Near-Field Pressure Fluctuations of an Elliptic Jet

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The near-field pressure fluctuations of an elliptic jet were experimentally investigated in this work. The characteristics of the fluctuating pressure were found to be only slightly different in the two planes containing the major and minor axes. A spectral analysis of the pressure fluctuations was performed and its relation to the velocity perturbations generated by vortex merging was examined.

Introduction

THE velocity field of an elliptic jet[1] is very different from that of a circular jet.[2] The spreading rates in the planes containing the major and the minor axes (hereafter referred to as the major axis and the minor axis planes) are far apart. The entrainment of a small aspect ratio ($AR=2:1$) elliptic jet was found to be a few times higher than that of a circular jet. Therefore, the use of an elliptic jet was suggested by the authors[1] as an effective *passive control* device for increasing the entrainment.

Measurements of the velocity field in elliptic and rectangular jets have been investigated by several authors.[3-5] The aspect ratios in those experiments were higher than 5:1 and the entrainments were not much different from that of an axisymmetric jet.[4] The major and minor axis eventually switch their orientation due to the different spreading rate. The distance from the nozzle to the switching location is almost linearly proportional to the aspect ratio.[5] The switching of the two axis planes of an isolated elliptic vortex ring was also reported.[6,7]

In this paper, the near-field pressure fluctuations were studied in view of jet noise problems. The fluctuations are generated by velocity perturbations in the jet and will radiate to the far field as noise. Recently, Laufer and Yen[8] investigated the noise produced by a low-speed circular jet with low background perturbations. They showed that the noise source could be traced to the vortex merging locations. The vortex merging location was identified as the region where the amplifying instability waves reached their peak value.[9] The noise radiated from an elliptic jet with a large aspect ratio ($AR>5$) was different in amplitude in the major and minor axis planes.[10,11] The difference in noise production was related to the instability characteristics in the two planes.[12,13] In the present work, the near-field pressure fluctuations were studied in light of the streamwise development of the stability waves.

Facility and Instrumentation

The air jet was driven by an axial blower. The blower was connected via a flexible hose to a diffuser and a cylindrical stagnation chamber. Honeycomb and fine-mesh screens were installed in the diffuser and stagnation chamber. The turbulence level was 0.4% at the nozzle exit. The specially designed contraction initially had a circular cross section and ended with an elliptic nozzle (Fig. 1). The major diameter, 2a, was 50.8 mm and the minor diameter, 2b, 25.4 mm. The contraction shape was a fifth-order polynomial in both axis planes. The area contraction ratio was 18:1. The Reynolds number, based on the major diameter and the jet exit velocity U_j, was equal to 3.9×10^4.

The velocity was measured by a hot-wire anemometer. The diameter of the hot wire was 2.5 μm. The hot-wire anemometer system had a frequency response of up to 20 kHz.

The near-field pressure was measured by a 3.2 mm (1/8 in.) B&K microphone. The microphone was calibrated by a B&K pistonphone (type 4220). The pressure measurements were made from the jet exit plane to five major radius lengths downstream and up to 51 mm from the outer edge of the jet shear layer. The outer edge of the jet was defined as the position where the local mean velocity was 5% of the jet exit velocity. The positions of the jet edges will be shown in Figs. 7 and 8 later.

Experimental Results

Instability Characteristics

In flows with a uniform distribution of the initial momentum thickness, e.g., circular jets or two-dimensional mixing layers, the linear stability theory[14] predicts the existence of a most amplified frequency, which scales with the jet velocity and momentum thickness. In an elliptic jet, the situation becomes very interesting because the initial momentum thickness θ_0 varies about 26% around the circumference of the nozzle exit in the present facility. How will the shear layer accommodate the variation in thickness? The data indicated that the amplified frequency f_i was constant around the nozzle. In other words, the jet tends to shed a single vortex at any instant.[1]

The eigenfunctions of the fundamental frequency and its first and second subharmonics were measured in both the major and minor axis planes. The energy of each frequency at a streamwise location was obtained by integrating the eigenfunction across the shear layer (Figs. 2 and 3). The instability waves amplified to a peak and then decayed. The dimensional growth rates of the instability waves were almost the same in both axis planes. The nondimensional growth rates $-\alpha_i\theta_i$ were different as a result of the difference in the momentum thickness.

