AIAA JOURNAL
Vol. 31, No. 4, April 1993

Effect of Tabs on the Flow and Noise Field of an Axisymmetric Jet

M. Samimy*
Ohio State University, Columbus, Ohio 43210
K. B. M. Q. Zaman†
NASA Lewis Research Center, Cleveland, Ohio 44135
and
M. F. Reeder‡
Ohio State University, Columbus, Ohio 43210

The effect of vortex generators, in the form of small tabs projecting normally into the flow at the nozzle exit, on the characteristics of an axisymmetric jet is investigated experimentally over the jet Mach number range of 0.3–1.81. The tabs eliminate screech noise from supersonic jets and alter the shock structure drastically. They distort the jet cross section and increase the jet spread rate significantly. The distortion produced is essentially the same at subsonic and underexpanded supersonic conditions. Thus, the underlying mechanism must be independent of compressibility effects. A tab with a height as small as 2% of the jet diameter, but larger than the efflux boundary-layer thickness, is found to produce a significant effect. Flow visualization reveals that each tab introduces an "indentation" into the high speed side of the shear layer via the action of streamwise vortices. These vortices are inferred to be of the "trailing vortex" type rather than of the "necklace vortex" type. It is apparent that a substantial pressure differential must exist between the upstream and the downstream sides of the tab to effectively produce these trailing vortices. This explains why the tabs are ineffective in the overexpanded flow, as in that case an adverse pressure gradient exists near the nozzle exit which reduces the pressure differential produced by the tab.

I. Introduction

THE problem of supersonic flow mixing is pertinent in many technological applications and has been the subject of numerous studies for many years. Within the past few years, engineers and scientists have faced two major challenges in which supersonic flow mixing is important. The first is the challenge of reducing supersonic jet noise in the high speed civil transport (HSCT) aircraft, and the second is the challenge of designing an efficient propulsion system for a hypersonic airbreathing vehicle. The jet noise level in the HSCT aircraft must be reduced by approximately 20 effective perceived noise decibels (EPNdB) without paying a substantial performance penalty.[1] Enhancing mixing in a hypersonic airbreathing vehicle is desirable for obvious reasons but is a technological challenge because experiments have shown that the growth rate and the turbulence levels in a supersonic mixing layer are significantly reduced as the compressibility level is increased.[2,3] The underlying process in both cases involves supersonic mixing that must be well understood and controlled.

The present investigation concerns the axisymmetric jet which is a basic flow element in many applications. Over the years a variety of concepts have been proposed for mixing enhancement and jet noise reduction.[1,4–9] These concepts basically involve variations in the nozzle geometry and exit flow conditions. A relatively simple concept involves the use of small tabs or protrusions at the jet exit, which has shown very promising results. Ahuja and Brown conducted a series of experiments on the effect of tabs on the mixing of supersonic jets.[10] With support from NASA, the work continued for rectangular jets,[11] as well as for jet noise aspects.[9] In terms of jet plume reduction, i.e., a faster spreading of the axisymmetric jet, the effect of the tabs was so dramatic that the technique has been at times referred to as the "supermixer" (E. J. Rice, private communication). The effect of the tabs is the subject considered in the following.

Tabs have long been known to reduce screech noise from supersonic jets. Screech noise is generated when a closed-loop acoustic feedback is established between the noise generated by the interaction of the shock wave and the large scale flow structures and the developing region of the mixing layer.[12] Tanna used a convergent nozzle with what he called a "lip projection," which is the same device as the tab referred to in this paper, to eliminate the screech noise.[13] He suggested that flow symmetry at the nozzle exit was required to establish the screech feedback loop, which was disrupted by the tab resulting in the elimination of the screech.[14,15]

Bradbury and Khadem,[16] to our knowledge, were the first to conduct a study on the jet flowfield under the influence of tabs. They used rectangular tabs in a subsonic jet and observed a significant increase in the jet centerline velocity decay when two tabs were located 180 deg apart at the jet nozzle exit. They also observed two high velocity cores on either side of the jet centerline on a plane normal to the two tabs. For a subsonic jet, the effect of the tabs is much more pronounced than that produced by other mixing enhancement techniques such as periodic forcing. The effects of various combinations of large amplitude, multimode, and multifrequency forcing on the axisymmetric jet have been studied by, among others, Raman and Rice.[17] In terms of the jet centerline velocity decay, none of these methods produces as much effect as observed with the tabs.

In spite of the studies just mentioned, the details of the jet flowfield as affected by the tabs have largely remained un-

Received March 10, 1992; revision received Aug. 25, 1992; accepted for publication Aug. 28, 1992.

*Associate Professor, Department of Mechanical Engineering. Associate Member AIAA.

†Aerospace Engineer, Internal Fluid Mechanics Division. Member AIAA.

‡Graduate Student, Department of Mechanical Engineering. Student Member AIAA.

known. It is not an exaggeration to say that even the basic distortions in the mixing layer caused by the tabs remained completely unclear. Thus, it was felt that further experiments, in particular flow visualization experiments, were called for.

The objective of the present study was to obtain a clearer understanding of the flow mechanisms with regard to the influence of the tabs. The goal was first to carry out limited quantitative measurements on the acoustic field and the flowfield of a jet, as affected by the tabs, to compare with and confirm the results of previous studies. Flow visualization was then used to shed further light into the flow mechanisms. Even though the emphasis has been on supersonic jets, flow regimes all the way from subsonic to moderately underexpanded supersonic conditions have been covered in an effort to understand the role of compressibility in the effect of the tabs. Preliminary results of the experiment have been reported in two conference papers.[18,19]

II. Experimental Facility and Methods

A. Facility and Instrumentation

The experiments were carried out in a small supersonic jet facility at the NASA Lewis Research Center. Compressed air at approximately ambient temperature and 560 kPa (80 psig) was supplied to a cylindrical plenum chamber of about 10 cm diameter (Fig. 1). The flow exited through a 3.81-cm-diam tube which could be fitted with three different nozzles, the characteristics of which are listed in Table 1. Both nozzles 1 and 2 were designed using the method of characteristics and machined from Plexiglas®. The tabs, designed after the findings of Ref. 10, were machined from approximately 0.25-mm-thick stainless steel. For nozzles 1 and 2, each tab was about 0.55 mm wide and protruded about 1 mm into the jet. The corresponding blockage for each tab was about 1.5% of the nozzle exit area. The tabs were attached to the end of the nozzle using small machine screws (Fig. 1). Nozzle 3 was also machined from Plexiglas®; the inner surface was contoured, according to a fourth-order polynomial, ending with a short cylindrical section. Nozzle 3 could be fitted with tabs of different length and width, so that the effect of varying tab dimension relative to the boundary-layer thickness could be studied.

A standard pitot tube (0.76 mm o.d.) was used to measure the stagnation pressure at various locations in the jet. Two 0.635-cm Bruel and Kjaer microphones were used to measure the far-field sound pressure spectra. The microphones were located in the exit plane of the nozzle, 90-deg from each other, and $135D_t$ from the jet centerline. A Nicolet 660B analyzer was used for spectra measurement. Standard hot-wire anemometers, microphone amplifiers, and pressure transducers were used. All probe traverses and data acquisition were done remotely under computer control.

A single hot wire was used to obtain longitudinal mean velocity and rms velocity fluctuation for subsonic conditions.

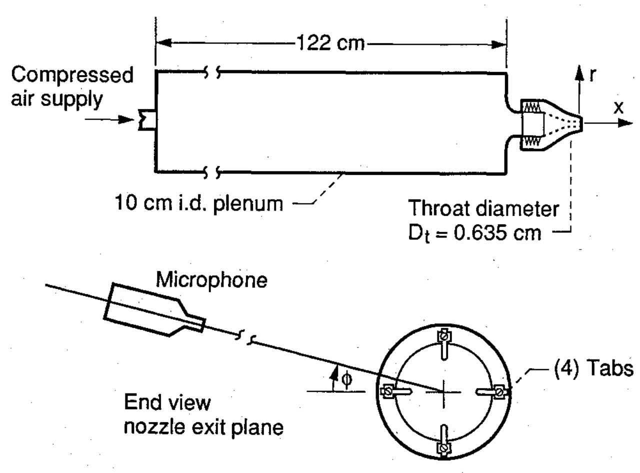

Fig. 1 Schematic of flow facility.

