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Experimental Observations of Instability Modes in a Rectangular Jet

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The instability modes of a jet issuing from a rectangular nozzle of aspect ratio 4 have been studied experimentally at exit Mach numbers ranging from 0.03 to 1.5. Depending on the exit Mach number, several distinct characteristics are identified according to the arrangement of the flow structure with respect to the jet centerline. In the very low velocity range, $U \leq 20$ m/s, a symmetric mode prevails. An antisymmetric mode dominates at all other Mach numbers, except in the range $0.6 \leq M \leq 0.85$, where both symmetric and antisymmetric modes exist and there is a continuous switching between them. In the supersonic Mach number range, there is a continuation of the antisymmetric mode extending from its subsonic counterpart. Finally, screech tones develop at higher Mach numbers, $M \geq 1.1$, which are accompanied by the emergence of a strong flapping motion at the end of the potential core and a significant increase of the jet spreading angle. The variation of the screech tone Strouhal number is found to be independent of the aspect ratio of the nozzle.

Introduction

BECAUSE of the recent emphasis on thrust vectoring for reduction of landing and takeoff distances and improved maneuvering capability of high performance aircraft, much attention has been focused on supersonic jet flows issuing from rectangular nozzles. When an imperfectly expanded jet exceeds the sonic speed at exit, the near-field noise spectrum is dominated by discrete tones, commonly known as "screech tones."[1] Under certain conditions, they help to induce large-scale vortical motions in the jet and accelerate the spreading of the jet.[2,3] The jet screech tone phenomenon was described by Powell[1] as arising through a feedback mechanism. One of the key elements of this mechanism is the coupling between the shear layer instabilities and the acoustic field adjacent to the jet. The frequency of the screech tone is observed to match closely with that of the most amplified instability wave of the jet.[4] It has been suggested that these instability waves play an important role in the noise generation of supersonic jets.[5]

For subsonic and supersonic jets, ample evidence is present in the literature to indicate the presence of large vortical structures in the mixing layers of these jets. Most previous investigations related to this subject were carried out on either two-dimensional or axisymmetric jets. An in-depth review of large structures in low Mach number jets can be found in the literature.[6,7] The instability characteristics of a supersonic axisymmetric jet were studied by McLaughlin et al.[8] and Seiner et al.[9] Their data revealed the existence of large-scale structures in the jet, both at low and moderate Reynolds numbers. It was found that the unsteady flow characteristics of the jet were dominated by a band of large-scale instability waves and that the acoustic field associated with these waves dominated the total noise field of the jet. Their results also showed that the acoustic near field contained remarkable similarities between low and high Reynolds number supersonic jets.

The acoustic near field of a rectangular supersonic jet has recently been investigated by Gutmark et al.[3] At low Mach numbers, they observed an asymmetric arrangement of vortices corresponding to a flapping mode of the jet in the minor axis plane, whereas at high Mach numbers the large vortical structures in the jet became quasisymmetric. However, a description of the different modes that correspond to the arrangement of the large vortical structures in a rectangular jet is still lacking. In view of this, an experiment was conducted to examine the instability of a jet issuing from a rectangular nozzle of aspect ratio 4. Because of the similarities found in axisymmetric supersonic and subsonic jets, the exit Mach number in the present experiment was varied from low subsonic to moderate supersonic values.

The principal parameters or variables governing the flowfield of a rectangular jet issuing into an ambient medium are the exit Mach number, the exit Reynolds number, the aspect ratio, and the conditions of the flow at the nozzle exit. In the present investigation the exit Mach number is varied from 0.03 to 1.5. The Reynolds number employed here is based on the small dimension of the nozzle and the mean exit velocity, calculated using a fully expanded isentropic flow assumption. This Reynolds number was varied from 7×10^3 to 3×10^5. A rectangular nozzle with an aspect ratio of 4 was used. The mean velocity at the exit plane of the nozzle was found to be quite flat with laminar boundary layers up to a velocity of about 100 m/s. At higher velocities, although not measured here, it is expected that the boundary layer is either transitional or turbulent.

Experimental Facilities and Procedures

The experimental facility is shown schematically in Fig. 1. A high-pressure blown-down facility was used to supply the air. The flow was directed into the nozzle through a settling chamber containing a perforated plate, screens of different mesh sizes, and a section of acoustic foam. The settling chamber and the nozzle exit were connected by a two-stage, three-dimensional contraction with an overall area ratio of 100. The inlet geometry of the nozzle followed fifth-order polynomials. The long (w) and short (h) dimensions of the rectangular nozzle exit are 4 and 1 cm, respectively.

Mean and fluctuating velocity measurements were made with Dantec 55M10 constant-temperature hot-wire anemometers in conjunction with Dantec 55M25 linearizers. The frequency response of the hot-wire system was found to be approximately 100 kHz using a 5-μm-diam platinum-coated

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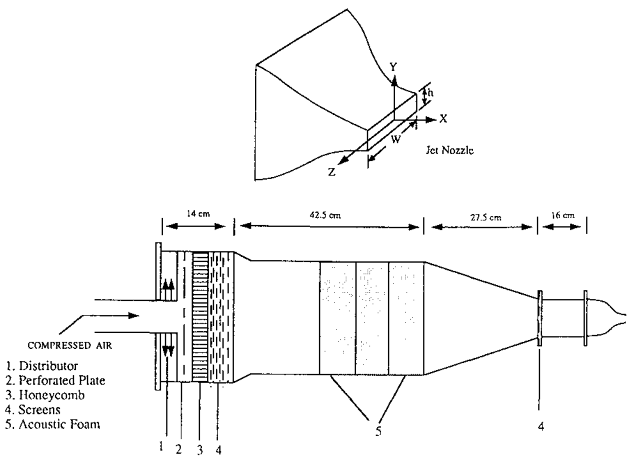

Fig. 1 Schematic of the experimental setup.