The initial Strouhal number $f_i\theta_0/U_j$ was 0.0207 at the major axis side. In the minor axis plane, the value was 0.0165, which is the same as that calculated by the linear stability analysis for uniform momentum thickness.[14] However, this could be a coincidence and might not be the reason determining the most amplified frequency. Morris and Miller[13] found that the frequency scaled with the minimum momentum thickness in the elliptic jet and their result agrees with the present data, but their analysis had the minimum thickness in

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the major axis plane. The situation was different in this experiment. Also, no definite clue can be obtained from the dimensional amplification rates. This is because they are the same in both axis planes. It is interesting to note that the elliptic jet has the same instability frequency around the nozzle, but the reason for choosing the specific value deserves further investigation.

The initial vortices at the frequency f_i undergo a merging process in the shear layer through a subharmonic instability mechanism. As proposed by Ho and Huang,[9] the axial distance of the subharmonic saturation points is correlated with the vortex merging locations. The saturation location of the fundamental corresponds with the formation of the initial vortices.

In the present case the energy of the first subharmonic peaks around $x/a = 0.6$, while the energy of the second subharmonic peaks in the major axis plane at $x/a = 1.2$. The fundamental frequency energy peaks between $x/a = 0.4$-0.5

Near-Field Pressure Fluctuations

The level of the total pressure fluctuations was measured at different radial positions along the jet. The isobar contours in the major and minor axis planes are depicted in Figs. 4 and 5. In these figures r_E is the radial distance from the jet edge. The shapes of the contours are slightly different in the major and minor axis planes. The levels of fluctuations decrease away from the jet edge. The maximum levels are in the vicinity of $x/a = 1$.

Spectral Distribution of the Pressure Fluctuations

Spectral analysis of the pressure fluctuations was performed at each measuring station. Clear peaks at the fundamental frequency and its subharmonics can be observed in the pressure fluctuation spectra (Fig. 6).

The contours of isospectral density of the fundamental frequency and its three subharmonics are given in Figs. 7 and 8. The contours of each frequency indicate the apparent origin of noise for the corresponding frequency. The origins of the contours at the first and second subharmonics ($x/a = 0.6$ and 1.2, respectively) correspond to the saturation points of the first and second subharmonics, which are the vortex-merging locations[9] (Figs. 2 and 3). Laufer and Yen[8] arrived at the same conclusion from the far-field noise measurement in a circular jet. They showed that the radiated noise sources are not convected and are associated with the nonlinear saturation of the instability waves in the shear layer occurring at the location of the merging. Another confirmation of this observation can be obtained from the distribution of the spectral peaks along a radial line at the jet edge. In Figs. 9 and 10, the spectral peaks of the fundamental and the subharmonics, were plotted vs x/λ_i, where λ_i is the ith subharmonic instability wavelength of each frequency. A clear collapse of all the data was observed. The peak of the data is located $x/\lambda_i \approx 2$, which is the location of the vortex merging.[9]

A further interesting observation from Figs. 7 and 8 is that the fundamental frequency f_i and its first subharmonic $f_i/2$ exhibit clear forward radiation directivity patterns at an angle of about 10 deg relative to the jet edge, while the contours of the other two subharmonics ($f_i/4$ and $f_i/8$) are symmetric relative to the normal direction of the jet edge. In a clean jet, the formation of the initial vortex and the first merging location are fairly localized. Therefore, the directional pattern has a clean preferred direction. Spatial jitter of the other

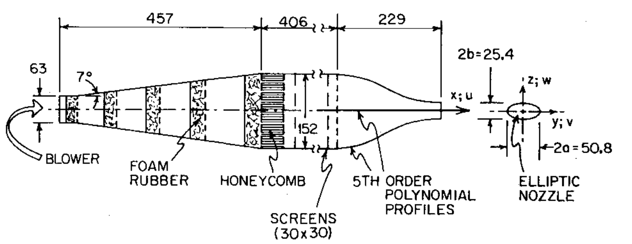

Fig. 1 Elliptic jet setup (units in millimeters).