Table 1 Characteristics of the three nozzles used in the experiment

Nozzle number	Shape	Design Mach number	Throat diameter D_t, cm	Exit diameter, cm
1	Convergent/divergent	1.36	0.635	0.664
2	Convergent/divergent	1.80	0.635	0.762
3	Convergent	1.0	1.27	1.27

Table 2 Exit boundary-layer characteristics for nozzle 3

Mach number, M_j	Reynolds number, $Re_D \times 10^{-4}$	Momentum thickness, θ/D_t	Shape factor, H_{12}	Maximum turbulence, u'_{max}/U_e
0.3	8.75	0.0034	2.54	0.079
0.5	14.6	0.0026	2.52	0.076

At jet Mach numbers of 0.3 and 0.5, the mean velocity distributions at the exits of nozzles 1 and 3 were found to be flat, with a core turbulence intensity of about 0.3%. Limited surveys showed that this was also the case for nozzle 2. The boundary-layer characteristics, at the two Mach numbers, were measured in detail only for nozzle 3 and are listed in Table 2.

The two data points for the momentum thickness satisfy the relationship $\theta/D_t = CRe_D^{-1/2}$ with the constant C having a value of about unity. The boundary-layer state at these subsonic conditions was inferred to be "nominally laminar."[20] The boundary-layer characteristics for the supersonic regime remain unknown, as it is extremely difficult to resolve the compressible flow with sufficient spatial resolution with currently available measurement techniques. However, it was also likely to be nominally laminar as the nozzle was short and the contraction ratio was large. The flow visualization pictures also supported this notion as the mixing layer close to the nozzle exit exhibited little or no sign of turbulent diffusion.

B. Flow Visualization

The flow visualization experiments were carried out using Mie-scattering-based laser sheet illumination and schlieren photography. A 4-W argon-ion laser was used as the light source in both techniques. A gated double-intensified charge-coupled device camera was used for obtaining the flowfield images. These were long exposure images, compared to the time scales of the flow, and were recorded on a super-VHS videotape at the rate of 30 frames/s.

Appropriate lenses were used to form a laser sheet of approximately 0.5 mm thickness to view a desired cross section of the jet. The flowfield illumination in the supersonic jet was done without any artificial seeding. The air supplied to the jet was dry and at a temperature of approximately 300 K. When this air expanded to a Mach number of 1.5, for example, the static temperature dropped to about 207 K (−66°C). The jet issued into the laboratory and entrained ambient air into the mixing region, dropping its temperature and causing the moisture in the entrained air to condense. The condensed water particles, which mark the mixing region, were the light-scattering sources for the laser sheet visualization experiments. A maximum condensed water particle size of 300 nm has been calculated in a similar experiment.[21] Based on a simulation,[22] particles of this size should follow the vortical structures in the flow relatively well. Note that the particle response plays a much less critical role in the long time exposure results presented in this paper. Note also that even though natural condensation would occur for a Mach number as low as about 0.5, the density of scattering particles for the subsonic cases was insufficient to produce reasonable images.

III. Results

Unless otherwise stated, the data presented in the following will pertain to nozzle 1. The notations p_t and p_a are used to denote the stagnation pressure and the ambient pressure, respectively; p_{t0} denotes stagnation pressure in the plenum chamber. The static pressure is denoted by P. Figure 1 describes the coordinate system used, and other notations are defined as they appear. The design Mach number of 1.36 for nozzle 1 corresponds to a pressure ratio $p_a/p_{t0} = 0.3323$. For a given plenum pressure p_{t0}, the notation M_j is used to denote the Mach number had the flow expanded to ambient pressure. In the supersonic regime, pressure ratios $0.3323 < p_a/p_{t0} < 0.661$ produced overexpanded jets and $p_a/p_{t0} < 0.3323$ produced underexpanded jets. Thus, overexpanded conditions existed for $0.79 < M_j < 1.36$, and the flow was underexpanded for $M_j > 1.36$. In the range $0.661 < p_a/p_{t0} < 0.72$, a normal shock would be expected to occur in the diverging section of nozzle 1. With the design Mach number of 1.8 for nozzle 2, the flow was overexpanded for most of the supersonic range covered. The flow, of course, was always underexpanded in the supersonic regime for nozzle 3.

A. Screech Noise Data

The far-field noise was measured at two azimuthal angles (ϕ), see Fig. 1. Figure 2 shows the noise spectra for the 1- and 4-tab cases in comparison with the no-tab case for an underexpanded jet at $M_j = 1.63$. Data are shown for $\phi = 0$ and 90 deg for the 1-tab case (tab at $\phi = 0$ deg) and for $\phi = 0$ and 45 deg for the 4-tab case (tabs at $\phi = 0$, 90, 180, and 270 deg). Even though these measurements were done in a laboratory that was not acoustically lined, the overall features of the noise should be well represented by the spectra and the comparisons for the relative effect of the tabs should be valid.

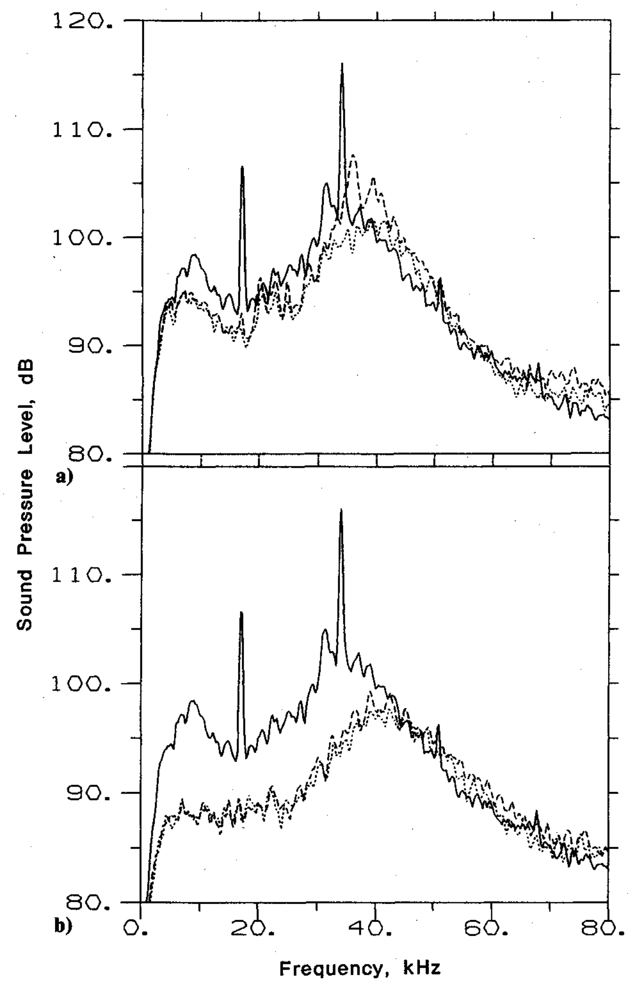

Fig. 2 Far-field sound pressure spectra for $M_j = 1.63$; solid line for no-tab case: a) 1-tab case -------, $\phi = 0$ deg, · · · · · · ·, $\phi = 90$ deg and b) 4-tab case -------, $\phi = 45$ deg, · · · · · · ·, $\phi = 90$ deg.

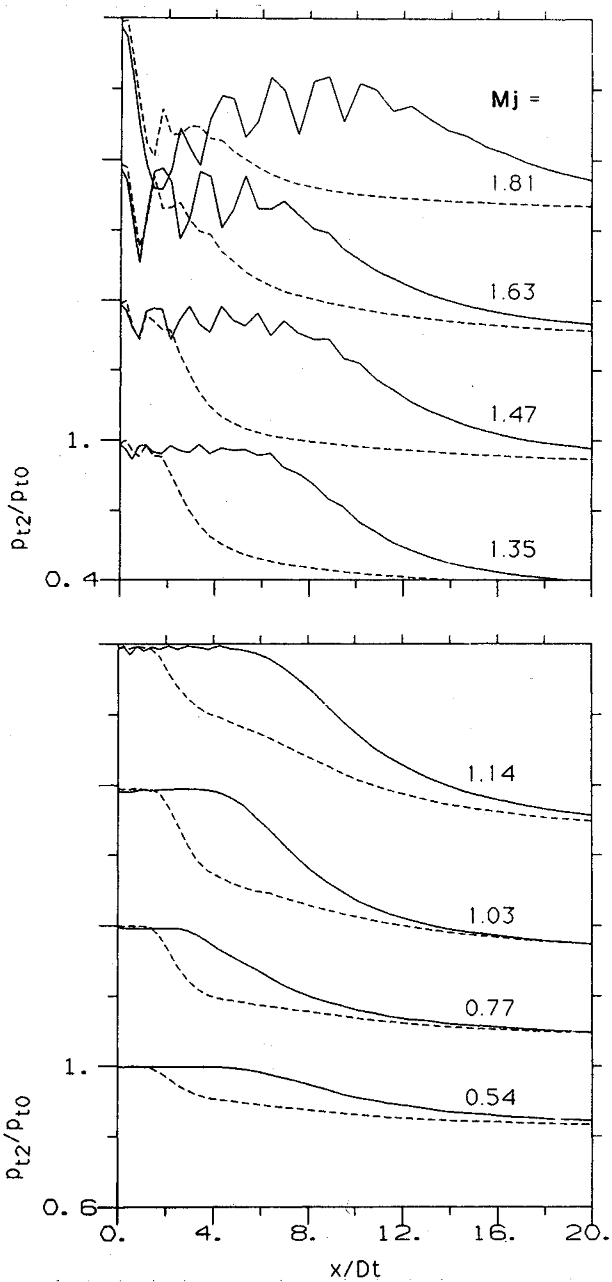

Fig. 3 Centerline variation of stagnation pressure, pairs of curves staggered by one major division: ——, no-tab case, -------, 2-tab case.