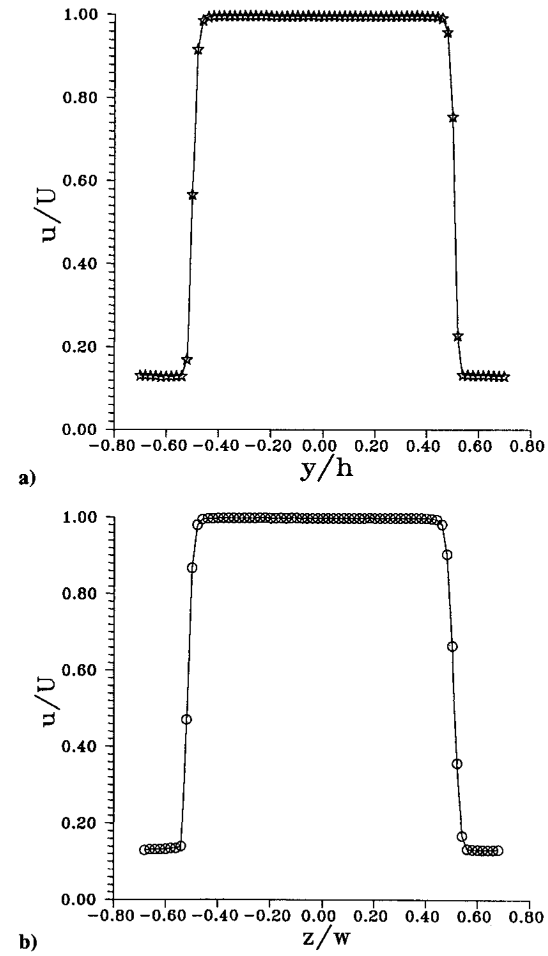

Fig. 2 Jet exit velocity profiles measured in the central planes; a) x-y plane, b) x-z plane, $U = 68$ m/s.

tungsten wire. A pitot tube, having a sensing tube diameter of about 1.5 mm, was used to measure the mean velocity data at high speeds.

Near-field pressure fluctuations were measured by one ⅛-in.-diam and two ¼-in.-diam Bruel and Kjaer condenser microphones and an associated B & K preamplifier and power supply. The microphones had open-circuit frequency responses of up to 100 and 50 kHz, respectively. Since the data obtained from the different microphones are identical, only the measurements from the ¼-in. microphone will be presented. Both the hot-wire probes and the microphones were mounted on a three-dimensional traversing mechanism that was regulated by a programmable controller. The analog data obtained from the instruments were digitized and analyzed using a personal computer. Auto- and cross-spectral analyses were also obtained directly by means of a B & K type 2032 dual-channel signal analyzer.

A Cartesian coordinate system (x,y,z), as shown in Fig. 1, was chosen with its origin located at the center of the nozzle exit and with the x axis oriented along the jet centerline. Detailed maps of the mean velocity fields, not included here, at five different exit Mach numbers from 0.2 to 0.8 indicate that the crossover point (switching of the major and minor axes) occurs around 25 widths downstream of the nozzle exit and is independent of the exit Mach number. For the purposes of the present investigation, all measurements included here are confined to the initial region of the jet extending from the nozzle exit to $14h$. In this region, the instability characteristics of the jet did not show significant variations along the span (the long dimension of the nozzle). Hence, the measurements presented here are confined to the central plane containing the small dimension of the nozzle.

Results and Discussion

Initial Conditions

Initial conditions are characterized by top-hat mean velocity profiles observed at the two central planes of the nozzle exit, as shown in Fig. 2. The centerline turbulence intensity at the jet exit was found to be about 0.15% for the velocity range

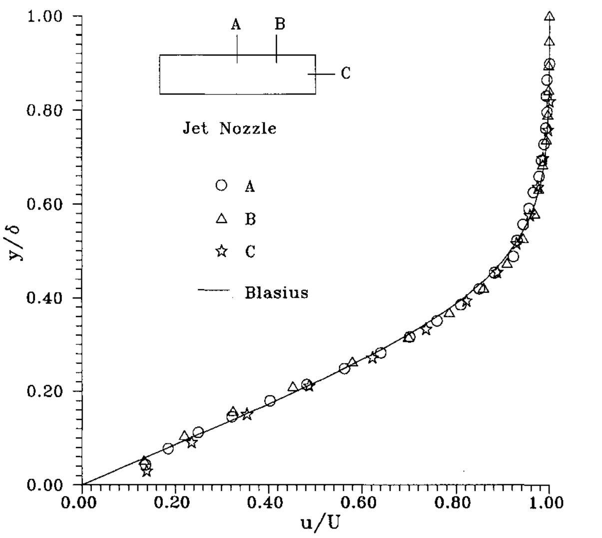

Fig. 3 Exit boundary-layer profiles measured at different locations, $U = 68$ m/s.

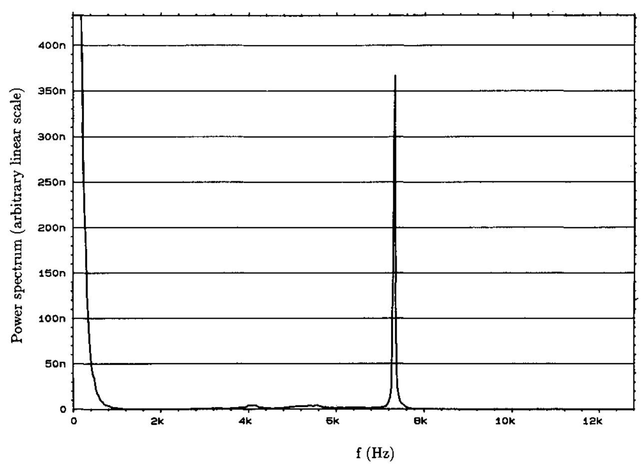

Fig. 4 Typical energy spectrum measured by hot wire inside the shear layer, $x/h = 0.4$, $U = 46$ m/s.

tested. The boundary-layer profiles agreed well with the Blasius laminar profile, indicated in Fig. 3 by the solid line. The variation in the initial momentum thickness, calculated from these profiles, ranged between 0.055 to 0.059 mm. This variation was found to be less than 7% overall, except very close to the corner regions where higher values are expected because of the presence of corner vortices. These measurements for the initial boundary layer are confined to a maximum exit velocity of 100 m/s. Beyond 100 m/s, it is known from previous investigations that the exit boundary layers become either transitional or turbulent.[10] Based on these results and our shear layer frequency measurements, to be discussed later, it is suggested that such exit boundary-layer behavior is also present in our experiment.