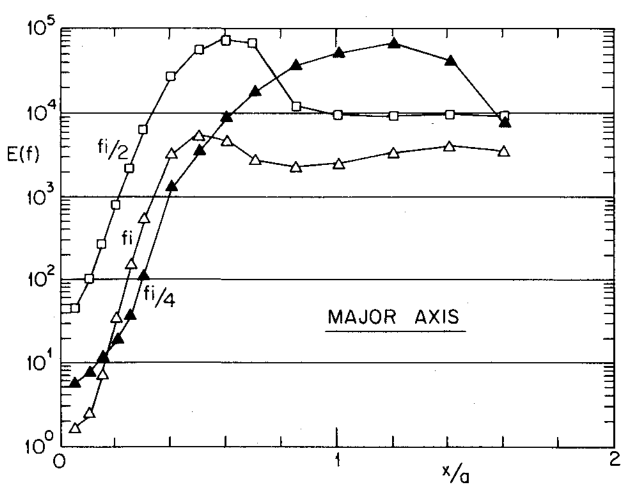

Fig. 2 Growth of the instability waves in the major axis plane.

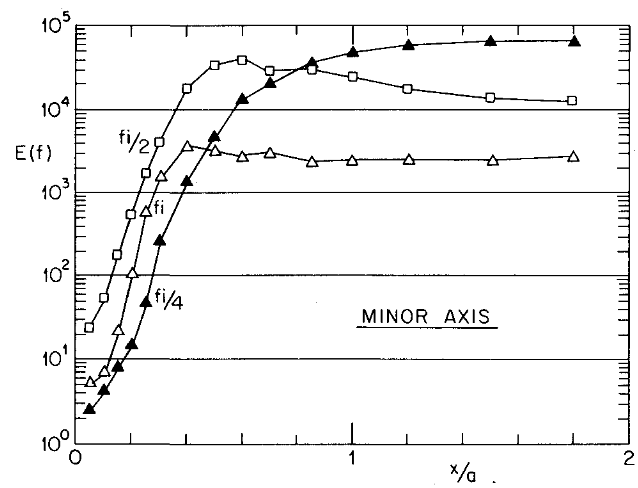

Fig. 3 Growth of the instability waves in the minor axis plane.

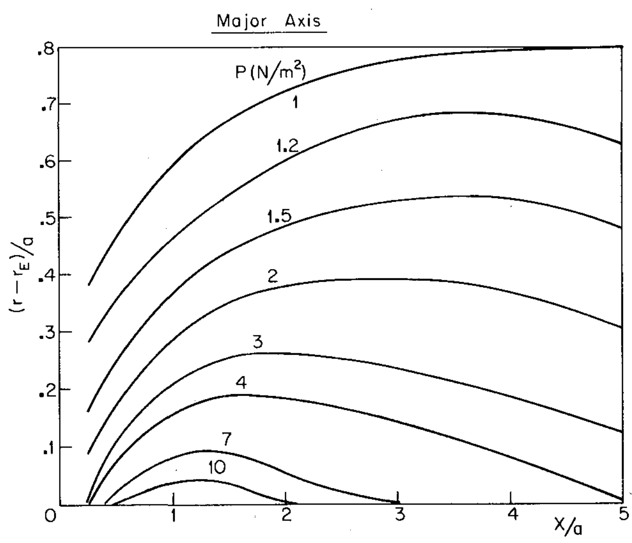

Fig. 4 Isobar contours of the pressure fluctuations in the major axis plane.

mergings is increased and, hence, the near-field pressure contours become more symmetric with respect to the line perpendicular to the jet edge. The spatial jitter will increase with increasing Reynolds number. Therefore, the clear forward radiation patterns of the fundamental and the first subharmonic could diminish in a jet with a higher Reynolds number than the present one.

The decay of the intensities of the fundamental and its subharmonics with normal distance from the jet edge is shown in Figs. 11 and 12. These curves are plotted for the decaying pressure fluctuations at $x/\lambda_i = 2$ in the major axis plane and at $x/\lambda_i = 1.8$ in the minor axis plane. These streamwise positions correspond to the peak level of all the different frequencies in Figs. 9 and 10. The level of the fluctuations at all frequencies decay exponentially near the jet. Farther away from the edge, the slope decreases gradually, in some cases reaching the -2 slope. It is impossible to present both the exponential decay region and the algebraic decay region with straight lines on one graph. We chose a log – log plot. The exponential decay region is still close to a straight line. The number of data points far away from the jet edge is limited, because the measured pressure signal reached the background noise level of the microphone. The exponential decay region is usually referred to as the hydrodynamic pressure field of the jet. The