The tabs eliminated the screech components and the effect is clearly more prominent with four tabs. The drop in the total sound pressure level for the 4-tab case was about 6.5 dB. In Fig. 2, the smaller peak at about 17 kHz is the fundamental screech component as the corresponding Strouhal number, about 0.2 based on the jet exit velocity and diameter, agrees with previous observations.[4] Data that show the amplitude of the fundamental to be smaller than that of the harmonics, when measured at the nozzle exit plane, have also been presented by others.[13] Note that for the 4-tab case the broadband levels of the noise are also reduced over most of the frequency range of the spectrum.

B. Flowfield Data

The pitot probe was used to measure the stagnation pressure on the jet centerline at various operating conditions. Figure 3 shows the measured stagnation pressure for eight values of M_j as indicated. Each set of data has been normalized by the respective plenum pressure p_{t0}, which was 105, 128, 169, 194, 255, 304, 383, and 504 kPa for the eight cases.

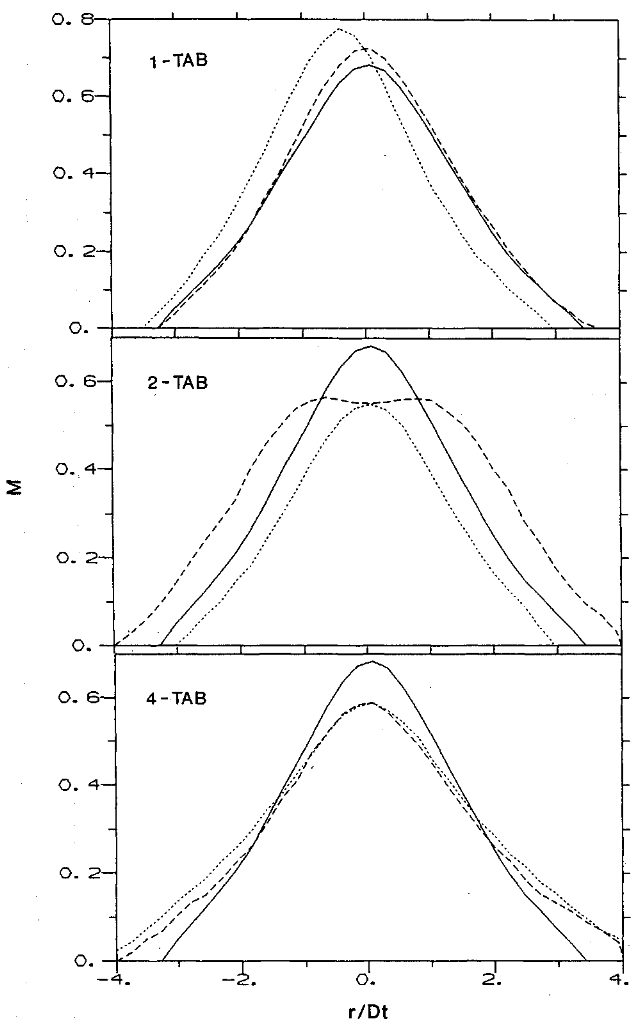

Fig. 4 Radial profiles of Mach number, $M_j = 1.63$, $x/D_t = 19$: ——, no-tab case, · · · · · · ·, $\phi = 0$ deg, - - - - - - -, $\phi = 90$ deg (45 deg for 4-tab case).

In the supersonic regions of the flow, the measured stagnation pressure p_{t2} corresponds to the stagnation pressure behind the standing bow shock in front of the pitot probe. The oscillations in the data in the upstream regions are due to the stationary shock structure in the jet. Let us emphasize that due to probe interference with the shock structure there is some measurement error and the amplitudes in the supersonic regions should be considered only qualitative. Nonetheless, the data are accurate enough to capture the overall features; for example, the number of shocks and their spacing are captured well as indicated by comparison with schlieren photographs discussed later. Of course, in the subsonic regimes of the flow there is no shock/probe interference and the data represent the local stagnation pressure; in this case $p_{t2} = p_t$. Figure 3 indicates a drastic increase in the jet centerline velocity decay when the tabs are used, at all M_j. In the supersonic regime, the shock structure is also affected rather drastically.

The variation of the static pressure (P_1) and the Mach number, corresponding to the data of Fig. 3, as well as hot-wire measurements for the subsonic jets have been reported in Refs. 18 and 19. These data, not shown here, lead to the same conclusion as reached from Fig. 3 with regard to the effect of the tabs. One finds that the effect is similar at subsonic and supersonic conditions. The length of the jet potential core is reduced drastically under the action of the tabs. For the subsonic case, the reduction is by more than a factor of 3. In the supersonic cases, the shock-expansion train is altered with a reduction in the shock spacing. Similar results have been reported in Refs. 10 and 16.

The faster decay of the centerline velocity is usually a reasonable measure of faster jet spread. However, as will be shown later by the flow visualization pictures, two tabs essentially bifurcate the jet and thus the centerline data in this case could overemphasize the effect of the tabs. Mass flux measurements, discussed in the following, are required to clearly assess the spreading rates.

Radial profiles of the axial Mach number were measured for $M_j = 1.63$. Pitot tube measurements were made in the range $14 < x/D_t < 30$ where the shock/expansion train had already decayed and the flow was subsonic. In the calculation of the Mach number, the static pressure was assumed to be the same as ambient which was a reasonable assumption for the x range covered.[19] Figure 4 shows the radial profiles of Mach number for 1-, 2-, and 4-tab cases in comparison with the corresponding no-tab case, at $x/D_t = 19$. The profiles are shown for two azimuthal locations relative to a tab. Data are presented for $\phi = 0$ and 90 deg (see Fig. 1) for the 1- and 2-tab cases, and for $\phi = 0$ and 45 deg for the 4-tab case. For the 1-tab case, as expected, there is an off-center shift for the $\phi = 0$-deg profile but not so for the $\phi = 90$-deg profile. For the 2-tab case, the dip at the center for $\phi = 90$ deg; together with a larger jet diameter, are signs of the bifurcation of the jet. For the 4-tab case, the jet has become wider in both planes. Note that the peaks in the profiles for the two ϕ locations coincide at $r = 0$. This indicates that the jet axis and the probe traversing axis were aligned properly in the measurements.

Several radial profiles, similar to the ones shown in Fig. 4, were integrated to obtain the mass flux at each x station.[19] Figure 5 shows the mass flux variation with x/D_t for the 2- and 4-tab cases compared to the no-tab case. The flux is normalized by the corresponding value at the nozzle exit which is the same for all the cases. Since these data are for a convergent/divergent nozzle (1) and since the area blockage due to the tabs is such that the exit area is always greater than the throat area, the mass flow through the nozzle should remain unchanged with and without the tabs for a given p_{t0}. For comparison, data for a subsonic case at $M_j = 0.5$ is also included.[23] It can be clearly seen that compared to a subsonic jet, mixing in the supersonic jet is less efficient resulting in a slower entrainment and spread rate. Tabs increase the spread rate. Data for the 4-tab case exhibit much higher flux at $x/D_t = 14$ than for the other cases. However, the jet with the two tabs eventually entrains more. This is commensurate with the flow visualization pictures presented in the following,

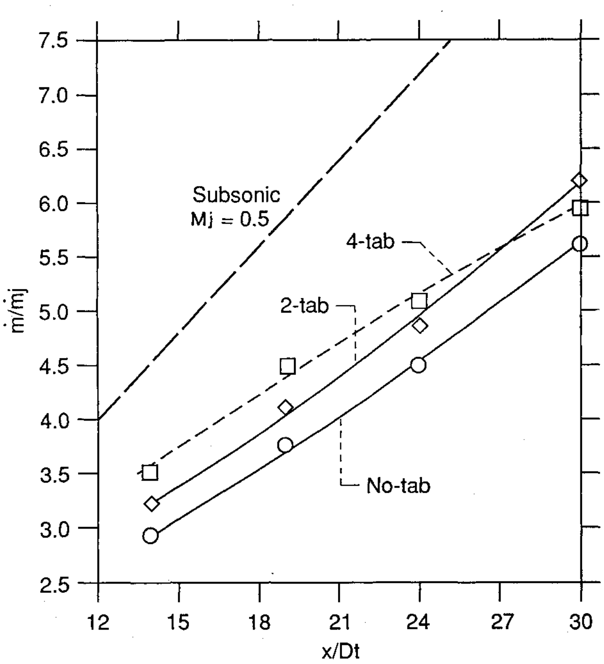

Fig. 5 Mass flux vs x/D_t, $M_j = 1.63$.

