 show that, in the far field also, introduction of wire suppresses the screech amplitude along the wire, but normal to the wire, the screech tones are not affected by the wire. However, introduction of the wire results in an OASPL reduction of 5.2 dB along the wire and 3.5 dB normal to the wire, as seen in Fig. 13.

At NPR 5, introduction of wire increases the screech amplitude. However, the frequency band of shock-associated noise becomes narrower with the introduction of the wire. This results in an OASPL reduction of 4.2 dB along the wire and 3.2 dB normal to the wire.

E. Acoustic Characteristics of Mach 2 Jet

To investigate the effect of streamwise vortices introduced by the cross wire on the acoustic characteristics of a jet, which is considered to be the limiting end of the screech prone Mach number, noise measurements were made for a Mach number 2 jet from a nozzle with and without wire. Here again, as in the case of Mach numbers 1.6 and 1.79 jets, the measurements were made for NPRs 2–5 only.

The frequency spectra at $X/D = 0$ show no screech tone even for the plain nozzle. Introduction of wire brings down the mixing noise amplitude at lower frequencies, along the wire. However, the amplitude of the mixing noise has been enhanced at all frequency levels normal to the wire. This may be due to the direct effect of the convection of the streamwise vortices away from the wire in the direction normal to it.

The frequency spectra for $R/D = 100$ and NPR 2 show that the shock-associated noise amplitude comes down significantly along the wire and marginally normal to the wire. An OASPL reduction of 3.2 dB along the wire and 2.1 dB normal to the wire are experienced in this case.

The frequency spectra at $X/D = 0$ and NPR 3 exhibit screech with three harmonics, with the second harmonic being that with the highest amplitude. The introduction of the wire suppresses the screech completely and the amplitudes at all frequency levels come down along the wire, however, normal to the wire, the amplitudes go up. It is important to note that screech at Mach 2 is unusual and, as per literature, it is not probable. Hence, this aspect of screech appearance at Mach calls for a deeper investigation.

The far-field ($R/D = 100$) spectra at NPR 3 show that the amplitudes of both shock-associated and mixing noise come down when the wire is introduced. This results in an OASPL reduction of 4 dB along the wire and 4.5 dB normal to the wire.

The frequency spectra at $X/D = 0$ for NPR 4 show four harmonics for the screech for the plain nozzle. However, the screech is completely suppressed when the wire is introduced. The corresponding frequency spectra for $R/D = 100$ show a screech tone for the plain nozzle, whereas the screech is completely eliminated along the wire, and screech amplitude is reduced from 102 to 88 dB normal to the wire. The amplitude of the shock-associated noise has also been reduced significantly, both along the wire and normal to the wire. This is because the shocks have been made significantly weaker by the wire, as seen in Fig. 13. An OASPL reduction of 6.1 dB along the wire and 5.9 dB normal to the wire are achieved for this case.

The frequency spectra for NPR 4 at $X/D = 0$ show that, for the plain nozzle, there are three harmonics for the screech. The screech is suppressed by the wire and the amplitudes come down at all frequency levels along the wire, but they go up significantly at all frequencies in the direction normal to the wire.

Frequency spectra for $R/D = 100$ and NPR 5 reveal that the introduction of wire brings down the amplitude of both shock-associated and mixing noises at all frequencies in the directions along and normal to the wire. For this case, an OASPL reduction of 6 dB along the wire and 5 dB normal to the wire are achieved.

IV. Conclusions

This investigation provided an evaluation of the aerodynamic and aeroacoustic effectiveness of passive control in the form of a cross wire at the nozzle exit on the decay and noise characteristics of Mach 1.6, 1.79, and 2.0 jets from convergent–divergent circular nozzles, at different levels of expansion. The streamwise vortices introduced by the cross wire are found to enhance the mixing of the jet mass with the mass entrained from the surroundings and weaken the shocks in the jet core significantly, resulting in considerable reduction of shock-associated noise, leading to reduction of overall jet noise. The controlled jets exhibit significant reduction in core length compared to the uncontrolled jets, owing to the enhanced mixing caused by the mixing promoting vortices shed by the wire. The cross wire results in the core length reduction as high as 50% for $M = 1.79$ at NPR 5.66. It is found that the maximum core length reduction is around the correct expansion, namely around NPR 4.25 for the Mach 1.6 jet and NPR 5.66 for the Mach 1.79 jet. The control in the form of a cross wire is found to be an effective mixing promoter even in the presence of adverse pressure gradient. The combination of the shocks in the core and their interaction with the detached shock generated by the wire has a strong influence on the jet mixing, the overall jet noise, and its spectral content.

Even though the wire reduced the overall noise of the jet and the reduction is significant for many cases of the present study, it caused increase of screech amplitude for some cases. Jet noise reduction is found to be sensitive to the wire orientation.

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