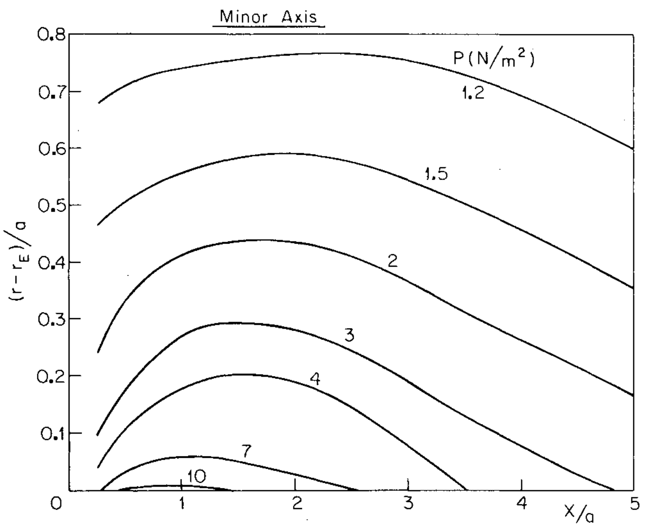

Fig. 5 Isobar contours of the pressure fluctuations in the minor axis plane.

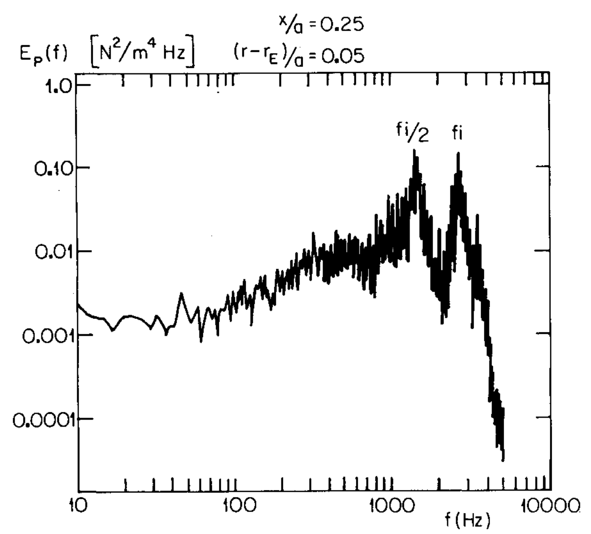

Fig. 6 Power spectrum of the pressure fluctuations in the minor axis plane.

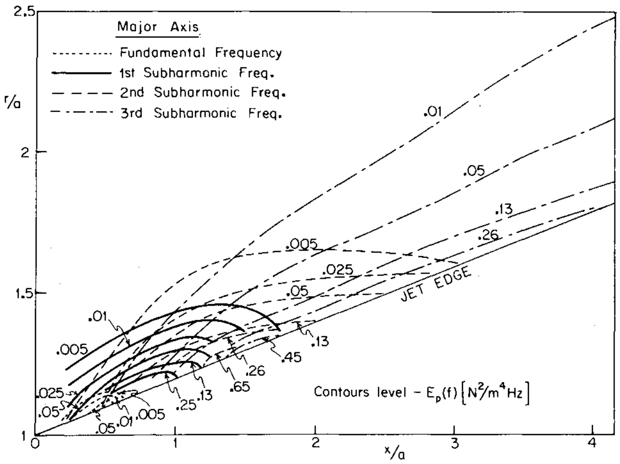

Fig. 7 Isospectral density of the pressure fluctuations in the major axis plane.

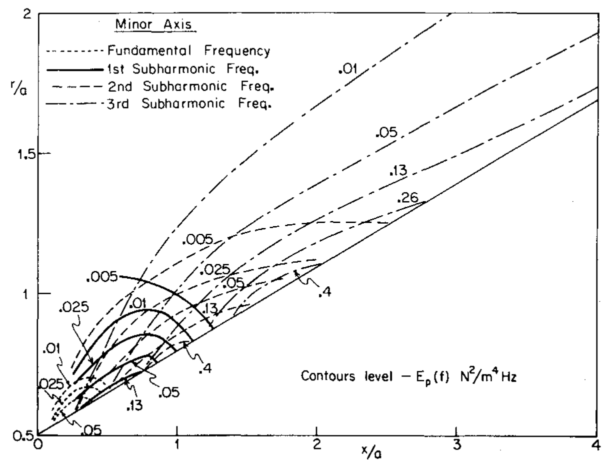

Fig. 8 Isospectral density of the pressure fluctuations in the minor axis plane.