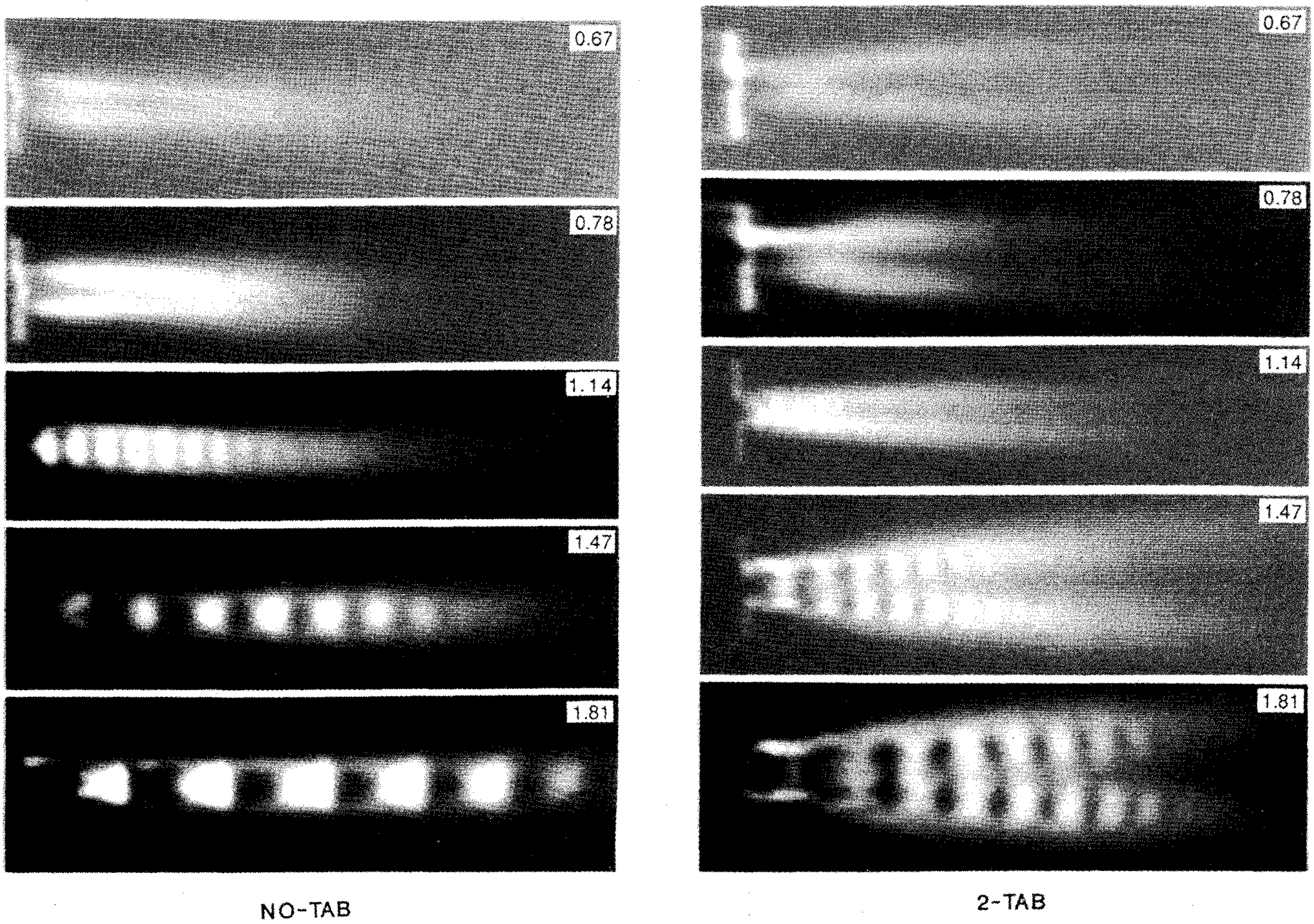

Fig. 6 Schlieren photographs at indicated M_j.

which show that the distortion produced by two tabs persists farther downstream. The data of Fig. 5 confirm that the tabs indeed enhance the jet mixing substantially.

C. Flow Visualization

Figure 6 shows schlieren photographs of the flowfields at five different M_j as indicated. These pictures were obtained using a vertical knife edge and thus provide a visualization of the density gradients in the streamwise direction. The flow is from left to right and covers the x/D_t range of about 0–13. The shock spacing is observed to increase with increasing M_j in the supersonic regime for the no-tab case. The shock spacings, for example at $M_j = 1.81$, are found to be the same as those observed in the p_{t2} measurements (Fig. 3). The pictures on the right column show the flowfield under the influence of two tabs in a plane perpendicular to the line joining the two tabs. It is clear that the jet bifurcates in that plane, at all M_j. In the supersonic regime, the shock spacings have also been significantly reduced. Note that the effect for the overexpanded case at $M_j = 1.14$ appears less than that at other Mach numbers. This is a point which will be addressed further in the following.

The bifurcation of the jet observed in Fig. 6 is in agreement with the data of Refs. 10 and 16, and with the flowfield data shown in Fig. 4. The overall structure of the jet is similar to that achieved by using a dual mode helical acoustic excitation,[24] or by using simple lateral vibration of the jet nozzle.[25]

Figure 7 shows the laser sheet illuminated jet cross section at four different axial locations at $M_j = 1.63$. The pictures on the left column are for the no-tab case. The bright and initially narrow ring shows the mixing layer that grows with the streamwise distance and eventually covers the entire cross section of the jet. The departure from axisymmetry in these pictures is due mainly to the camera angle. Corresponding pictures for the flowfield with one, two, and four tabs are shown in the columns on the right as indicated. The presence of a tab significantly distorts the mixing layer. The effect is to leave an "indentation" or a bulge into the high speed side of the mixing layer. Clearly, this indentation grows and persists far downstream. Using laser sheet illumination, Clemens and Mungal recently studied distortions in a plane, compressible mixing layer produced by shocks originating from the wind-tunnel side wall.[26] The distortions reported in that work had curious similarities with the present case, although it appeared that most of the "bulging" occurred into the lower speed side of their mixing layer. Possible vorticity dynamics producing the distortions in the tab case are discussed in Sec. IV.

In Fig. 7, whereas the jet has regained the axisymmetric shape for the 1- and 4-tab cases by $16D_t$, it has remained quite elongated in the plane perpendicular to the tabs for the 2-tab case. In fact, visualization at $30D_t$ for the 2-tab case still shows a very elongated cross section.[19] The initial evolution of the mixing layer under the action of two tabs is shown in Fig. 8. At the farthest upstream location, evidence of azimuthal waviness in the mixing layer in the regions undisturbed by the tabs can be observed on close inspection. Pictures clearly showing these waves have been presented in Ref. 18. It is clear that the distortions produced by the two tabs grow with downstream distance and result in essentially a bifurcation of the jet by about $4D_t$.

D. Overexpanded Flow from Nozzle 2

Figure 9 shows data from nozzle 2 having a design Mach number of 1.8. The effect of two tabs is compared for $M_j = 1.45$ and 1.81. The pictures are for $x/D_t = 2$ and it is apparent that very little distortion is introduced by the tabs in the overexpanded case at the lower M_j. It is as though the flow were almost oblivious to the presence of the tabs. For the same