Shear Layer Instability

To study the instability characteristics of the initial shear layer, energy spectra of the longitudinal velocity fluctuations were measured near the nozzle exit ($0.3 \le x/h \le 0.6$) by means of a single hot-wire probe. Figure 4 shows a typical power spectral distribution. The most amplified frequency f_0 can easily be identified as the peak frequency in the spectrum. The corresponding Strouhal number, $St_\theta = f_0\theta/U$, where θ is the initial momentum thickness and U is the jet exit velocity, is found to be equal to 0.012.

For a laminar boundary layer, the momentum thickness varies as $U^{-1/2}$ with increasing velocity. This implies that the peak frequency in the spectral measurement is proportional to $U^{3/2}$ if the Strouhal number based on θ is considered to be a constant. Such a relationship was examined by measuring the most unstable shear layer instability frequency over a velocity range of 10–100 m/s. Figure 5 shows the variation of this frequency with the mean exit velocity. For the velocity range studied, the data confirm the previous assumption, suggesting the persistence of the laminar condition of the initial boundary layer up to about 100 m/s. However, beyond a velocity of 100 m/s, the data do not follow the $U^{3/2}$ variation, an indication that the initial boundary layer is no longer laminar.

In the low-velocity range, the frequency variation shows a stepwise change. The shear layer frequency appears to lock onto a lower frequency stage as the velocity changes from very low values to approximately 20 m/s. After that, the low-frequency peak gradually diminishes in amplitude, and a second peak, presented as different symbols in Fig. 5, which follows the 3/2 power relation, appears with a comparable or higher amplitude. Similar staging behavior can also be seen in the range of 20–30 m/s. If the velocity is slightly increased above 30 m/s the low-frequency peak disappears and the 3/2 power

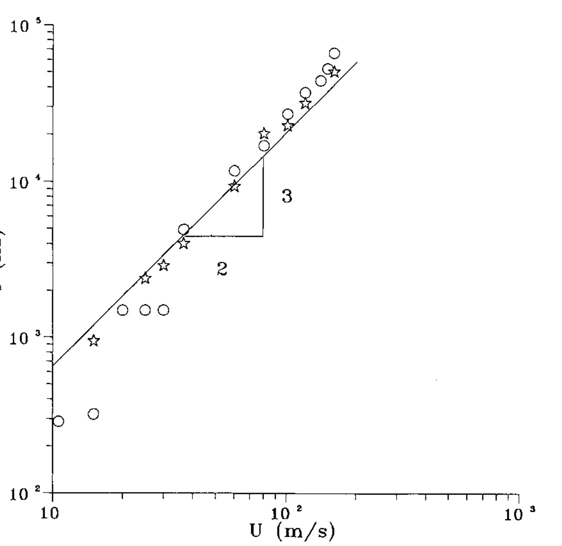

Fig. 5 Variation of the most amplified shear layer frequency with the jet exit velocity.

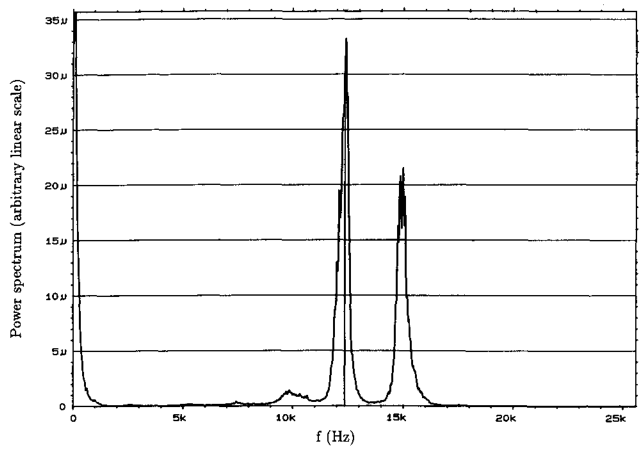

Fig. 6 Energy spectrum measured inside the shear layer; $f_{high} = 15$ kHz, $f_{low} = 12.4$ kHz; $x/h = 0.4$, $U = 68$ m/s.

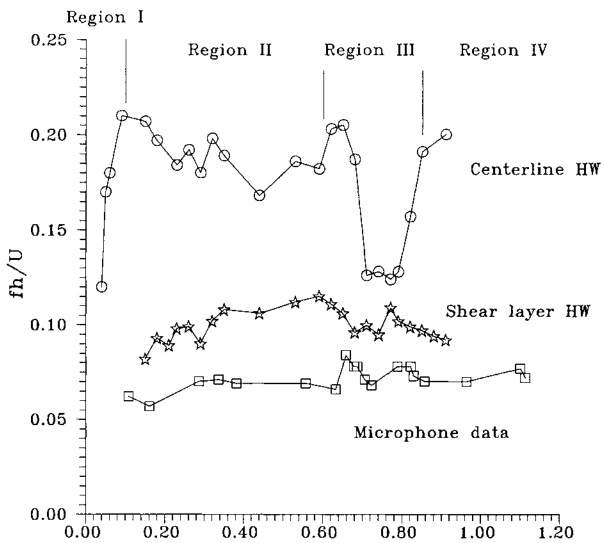

Fig. 7 Variation of the preferred Strouhal number with Mach number; comparison of data measured by different techniques.

relation prevails throughout the velocity range tested. This stepwise change of shear layer instability frequency has been discussed by Gutmark and Ho[11] and attributed by them to the possible existence of spatially coherent disturbances resulting from resonance within the facility.

In the moderate-to-high velocity range, 30 m/s $\le U \le$ 150 m/s, the energy spectra measured inside the shear layer show two distinct peak frequencies (see Fig. 6). To identify their respective flow structures, cross-spectral measurements were made with two hot wires placed in the two shear layers corresponding to the central plane of the small dimension of the nozzle. From phase measurements it appears that these frequencies correspond neither to symmetric nor to antisymmetric modes of the instability. More detailed investigations are needed to clarify these observations. Because of the well-known hot-wire breakage problem at high speeds, measurements in the shear layer were confined to a maximum velocity of 200 m/s.