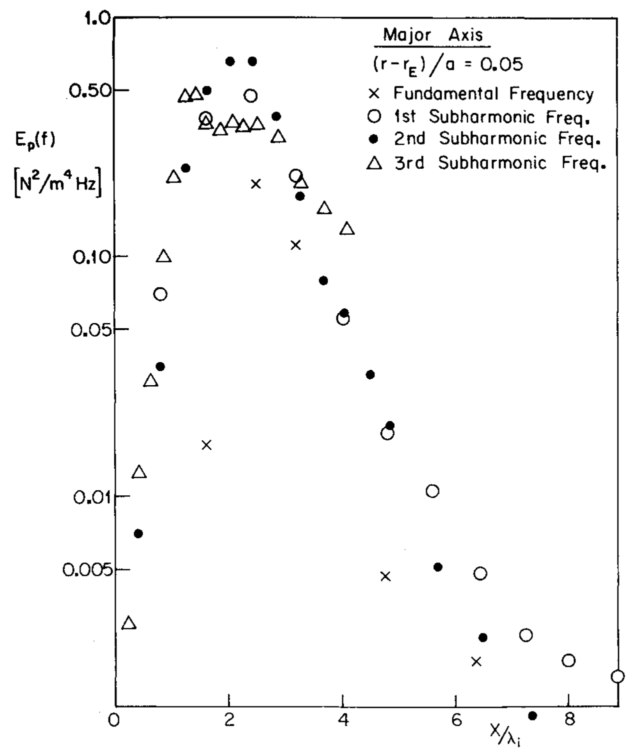

Fig. 9 Spectral density of the pressure fluctuations (major axis) along the jet edge.

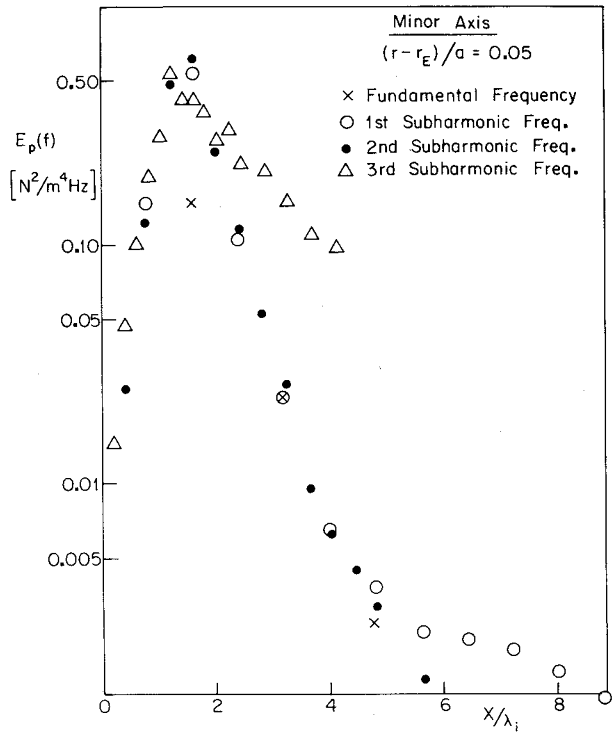

Fig. 10 Spectral density of the pressure fluctuations (minor axis) along the jet edge.