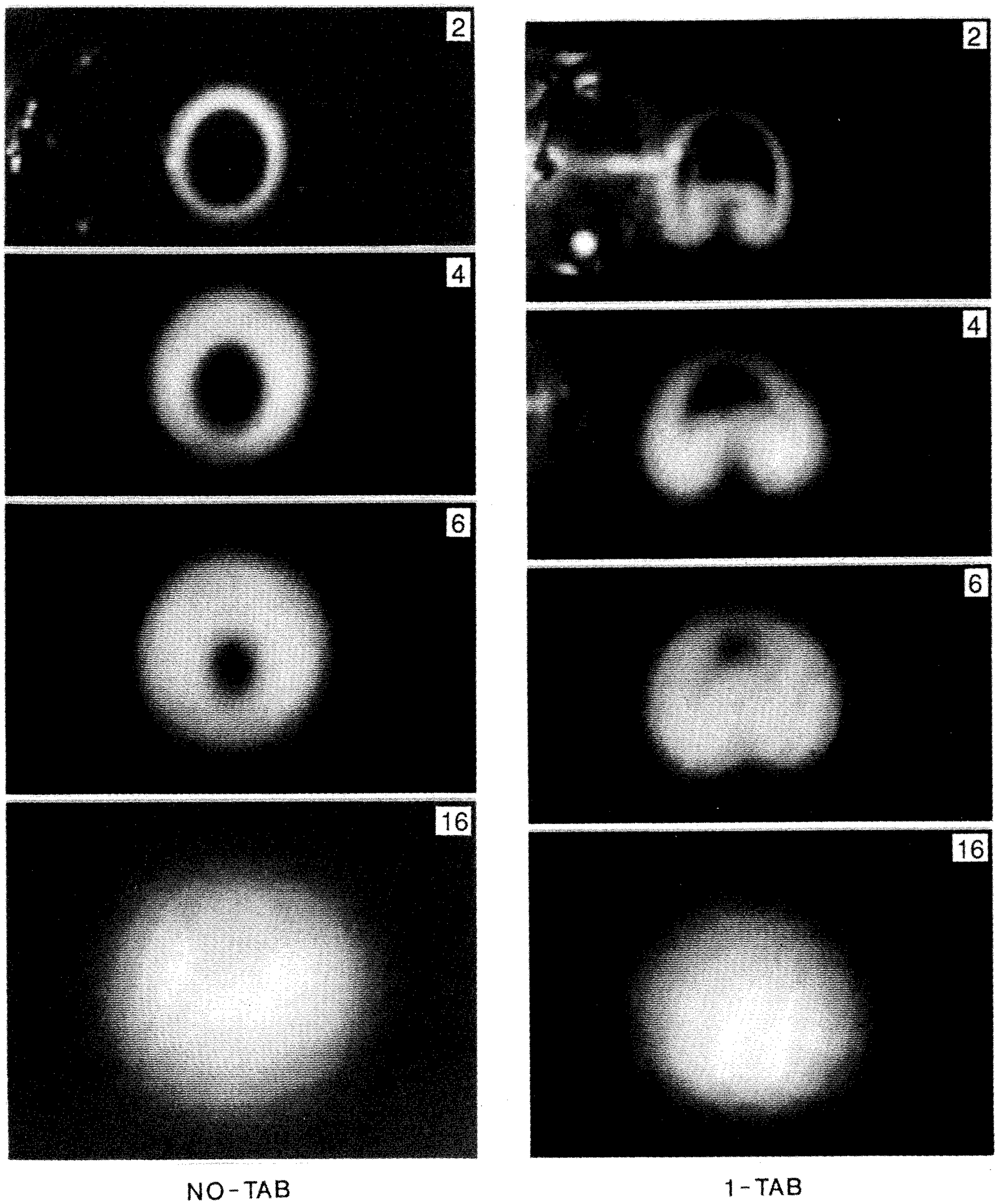

Fig. 7 Laser sheet illuminated cross section of jet at indicated x/D_t, $M_j = 1.63$.

M_j (= 1.45), flow visualization of the jet cross section farther downstream showed that the wake from the tab, initially seen as a dark band in the bright ring of the mixing layer, practically vanished by about $4D_t$.

At the higher M_j, however, where the flow has just become fully expanded, a pronounced effect is achieved with the same tab configuration. Pictures at farther downstream locations for the $M_j = 1.81$ case (not shown) exhibit an essentially similar bifurcation as observed with nozzle 1. The p_{t2} data for this nozzle, as in Fig. 3, confirmed these trends. The tabs were not effective in the overexpanded condition, but were quite effective both when the underexpanded condition was approached and in the subsonic regime. A possible reason for this behavior is addressed in Sec. IV.

E. Flow Visualization for Nozzle 3

Whereas nozzles 1 and 2 were of the convergent/divergent type, nozzle 3 was a convergent type similar to the ones used in a vast majority of previous studies on subsonic jets.[16,20] The geometry and the boundary-layer characteristics of this nozzle were discussed in Sec. II. Note that while tabs with pointed ends, in accordance with the design of Ref. 10, were used with nozzles 1 and 2, all the data shown in the following for nozzle 3 were obtained with tabs having square ends. It was determined that the shape of the end of the tab had an insignificant effect on the distortion produced as long as the area blockage to the flow was kept constant. This was inferred from visualization of subsonic as well as supersonic jets from nozzle 3 while using tabs of a constant width but varying the shape of the end from pointed to rounded to square.

Although the laser sheet illumination technique worked fine for the natural supersonic flow, visualization for the subsonic flow required appropriate seeding. Figure 10a shows laser sheet illuminated cross sections of the jet seeded with smoke. Cigar smoke was forced into the plenum chamber so that the core of the jet was illuminated. The pictures are for $M_j = 0.3$ at $x/D_t = 2$. The picture on the left side of Fig. 10a is for two tabs of dimensions essentially similar to those used for all previous data (height $h/D_t = 0.17$ and width $w/D_t = 0.08$). Keeping in mind that the core of the jet is illuminated here, whereas in the supersonic case the mixing layer is illuminated, the distortion produced by the tabs can be seen to be quite similar in either flow regime. The picture on the right side of Fig. 10a is for two tabs which protruded only 2% of the jet diameter. The tabs here extended just about the thickness of the boundary layer (the 95% velocity point was $0.023D_t$ from the nozzle wall). Yet, this already produced a noticeable indentation into the jet core. The distortion disappeared for smaller tab heights at this M_j.

Figure 10b shows data taken with the same tab dimensions as in Fig. 10a but at $M_j = 1.63$. The picture on the left side, for tab dimensions similar to those used for nozzles 1 and 2,

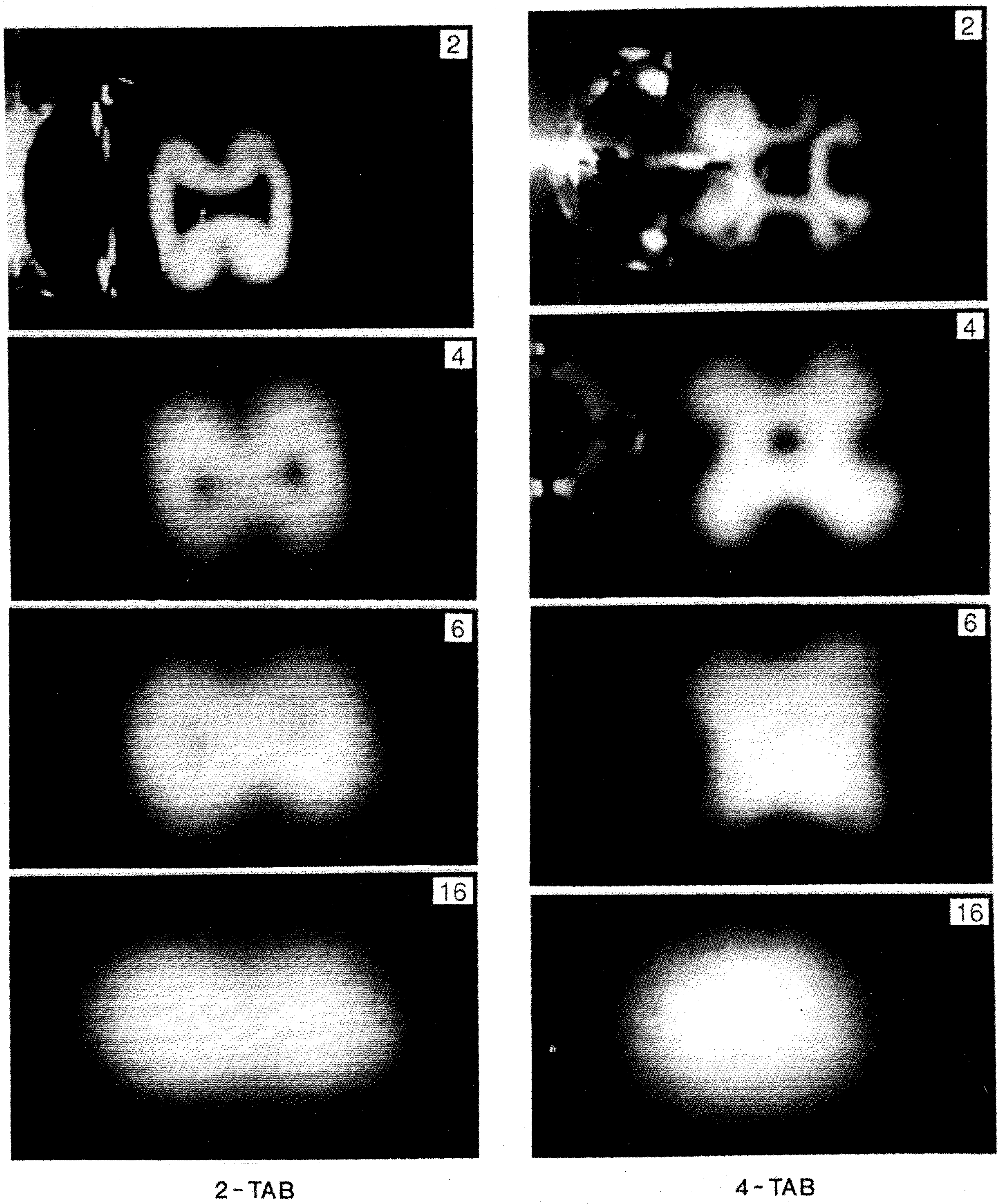

Fig. 7 (Cont.) Laser sheet illuminated cross section of jet at indicated x/D_t, $M_j = 1.63$.