Jet Preferred Modes

At the end of the potential core, $x/h = 5.5$ (considered here only in the central x-y plane), a preferred frequency corresponding to the passage frequency of the dominant vortical structures f_p can be detected. The Strouhal number St_h normalized with the height of the jet h and the exit velocity U corresponding to this frequency is commonly referred to as the jet *preferred mode*. In this experiment, both hot-wire and near-field microphone measurements were used to study the variation of the preferred mode with exit Mach number, ranging from low subsonic to supersonic values.

Figure 7 shows the variation of the preferred mode Strouhal number obtained from a hot wire placed both at the centerline and in the shear layer of the jet. Also included are the data obtained from a near-field microphone placed at $y/h = \pm 3$. From the centerline hot-wire data, four distinct regions can be identified and are labeled as regions I–IV.

In the low-velocity range, less than about 20 m/s, denoted here as region I, the preferred frequency is approximately proportional to the most amplified frequency f_0 of the shear layer. This relation can be demonstrated by examining the variation of the peak frequency of the energy spectra measured along both the shear layer and centerline of the jet, as shown in Fig. 8. This frequency variation shows a staging behavior with downstream distance. The initial peak frequency is first halved at $x/h = 2$ and then again at $x/h = 3.5$. Based on similar observations by Ho and Hsiao[12] and Kibens,[13] these stages correspond to two successive pairing locations and the growth of the first and second harmonic of the initial instability frequency components. This type of vortex interaction mechanism seems to dominate the jet instability process in region I. Considering the fact that the Strouhal number for the most amplified wave in the shear layer is a constant, and using the relationship for the variation of momentum thickness of a laminar boundary layer with the Reynolds number, it can be easily shown that the jet preferred Strouhal number is approximately proportional to the square root of the Reynolds number. The data in region I follow such a relationship. In the region II, the Strouhal number appears to be fairly constant and assumes an average value of about 0.19. Any variations in this region are found mainly because of the probe location and experimental uncertainty. The variation of the Strouhal number in region III, $0.6 \leq M \leq 0.85$, is characterized by a sudden decrease followed by a rapid rise. The Mach number at which such a decrease in Strouhal number occurs seems to be quite sensitive and displays hysteresis effects. The reasons for this type of behavior will be examined subsequently. Finally, in region IV the Strouhal number increases toward a relatively constant value and extends into the supersonic flow.

From the centerline and shear layer hot-wire data, shown in Fig. 7, the values of the corresponding Strouhal numbers differ by a factor of two, with the exception of region III. The near-field microphone data are consistently lower than the shear layer hot-wire data. The difference between the microphone and shear layer hot-wire data is mainly due to different response characteristics of these two instruments. Generally, a near-field microphone measures both the hydrodynamic pressure fluctuations and sound generated by flow structures in the flow. It has a tendency to detect more favorably toward signals produced by large-scale coherent structures that prevail downstream of the potential core region because they are relatively more energetic. It is also known that those structures grow in size moving downstream and that their corresponding frequency decreases. Therefore, it is expected that the peak frequency measured by a microphone should be lower than that measured by a hot-wire probe placed in the flow. While considering the different response characteristics of the two instruments, it appears that the Strouhal number is constant over the range of Mach numbers tested as indicated by both microphone and shear layer hot-wire data.

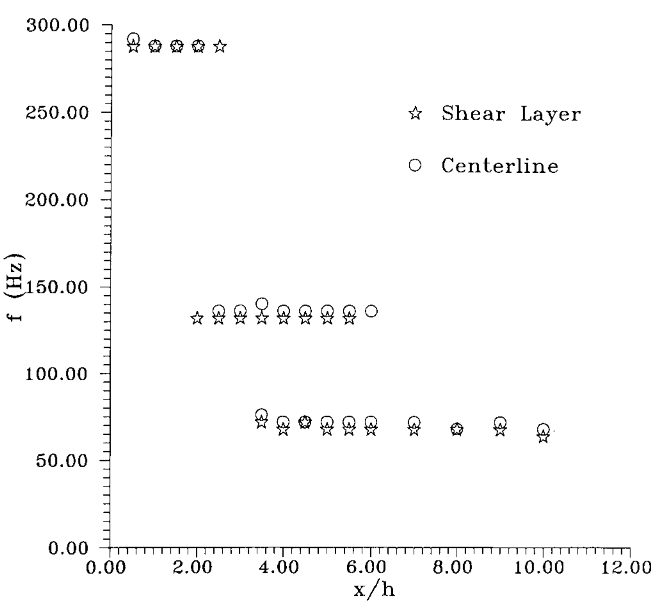

Fig. 8 Variation of the most amplified instability frequency with the downstream distance, $U = 10$ m/s.

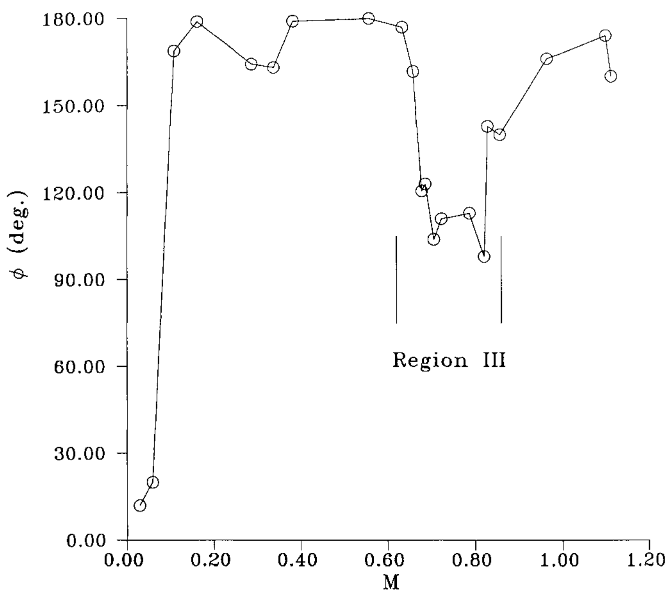

Fig. 9 Variation of the cross-spectral phase with jet exit Mach number, microphone measurement.