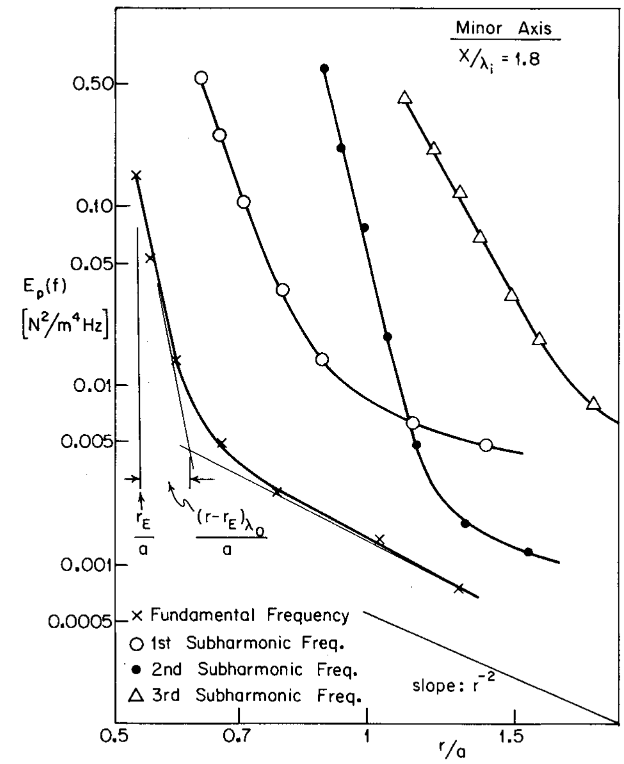

Fig. 12 Decay of the pressure fluctuations with the radial distance (minor axis).

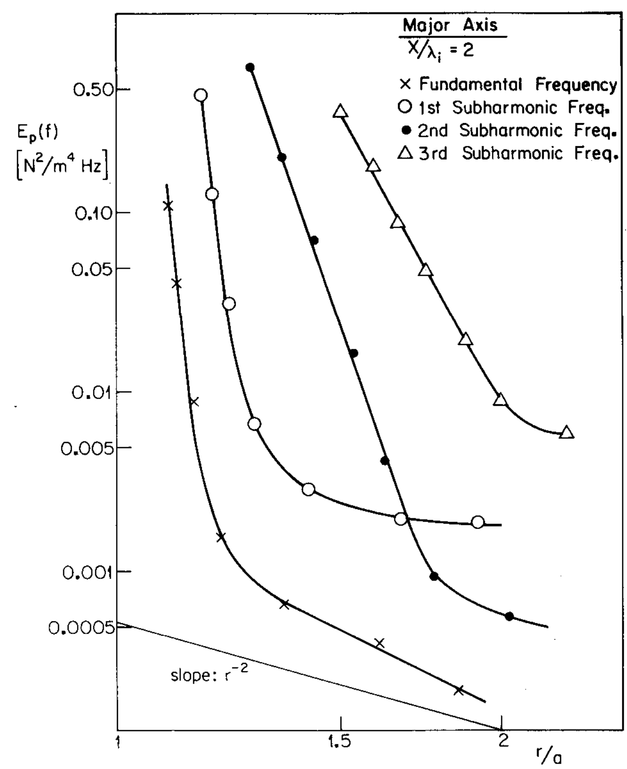

Fig. 11 Decay of the pressure fluctuations with the radial distance (major axis).

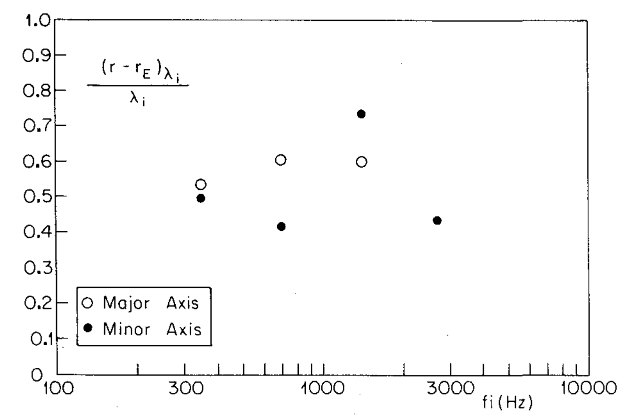

Fig. 13 Radial extent of the near-field pressure fluctuations.

extent of this region is defined here by finding the intersection point of the exponential and -2 slopes (an example of this procedure is given in Fig. 12). Figure 13 shows that the region of the hydrodynamic field can be approximately scaled with the instability wave length λ_i. The average extent of the near-field region from the edge of the jet is in the order of one λ_i for all the frequencies. Thus, the exponential decay region of near-field pressure fluctuation in an elliptic jet is very small compared to the acoustic wave length.

Summary

The near-field pressure fluctuations of an elliptic jet with a small aspect ratio were experimentally investigated in both the major and the minor axis planes. The exponential decay regions of the hydrodynamic pressure fluctuations are confined to about one instability wavelength away from the jet edge. The apparent source locations of the pressure fluctuations at the fundamental and the subharmonics are the same as those of the vortex merging locations. This fact supports the concept that the pressure perturbations are produced mainly by the merging process in low Mach number jets.

Acknowledgments

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