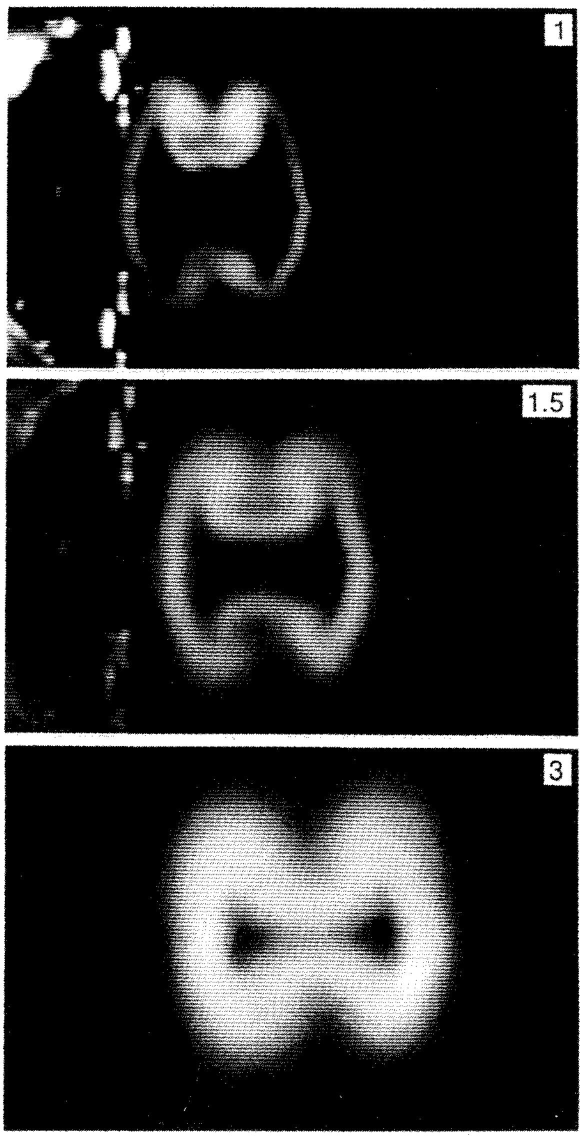

Fig. 8 Effect of two tabs at indicated x/D_t, $M_j = 1.63$.

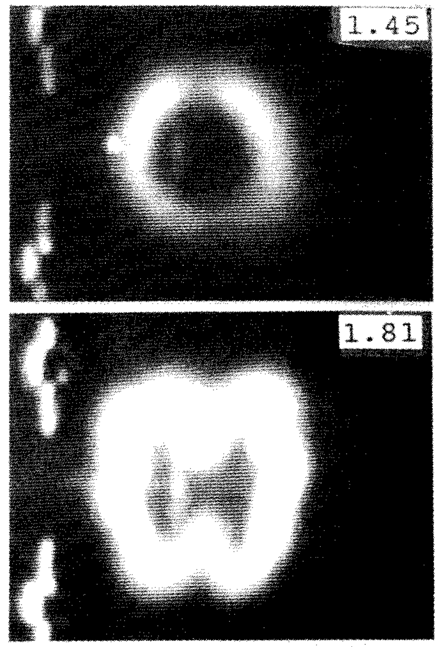

Fig. 9 Effect of two tabs at indicated M_j, $x/D_t = 2$: nozzle 2.

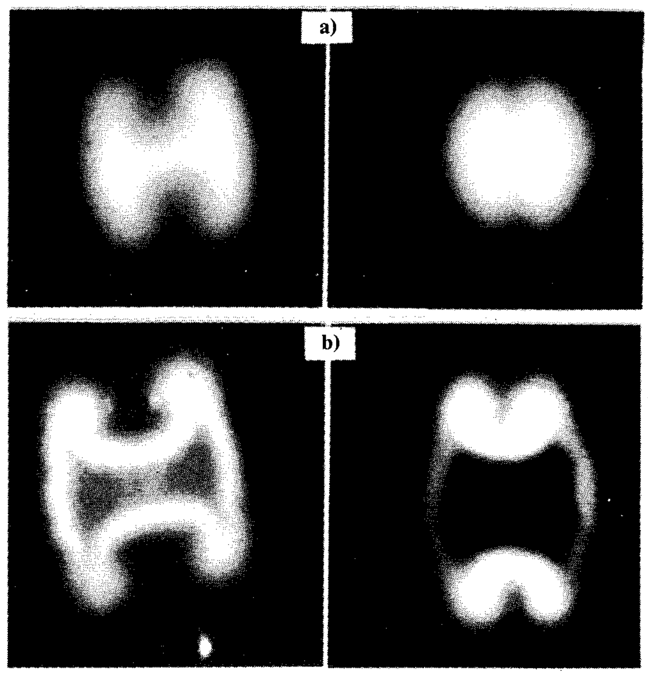

Fig. 10 Effect of two tabs at $x/D_t = 2$; a) $M_j = 0.3$, b) 1.63: tab height $h/D_t = 0.17$ for pictures on left side, 0.02 for pictures on right side, tab width $w/D_t = 0.08$: nozzle 3.

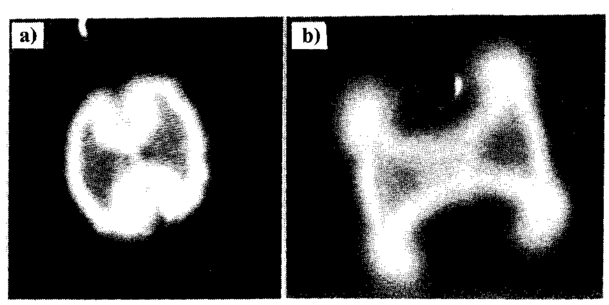

Fig. 11 Effect of two tabs at $M_j = 1.63$, $x/D_t = 2$: w/D_t and h/D_t are a) 0.04 and 0.5 (tab spans nozzle exit); b) 0.20 and 0.17: nozzle 3.

shows essentially the same distortion (compare with Figs. 7 and 9). The picture on the right side is for $h/D_t = 0.02$, and the distortion is already very pronounced. In fact, at $M_j = 1.63$ a tab height of only $0.01D_t$ produced noticeable distortion. Note that at the supersonic condition the boundary-layer thickness remains unknown. It is possible that at $M_j = 1.63$ the boundary layer is still nominally laminar and thinner than that at $M_j = 0.3$. Thus, these data make it evident that a tab with height greater than the boundary-layer thickness is required to produce a significant distortion of the jet. On the other hand, a tab with height substantially smaller than the boundary-layer thickness is not effective.

Flow visualization was conducted for different combinations of tab height and width. Sample data are shown in Fig. 11. It was found that with approximately the same flow blockage, the distortion was greater when the tab width was larger. Variation of length, for a given width, did not seem to make much difference as long as the length was larger than the boundary-layer thickness. The picture in Fig. 11a was taken with a tab that spanned the entire jet exit. Yet it can be seen that the distortion produced is similar to that produced by tabs of much smaller length. On the other hand, when the tab width was large, gross distortions occurred as illustrated by the picture in Fig. 11b. As expected, however, a wide tab spanning the nozzle exit also produced gross distortion and a bifurcation of the jet.

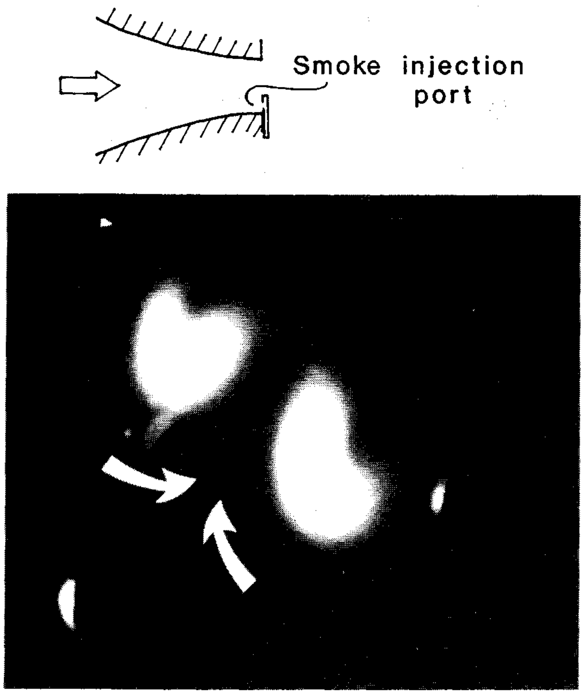

Fig. 12 Jet cross section at $x/D_t = 1$, $M_j = 0.3$: tab is a flattened tube with $w/D_t \approx 0.15$ and $h/D_t \approx 0.2$.