To explain the difference between the centerline and shear layer hot-wire data, cross-spectral phase measurements were made using two microphones located symmetrically with respect to the jet centerline at $y/h = \pm 3$ in the x-y plane. Results of these measurements are presented in Fig. 9. The variation of the phase with Mach number clearly shows a transition from a symmetric mode in region I (note, at low-velocity range, the phase was determined by cross-spectral measurement of two hot-wire probes) to an antisymmetric mode in region II. The antisymmetric mode persists in region II. In region III, the phase decreases to a constant value of about 100 deg followed by a rise close to 180 deg again. At higher velocities, in region IV, the antisymmetric mode once again prevails and appears to extend to the low supersonic range.

Figures 10a and 10b show a comparison of typical cross-spectral plots in regions II and III. In Fig. 10a, $M = 0.25$, the preferred mode is dominated by an antisymmetric mode with an average phase of 175 deg. Random phase fluctuations close to the frequency range with the peak amplitude resulted from small phase jitter of the flow structures. Consequently, the phase oscillates between 180 and -180 deg and appears to be fluctuating. In region III, as shown in Fig. 10b, a broadband peak with an averaged phase angle of 90 deg is observed. The simultaneous existence of both symmetric and antisymmetric instability modes in two-dimensional jets has been observed by Sato[14] and others. It is believed that the decrease of phase angle in the cross-spectral measurement in region III is a direct result of the emergence of the symmetric mode and its competition with the antisymmetric mode. In the transition region

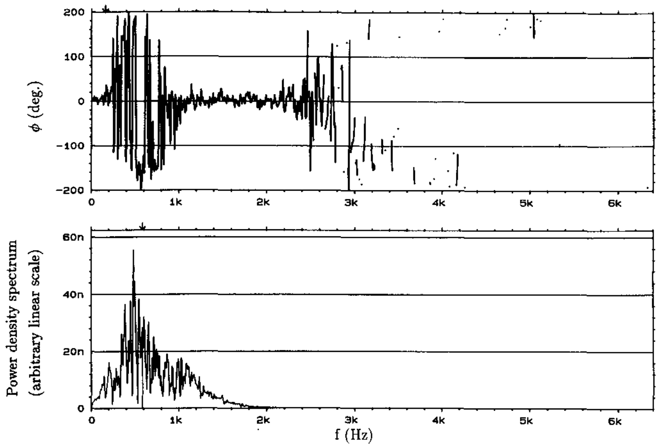

Fig. 10a Cross-spectral data measured by microphones, $M = 0.25$, region II.

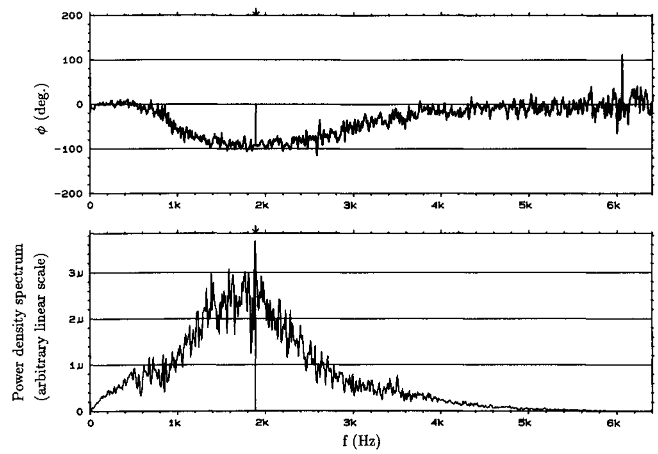

Fig. 10b Cross-spectral data measured by microphones, $M = 0.69$, region III.

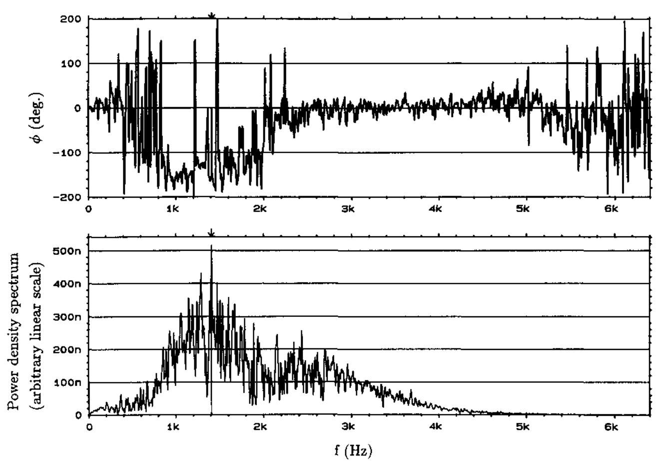

Fig. 10c Cross-spectral data measured by microphones, $M = 0.56$, transition region.

between regions II and III, as shown by Fig. 10c, the simultaneous existence of these two modes is clearly evident with their respective phases of approximately 180 and 0 deg. It is speculated that there is a continuous switching from one mode to the other, and consequently the phase identity of the individual modes is lost because of the long time average of the cross-spectral measurement. The broadband peak in Fig. 10b is in fact a result of the presence of two competing modes with comparable strengths. These observations are also supported by the simultaneous measurement of instantaneous microphone signals as shown in Fig. 11. In the figure the symmetric (S) and antisymmetric (A) modes are identified using the corresponding symbols. It is rather arbitrarily determined that the instability mode is classified as symmetric when the relative phase between two signal phases falls within 30 deg and is antisymmetric when the phase exceeds 150 deg. The switching between modes is quite evident.

From our phase measurement, it is concluded that the doubling of the preferred mode frequency between the centerline and shear layer hot-wire measurements is a result of the dominance of antisymmetric large structures in the shear layers. Similar observations have also been made by Thomas and Goldschmidt[15] in their study of a plane jet, and they attributed the frequency doubling to the artifact produced by placing the probe in the center of the jet (see Fig. 12). Since the centerline probe can detect fluctuations induced from structures on either side of the jet, it will measure an effective wavelength that is half of that in the shear layer if the arrangement of structures is antisymmetric. Hence, the frequency measured at the centerline is twice that of the shear layer. If the structures are arranged symmetrically, it is expected that the frequencies measured at both locations will be the same. However, when a combination of antisymmetric and symmetric structures is present, the difference in frequencies is not as significant as shown in region III of Fig. 7.

The large scattering of jet preferred frequency data has been noted for some time. Many possible reasons have been suggested; for example, Gutmark and Ho[11] suggested that the preferred frequency is sensitive to the measuring position, to the vortex merging process in the shear layer, and to the transition of the shear layer. Based on our observations, it is suggested that the preferred frequency measured along the centerline of the jet can vary if there is mode switching be-

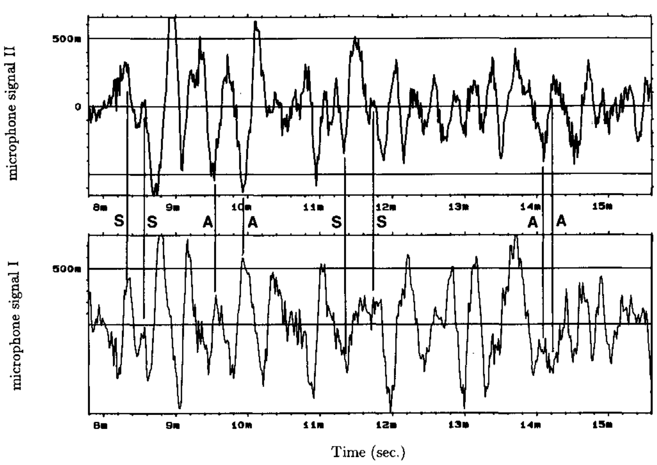

Fig. 11 Simultaneous measurement of instantaneous near-field acoustic data using two microphones placed symmetrically at $y/h = \pm 3$, $x/h = 5.5$, $M = 0.8$; S = symmetric mode, A = antisymmetric mode.

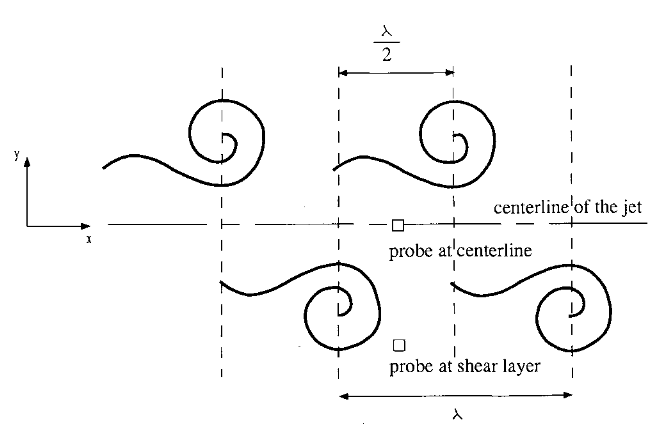

Fig. 12 Hot-wire response to antisymmetric flow structures.

tween antisymmetric and symmetric modes. Therefore, measurements taken inside the shear layer or in the near acoustic field should be used because of their relative insensitivity to the switching of the symmetric and antisymmetric modes.

Supersonic Jet Flow Instability

In addition to instability modes described earlier, the spectrum of an underexpanded supersonic jet displays intense discrete tones commonly known as screech tones and broadband shock-associated noise. To study the various instability modes, experiments were conducted using small increments of the jet exit Mach number (calculated based on ideally expanded isentropic flow) in the range from 0.85 to 1.5. All of the measurements are confined to the acoustic near field using microphones. Most of the data presented here were taken with the microphones located at $x/h = 5.5$ and $y/h = \pm 3$. Both auto- and cross-spectra from the microphones were measured using a B & K spectrum analyzer with a frequency band up to 25 kHz. For frequency measurement beyond 25 kHz, a high-speed analog-to-digital converter in conjunction with a personal computer was used to collect the data.

Figure 13 shows a typical spectrum of the near-field microphone signal at an exit Mach number of 1.12. The spectrum shows a distinct low-frequency and a broadband high-frequency peak. The Strouhal number St_h corresponding to the low-frequency peak is about 0.075 and is associated with the preferred mode extending from the subsonic flow range. The broadband peak seems to correspond to the shock-associated noise. From past experimental observations,[16] it is found that this peak frequency is a strong function of the direction of radiation. To further verify these observations, measurements were made at different locations downstream of the nozzle exit. Figure 14 shows a spectrum at $x/h = 3.0$ for the same conditions of Fig. 13. As expected, the broadband peak shifted toward a lower frequency. It is clear that the low-frequency peak associated with the large-scale structure at the end of the potential core has relatively higher amplitude than the shock-associated broadband noise.

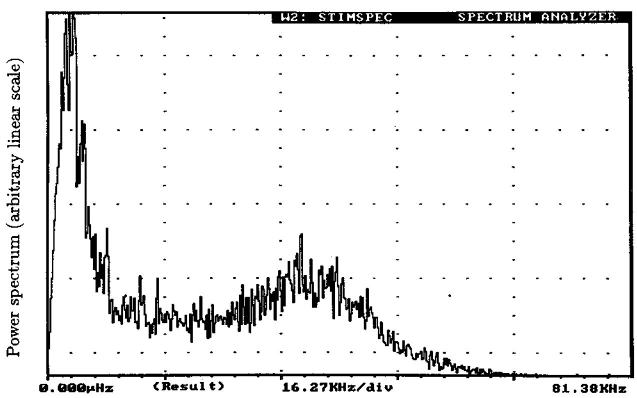

Fig. 13 Power spectrum measured by microphones; $x/h = 5.5$, $y/h = 3$, $M = 1.12$

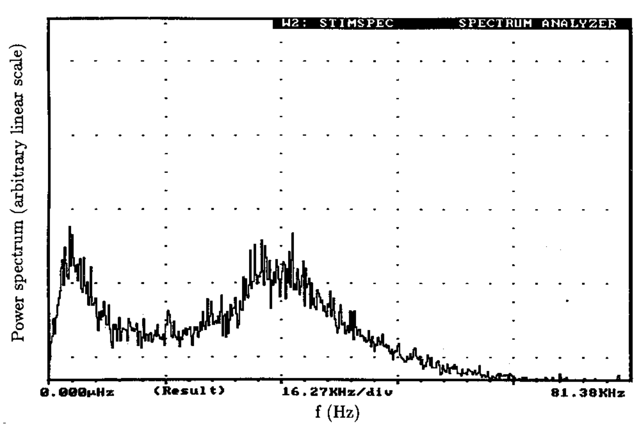

Fig. 14 Power spectrum measured by microphones; $x/h = 3$, $y/h = 3$, $M = 1.12$.