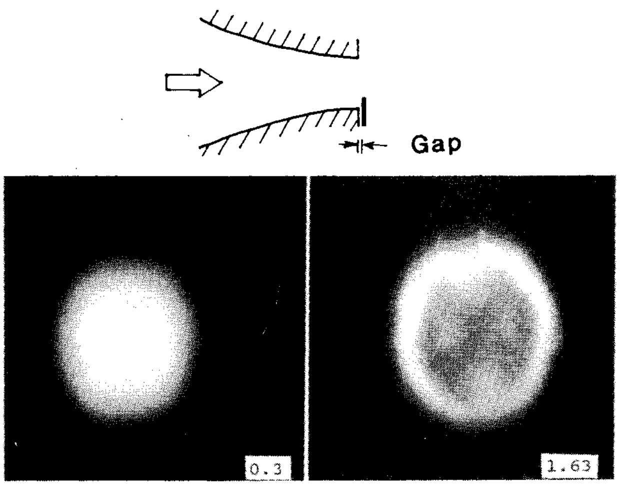

Fig. 13 Effect of two tabs at $x/D_t = 2$ for indicated M_j, nozzle 3; $w/D_t = 0.08$, $h/D_t = 0.17$, and gap = $0.08D_t$.

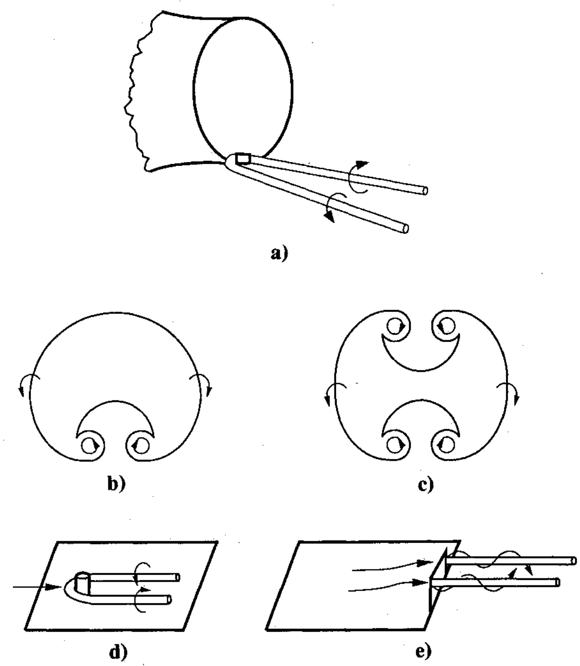

Fig. 14 Likely vorticity field: a) streamwise vortex pair from tab; b) and c) vorticity distribution for 1-tab and 2-tab cases, respectively; d) necklace vortex; e) trailing vortex.

It should be apparent, in view of the flow visualization results presented so far, that the distortion introduced by a tab is most likely due to the action of a pair of streamwise vortices. The cross sections of the two vortices are quite evident in the pictures close to the nozzle exit (Fig. 8). An effort was made to view these vortices more clearly. However, since these vortices were embedded in the sheet of azimuthal vorticity emanating from the nozzle, it was difficult to identify them. Figure 12 shows the laser sheet illuminated cross section of a subsonic jet seeded with smoke from the tab itself. The tab consisted of a flattened tube with a hole on the upstream face through which smoke was injected. The observed cross section of the jet is commensurate with the distortions shown before.

Close observation of the illuminated flowfield, during the experiment, indicated a spiralling motion into the cores of the two comma-shaped structures (Fig. 12). The spiralling motion was apparent from the path of stray particles being entrained into the flow from outside. The motion of the outside particles was more clearly discernible in both subsonic and supersonic jets when the ambient air was seeded with smoke. Unfortunately, this motion could not be captured satisfactorily in the photographs but the observed path is shown qualitatively by the arrows in the picture. These observations quite clearly indicated that a pair of streamwise vortices originated from each tab.

Figure 13 presents pictures of the jet cross section, at the indicated M_j, obtained with a gap deliberately left between the tabs and the nozzle end. It was serendipitously observed that even a small piece of masking tape left between the tab and the nozzle end would diminish the effect of the tab considerably. The flowfield was studied with shims of varying thickness wedged between the tab and the nozzle end. The effect of the tab diminished progressively with increasing gap and almost disappeared, as shown in Fig. 13, when the gap size approximately equalled the tab width for the case investigated. The dramatic effect of the gap can be appreciated by comparing these pictures with the corresponding pictures for no gap shown on the left side of Fig. 10. Once again the effect is the same at subsonic and supersonic conditions. The significance of this is discussed in the next section.

IV. Discussion and Concluding Remarks

An inference that can be made from the present and previous experiments by others is the fact that compressibility may have little to do with the effect of the tabs. Essentially the same effect is observed all the way from incompressible to moderately underexpanded supersonic conditions. The tabs, however, weaken the shock structure drastically in the supersonic regime which is accompanied by an elimination of the screech noise. But the basic effect must originate from changes in the vorticity distribution caused by the tabs.

Perhaps the most illuminating results in the present study are the laser sheet visualization pictures. The enormous distortion introduced by the tabs on the jet cross section is clearly unravelled for the first time by these pictures. It should be apparent that the indentation in the mixing layer produced by a tab is not simply a wake from the tab. The flowfield, say at $4D_t$ in Fig. 7, is about 50 tab widths downstream, yet the distortion appears to be growing and affecting the entire jet cross section. Recall that when the tabs were ineffective (Fig. 9), the wake practically vanished by about $x/D_t = 4$. Based on the flow visualization pictures, the following inference can be made in regard to the vorticity dynamics of this flow.

Referring back to the discussion of Fig. 12, it is apparent that a pair of counter-rotating streamwise vortices are shed from each tab as sketched in Fig. 14a. These should be stationary vortices and not like hairpin vortices which are shed periodically.[27] This is evident because the photographs shown are images with a long time exposure where any periodic structure would be averaged out. The streamwise vortices interact and evolve with the azimuthal sheet of vorticity issuing from the nozzle. The resultant vorticity distribution on a cross-sectional plane can be expected to be as in Figs. 14b and 14c for one and two tabs, respectively.

The streamwise vortices should produce the indentations in the mixing layer as observed and as previously shown, for example, in Fig. 8. Farther downstream, the bifurcation of the jet, in the 2-tab case, may take place in a similar manner as suggested by Hussain and Husain[28] through what they termed the "cut-and-connect" process. In fact, the latter investigators observed a very similar sequence of deformations leading to a bifurcation of a jet originating from an elliptic nozzle (see their Fig. 17).

The question then arises as to the origin of the counter-rotating vortex pair sketched in Fig. 14a. Such a stationary vortex pair, formed over protuberances in boundary-layer flows, has been variously called a horseshoe vortex or a necklace vortex.[27,29] However, a little scrutiny should indicate that the vortex sketched in Fig. 14a should not be the same. A necklace vortex is sketched in Fig. 14d, following Ref. 29. The sense of rotation in this case is contrary to what is sketched in Fig. 14a. Lin et al.[30] recently investigated the flow over various vortex generating devices while studying their effect on boundary-layer separation. It is interesting to note that the pairs of streamwise vortices from several of these devices reported by them are also of the same sign as found with the tabs in the present experiment. In yet another experiment with tab-like protrusions in a laminar boundary layer, streamwise vortices were also observed having the same sign as in the present experiment (C. R. Smith, private communication).

It is more likely that the tab acts as a "winglet" and produces a pair of trailing vortices which have the same sense of rotation as the trailing vortices originating from the sides of a wing (see e.g., p. 51, Ref. 31). This is sketched in Fig. 14e. It should be recognized that for the trailing vortices to form, the wing should be at an angle of attack producing a resultant lift. The tabs, however, are projected normal into the flow. It is plausible that the boundary layer immediately upstream of the tab is lifted away from the nozzle wall, over a small recirculating zone, so that the streamlines are at an angle of attack with respect to the tab, producing a resultant force acting radially and away from the jet axis. In such a case, the pair of counter-rotating vortices as sketched in Fig. 14e would be quite realistic.

One may conjecture that the mechanism of streamwise vortex generation from the "ramps" of Ref. 16, as well as from the "wishbones" or "doublets" of Ref. 30 is essentially the same as that described. It seems that a triangular-shaped tab with the base on the nozzle wall may act similarly.[32] However, if that were placed like a delta wing, with the apex leaning upstream, it seems that vortices of sign opposite to what is sketched in Fig. 14e will be produced. If it is possible to produce such a vortex pair, then the indentation would be outward into the low-speed side of the mixing layer. Some preliminary experiments have indicated that this is indeed the case.