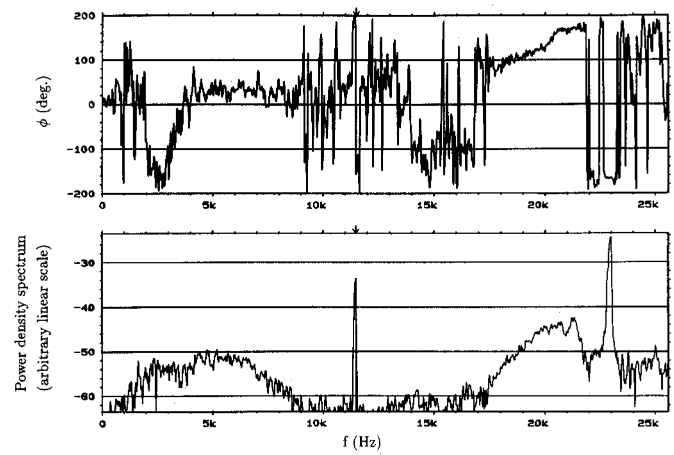

Fig. 15 Cross-spectral data measured by microphones; $x/h = 5.5$, $y/h = \pm 3$, $M = 1.18$.

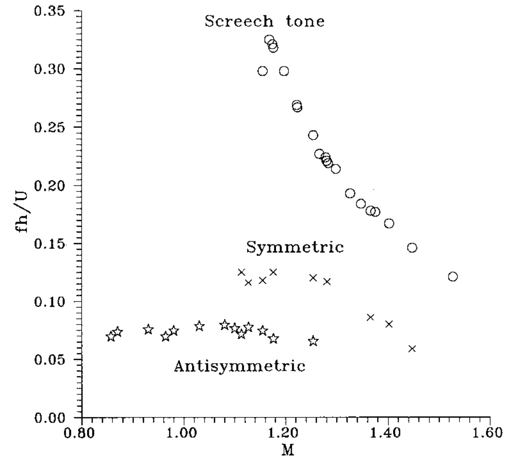

Fig. 16 Variation of Strouhal number for different modes with jet Mach number, supersonic range.

With increase in exit Mach number to 1.18, additional peaks in the near-field frequency spectrum have been observed as shown in Fig. 15. The discrete peaks at 11.5 and 23 kHz correspond to the fundamental and harmonic of the screech tone. The high-frequency broadband peak at 20.5 kHz is associated with the broadband shock-associated noise. In the low-frequency region, the antisymmetric mode is identified with the peak at 2.5 kHz ($St_h = 0.075$). An additional broadband peak appears in the spectrum at about 4.5 kHz ($St_h = 0.125$). From corresponding phase measurements, this peak can be associated with the symmetric mode. The different dominant frequencies observed earlier are plotted in Fig. 16 in terms of Strouhal number vs the exit Mach number. It is apparent that there is a continuation of the preferred mode that extends from subsonic to supersonic Mach numbers and takes on a constant value of about 0.075. The flow structure associated with this is antisymmetric and is similar to its high subsonic counterpart.

Additionally, at supersonic Mach numbers, another dominant symmetric flow structure appears at a Strouhal number of 0.125. This structure appears to be reminiscent of the symmetric mode which appears at moderate subsonic Mach numbers (Fig. 10c). The frequency corresponding to this mode decreases gradually as the exit Mach number is increased further. At high Mach number, this frequency appears to lock onto the subharmonic of the screech tone.

As the Mach number increases beyond 1.15, the well-known screech tone emerges and the flow structure changes signifi-

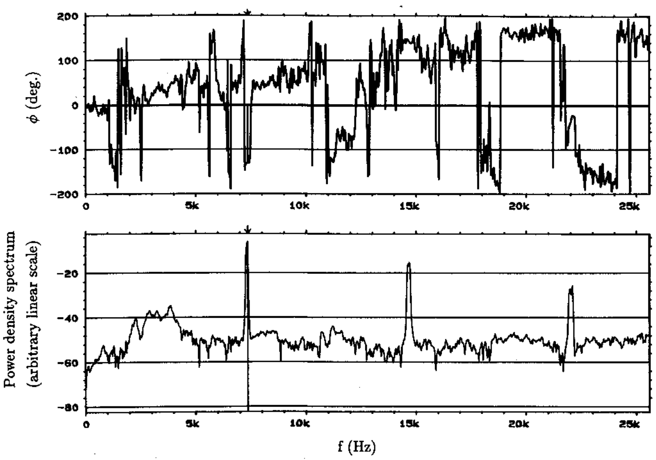

Fig. 17 Cross-spectral data measured by microphones, $x/h = 5.5$, $y/h = \pm 3$, $M = 1.35$.

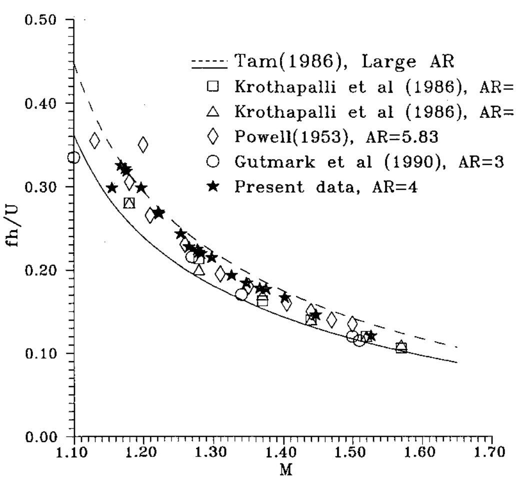

Fig. 18 Variation of the screech tone Strouhal number with the jet exit Mach number.

cantly. Energy spectra measured by microphone show several discrete frequencies with the lowest frequency being defined as the fundamental frequency. The other frequencies are harmonics of the fundamental. As shown by the cross-spectral data in Fig. 17, the fundamental frequency of the screech mode is determined to be antisymmetric, which is consistent with the flow visualization observations.[2,3] The variation of the fundamental frequency of the screech tone with jet Mach number is shown in Fig. 18. Comparisons with previous experimental data and the theoretical model proposed by Tam[17] are also included. To use Tam's model, the convection velocity u_c of the large-scale structures has to be estimated. The value of $u_c = 0.7U$ proposed by Tam[17] is used to produce the broken line in Fig. 18. The model appears to overestimate the screech tone Strouhal number. Mean convection velocity of one-half the jet exit velocity, suggested by Krothapalli et al.,[4] is also used and the result is shown by the lower solid curve; it seems to underestimate the frequency at the low end of the curve but shows better agreement in the high Mach number range. It is of interest to note that the screech tone Strouhal number is independent of the aspect ratio of the nozzle.

Conclusions

The instability modes of a jet exiting from a rectangular nozzle of aspect ratio 4 have been studied at exit Mach numbers ranging from 0.03 to 1.5. Within the range of Mach numbers between 0.1 and 0.3, the most amplified shear layer frequency shows a linear variation with exit velocity, consistent with linear stability theory. The variation of the most amplified jet instability frequency (preferred mode) with Mach number exhibits distinct regions. In region I, velocities range from 1 to 20 m/s, and the instability process is similar to that observed in two-dimensional jets. In this range, the jet preferred Strouhal number is found to be proportional to the square root of the exit Reynolds number. In region II, $0.1 \leq M \leq 0.6$, antisymmetric flow structures dominate the flow development. In region III, $0.6 \leq M \leq 0.85$, both antisymmetric and symmetric structures exist and there is a continuous switching between these modes. The average phase angle obtained from cross-spectral measurements between two microphones placed at the opposite sides of the shear layer is found to be approximately 100 deg.

There is a continuation of the antisymmetric jet preferred mode extending from the subsonic to supersonic Mach numbers, with a constant Strouhal number of 0.075. In addition, a symmetric mode with a higher Strouhal number of 0.125 emerges and eventually dominates at higher Mach numbers, $M \geq 1.2$. It appears that this symmetric mode locks into the subharmonic of the screech tone at even high Mach numbers, $M \geq 1.4$.

As the jet Mach number increases beyond 1.2, discrete tones, known as screech tones, emerge and are accompanied by an abrupt increase in the jet spreading angle with enhanced mixing. The variation of the screech Strouhal number with the jet exit Mach number agrees well with previous experiments, and is independent of the aspect ratio of the nozzle.

References

[1]Powell, A., "On the Noise Emanating from a Two-Dimensional Jet Above Critical Pressure," *The Aeronautical Quarterly,* Vol. 4, No. 3, 1953, pp. 103–122.

[2]Krothapalli, A., Hsia, Y., Baganoff, D., and Karamcheti, K., "The Role of Screech Tones in Mixing of an Underexpanded Rectangular Jet," *Journal of Sound and Vibration,* Vol. 106, No. 1, 1986, pp. 119–143.

[3]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.

[4]Krothapalli, A., Baganoff, D., and Hsia, Y., "On the Mechanism of Screech Tone Generation in Underexpanded Jets," AIAA 8th Aeroacoustics Meeting, AIAA Paper 83-0727, April 1983.

[5]Tam, C. K. W., "Jet Noise Generated by Large-Scale Coherent Motion," *Aeroacoustics of Flight Vehicles: Theory and Practice,* NASA Ref. Pub. 1258, Vol. 1, Aug. 1991, pp. 311–390.

[6]Ho, C. M., and Huerre, P., "Perturbed Free Shear Layers," *Annual Review of Fluid Mechanics,* Vol. 16, 1984, pp. 365–423.

[7]Hussain, A. K. M. F., "Coherent Structures—Reality and Myth," *Physics of Fluids,* Vol. 26, No. 10, 1983, pp. 2816–2850.

[8]McLaughlin, G. L., Morrison, G. L., and Trott, T. R., "Experiments on the Instability Waves in a Supersonic Jet and Their Acoustic Radiation," *Journal of Fluid Mechanics,* Vol. 69, Pt. 1, 1975, pp. 73–95.

[9]Seiner, J. M., McLaughlin, D. K., and Liu, C. H., "Supersonic Jet Noise Generated by Large-Scale Instabilities," NASA TP 2072, Sept. 1982.

[10]Lepicovsky, J., Ahuja, K. K., Brown, W. H., Salikuddin, M., and Morris, P. J., "Acoustically Excited Heated Jets; 1—Internal Excitation," NASA CR 4129, Pt. I, June 1988.

[11]Gutmark, E., and Ho, C. M., "Preferred Modes and the Spreading Rates of Jets," *Physics of Fluids,* Vol. 10, No. 7, 1983, pp. 2932–2938.

[12]Ho, C. M., and Hsiao, F. B., "Evolution of Coherent Structures in a Lip Jet," *Structure of Complex Turbulent Shear Layers,* edited by R. Dumas and L. Fulachier, Springer-Verlag, Berlin, 1983, pp. 121–136.

[13]Kibens, V., "Discrete Noise Spectrum Generated by an Acoustically Excited Jet," *AIAA Journal,* Vol. 18, No. 4, 1980, pp. 434–441.

[14]Sato, H., "The Instability and Transition of a Two-Dimensional Jet," *Journal of Fluid Mechanics,* Vol. 7, Jan. 1960, pp. 53–80.

[15]Thomas, F. O., and Goldschmidt, V. W., "Structural Characteristics of a Developing Turbulent Planar Jet," *Journal of Fluid Mechanics,* Vol. 163, Feb. 1986, pp. 227–256.

[16]Norum, T. D., and Seiner, J. M., "Broadband Shock Noise from Supersonic Jets," *AIAA Journal,* Vol. 20, No. 1, 1982, pp. 68–73.

[17]Tam, C. K. W., "The Shock-Cell Structures and Screech Tone Frequencies of Rectangular and Non-Axisymmetric Supersonic Jets," *Journal of Sound and Vibration,* Vol. 121, No. 1, 1988, pp. 135–147.