The suggested streamwise vorticity generation, therefore, is a pressure driven and inviscid phenomenon and not due to the wrapping of the viscous boundary layer around the tab. For the tab to work, a favorable pressure differential must exist across the tab. It was observed that in the overexpanded cases the effect of the tab was either reduced or absent. In the overexpanded case, an adverse pressure jump exists at the nozzle exit where the tab is located. The superimposition of this adverse pressure gradient dilutes the pressure differential created by the tab. In severe cases of overexpansion this could even result in a net adverse pressure gradient and boundary-layer separation in the vicinity of the tab. It is, therefore, not surprising that the tab is either less effective or ineffective in the overexpanded case. This also explains why the tab became ineffective when a gap was left between it and the nozzle end. In this case the upstream region of the tab communicated with the ambient, effectively reducing the pressure differential across the tab.

It should be emphasized that most of the inferences drawn here are based on the flow visualization study without quantitative confirmation. A systematic study will be required to address the role of pressure gradient on the effectiveness of the tab. Quantitative measurements will be required to determine the dependence of the streamwise vorticity distribution on the tab dimensions. It is possible that the generation of the streamwise vorticity may be independent of the boundary-layer thickness, but the relative magnitude of the streamwise vorticity, with respect to the azimuthal vorticity in the boundary layer, may determine the subsequent evolution of the distortion. Quantitative studies will be required to resolve these issues before the method is understood completely and can be applied intelligently in practice.

Acknowledgments

M. F. Reeder would like to thank the Ohio Aerospace Institute for a graduate student fellowship. Helpful discussions with C. R. Smith of Lehigh University, and T. D. Norum, J. M. Seiner, and P. R. Bandyopadhyay of NASA Langley are acknowledged. Thanks are due to J. Panda for helping with the subsonic flow visualization experiments, to J. E. Bridges for reviewing the manuscript, and to J. M. Abbott and E. J. Rice, for help in different forms throughout the course of this investigation.

References

[1]Seiner, J. M., and Krejsa, E. A., "Supersonic Jet Noise and High Speed Civil Transport," AIAA Paper 89-2358, July 1989.

[2]Papamoschou, D., and Roshko, A., "The Compressible Turbulent Shear Layer: an Experimental Study," *Journal of Fluid Mechanics,* Vol. 197, Dec. 1988, pp. 453–477.

[3]Elliott, G. S., and Samimy, M., "Compressibility Effects in Free Shear Layers," *Physics of Fluids,* Vol. 2, No. 7, 1990, pp. 1231–1240.

[4]Norum, T. D., "Screech Suppression in Supersonic Jets," *AIAA Journal,* Vol. 21, No. 2, 1983, pp. 235–240.

[5]Wlezian, R. W., and Kibens, V., "Influence of Nozzle Asymmetry on Supersonic Jets," *AIAA Journal,* Vol. 26, No. 1, 1988, pp. 27–33.

[6]Naughton, J., Cattafesta, L., and Settles, G., "An Experimental Study of the Effect of Streamwise Vorticity on Supersonic Mixing Enhancement," AIAA Paper 89-2456, July 1989.

[7]Gutmark, E., Schadow, K. C., and Bicker, C. J., "Near Acoustic Field and Shock Structure of Rectangular Supersonic Jets," *AIAA Journal,* Vol. 28, No. 7, 1990, pp. 1163–1170.

[8]Krothapalli, A., McDaniel, J., and Baganoff, D., "Effect of Slotting on the Noise of an Axisymmetric Supersonic Jet," *AIAA Journal,* Vol. 28, No. 12, 1990, pp. 2136–2138.

[9]Ahuja, K. K., Manes, J. P., Massey, K. C., and Calloway, A. B., "An Evaluation of Various Concepts of Reducing Supersonic Jet Noise," AIAA Paper 90-3982, Oct. 1990.

[10]Ahuja, K. K., and Brown, W. H., "Shear Flow Control by Mechanical Tabs," AIAA Paper 89-0994, March 1989.

[11]Brown, W. H., and Ahuja, K. K., "Enhancement of Mixing in a Rectangular Jet by Mechanical Tabs," Georgia Tech Research Inst., Atlanta, GA, NASA CR 185207, April 1990.

[12]Powell, A., "On the Mechanism of Choked Jet Noise," *Proceedings of the Physical Society, London, Sec. B,* Vol. 66, 1953, pp. 1039–1056.

[13]Tanna, H. K., "An Experimental Study of Jet Noise, Part II Shock Associated Noise," *Journal of Sound and Vibration,* Vol. 50, No. 3, 1977, pp. 429–444.

[14]Norum, T. D., and Seiner, J. M., "Location and Propagation of Shock Associated Noise from Supersonic Jets," AIAA Paper 80-0983, June 1980.

[15]Nagel, R. T., and Papathanasiou, A. G., "An Experimental Study of Supersonic Jet Shock Associated Noise," AIAA Paper 83-0708, April 1983.

[16]Bradbury, L. J. S., and Khadem, A. H., "The Distortion of a Jet by Tabs," *Journal of Fluid Mechanics,* Vol. 70, No. 4, 1975, pp. 801–813.

[17]Raman, G., and Rice, E. J., "Subharmonic and Fundamental High Amplitude Excitation of an Axisymmetric Jet," AIAA Paper 89-0993, April 1989.

[18]Samimy, M., Zaman, K. B. M. Q., and Reeder, M. F., "Supersonic Jet Mixing Enhancement by Vortex Generators," AIAA Paper 91-2263, June 1991.

[19]Zaman, K. B. M. Q., Samimy, M., and Reeder, M. F., "Effect of Tabs on the Evolution of an Axisymmetric Jet," *Proceedings of the 8th Turbulence Shear Flow Conference,* Univ. of Munich, Germany, Sept. 1991, Article 25-5.

[20]Zaman, K. B. M. Q., "Far-field Noise of a Subsonic Jet under Controlled Excitation," *Journal of Fluid Mechanics,* Vol. 152, 1985, pp. 83-111.

[21]Fourguette, D. C., Mungal, M. G., and Dibble, R. W., "Time Evolution of the Shear Layer of a Supersonic Axisymmetric Jet at Matched Conditions," *AIAA Journal,* Vol. 29, No. 7, 1991, pp. 1123-1130.

[22]Samimy, M., and Lele, S. K., "Motion of Particles with Inertia in a Compressible Free Shear Layer," *Physics of Fluids,* Vol. 3, Aug. 1991, pp. 1915-1923.

[23]Zaman, K. B. M. Q., "Flow Field and Near and Far Sound Field of a Subsonic Jet," *Journal of Sound and Vibration,* Vol. 106, No. 1, 1986, pp. 1-16.

[24]Parekh, D. E., Reynolds, W. C., and Mungal, M. G., "Bifurcation of Round Air Jets by Dual-Mode Acoustic Excitation," AIAA Paper 87-0164, Jan. 1987.

[25]Andrade, E. N., and Da, C., "The Sensitive Flame," *Proceedings of the Physical Society, London,* Vol. 53, July 1941, pp. 329-355.

[26]Clemens, N. T., and Mungal, M. G., "Effects of Side-Wall Disturbances on the Supersonic Mixing Layer," *Journal of Propulsion and Power,* Vol. 8, No. 1, 1992, pp. 249-251.

[27]Acarlar, M. S., and Smith, C. R., "A Study on Hairpin Vortices in a Laminar Boundary Layer, Part 1. Hairpin Vortices Generated by a Hemisphere Protruberance," *Journal of Fluid Mechanics,* Vol. 175, 1987, pp. 1-41.

[28]Hussain, F., and Husain, H. S., "Elliptic Jets, Part 1. Characteristics of Unexcited and Excited Jets," *Journal of Fluid Mechanics,* Vol. 208, 1989, pp. 257-320.

[29]Bandyopadhyay, P. R., and Watson, R. D., "Structure of Rough-Wall Turbulent Boundary Layer," *Physics of Fluids,* Vol. 31, July 1988, pp. 1877-1883.

[30]Lin, J. C., Selby, G. V., and Howard, F. G., "Exploratory Study of Vortex-Generating Devices for Turbulent Flow Separation Control," AIAA Paper 91-0042, Jan. 1991.

[31]Van Dyke, M., *An Album of Fluid Motion,* Parabolic Press, Stanford, CA, 1982.

[32]Rogers, C. B., and Parekh, D. E., "Noise Reduction and Mixing Enhancement by Using Streamwise Vortices in a Compressible Air Jet," *Bulletin, 43rd Annual Meeting, American Physical Society (Division of Fluid Dynamics),* Nov. 1990.