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The UVP Measurement of Flow Structure in the Near Field of a Square Jet

Yoshihiro INOUE*, Kunikazu KONDO† and Shintaro YAMASHITA*

* Dept. Mechanical and Systems Engineering, Gifu University, Gifu 501-1193, Japan
† Dept. Mechanical Engineering, Suzuka College of Technology, Suzuka 510-0294, Japan

ABSTRACT

Coherent structures in the near field of a three-dimensional jet have been investigated. The experiments were carried out for a free jet issuing from a square nozzle into a water channel. Instantaneous velocity profiles were measured in the streamwise and cross-stream directions using an ultrasonic velocity profile monitor. From power spectra, two dominant frequencies were found out with respect to the flow structures, and it is indicated from the wavelet transform that a coherency of vortical structures was changed in time as well as in frequency domain.

1. Introduction

Flow characteristics of various kinds of a jet have been extensively examined by many workers because of their wide applicability in the industry. Control of the turbulent mixing and diffusion and reduction of the noise have also been investigated, and interactive control of the jet is carried out in recent years.

The present study intends to examine the spatiotemporal flow structure in the near-field of a square jet. It is produced by a mixing layer between the jet stream and a surrounding still fluid, and there are sharp corners in the shear layer of the square jet. A very large curvature of the shear layer induces an intensive deformation of a vortex ring, and therefore, its understanding is not sufficient only by analogy from a circular jet [1] and an elliptic jet [2]. The square jets have been investigated by Tsuchiya et al. [3], Quinn and Militzer [4], Toyoda et al. [5], Grinstein and DeVore [6], Wilson and Demuren [7], and so on.

2. Experimental apparatus and procedure

The flow field and coordinate system are shown in Fig. 1. The x-axis is taken to coincide with the jet center line. The y-axis and z-axis are normal to each side of the nozzle, and the y_1-axis and z_1-axis are along the diagonals, respectively.

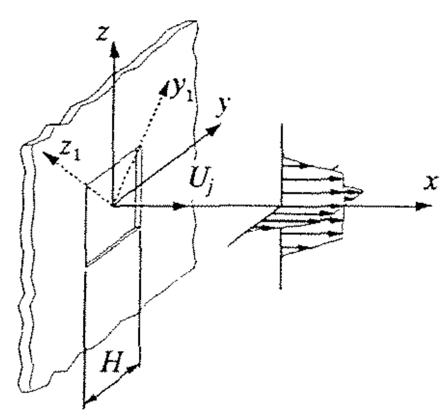

Fig. 1 Flow field and coordinate system.

The test channel is an open channel which is 0.7 m wide, 0.64 m depth and 3 m length. The nozzle is square with its side length of H = 100 mm. The jet velocity U_j remains constant in 100 mm/s, and the Reynolds number is $Re_j = U_j H / \nu \approx 1 \times 10^4$. From the results

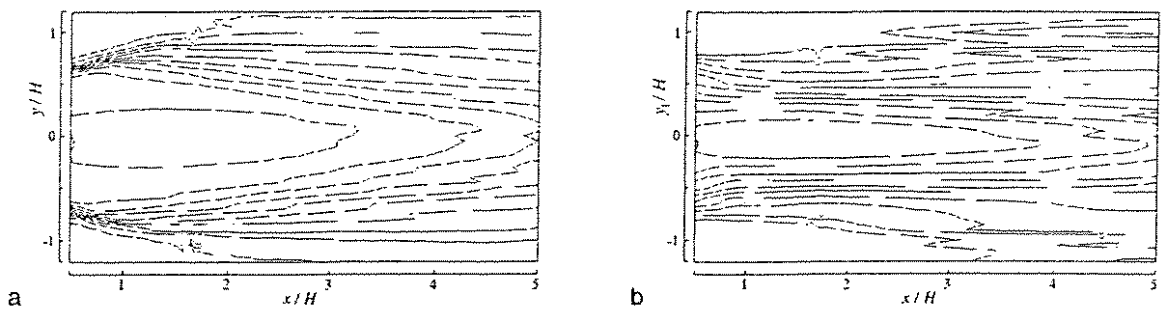

Fig. 2 Contour map of mean velocity in the streamwise direction. a x-y plane and b x-y_1 plane.

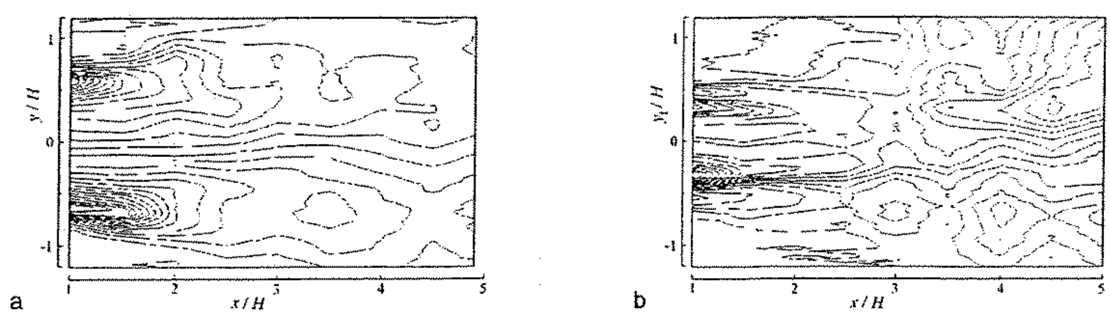

Fig. 3 Contour map of mean velocity in the lateral direction. a x-y plane and b x-y_1 plane.

obtained by hot-film measurements, the turbulence intensity in the jet core is about 1.1 % of the efflux velocity, and the momentum thickness of the shear layer is $\theta = 1.02$ mm at $x = 0.2\,H$.

UVP measurements are performed in the x-y plane and x-y_1 plane with an ultrasonic transducer of fundamental frequency of 4 MHz. Hydrogen bubbles are continuously generated from a platinum wire in the measuring plane, and are used as scattering particles for the ultrasound. The measuring time is about 57 ms for one velocity profile, and an interval time between the adjacent profiles is 160 ms.

3. Results and discussion

3.1 Mean flow fields

Figures 2 and 3 show contour maps of mean velocity in the streamwise direction and in the lateral direction in the x-y and x-y_1 planes, respectively. The mean velocity in the streamwise direction (Fig. 2) shows that the flow goes outside in the x-y plane, i.e., the opposite side direction, and the jet width rapidly extends. In the x-y_1 plane, the flow goes toward the center axis just behind the nozzle, and the jet width is gently extended in the downstream. This feature has also appeared well in the contour maps of mean velocity component in the cross-stream directions (Fig. 3). In the diagonal direction shown in Fig. 3b, the regions of the positive and the negative velocities are adjacent to each other at $|y_1 / H| \approx 0.4$ in the interval of $x / H < 1.5$. It seems that features of this flow are caused by axis-switching of the vortex ring formed in the initial shear layer.

3.2 Instantaneous velocity field

Spatiotemporal contour maps of the instantaneous velocity components in the lateral directions are shown in Figs. 4a-d at $x / H = 1$ and 3. In the upstream section of $x / H = 1$, the velocity fluctuation is relatively inactive near the jet axis, while it is developed in the mixing layer. Significant patterns of the contour line are visible about $|y| = 0.6\,H$ and $|y_1| = 0.4\,H$, and they correspond to the vortex structure in the mixing layer. In the normal direction to the nozzle side (Fig. 4a), the velocity in the mixing layer is positive for $y > 0$ and negative for $y < 0$, and in the diagonal direction (Fig. 4b), the regions of positive and negative velocities are arrayed with an

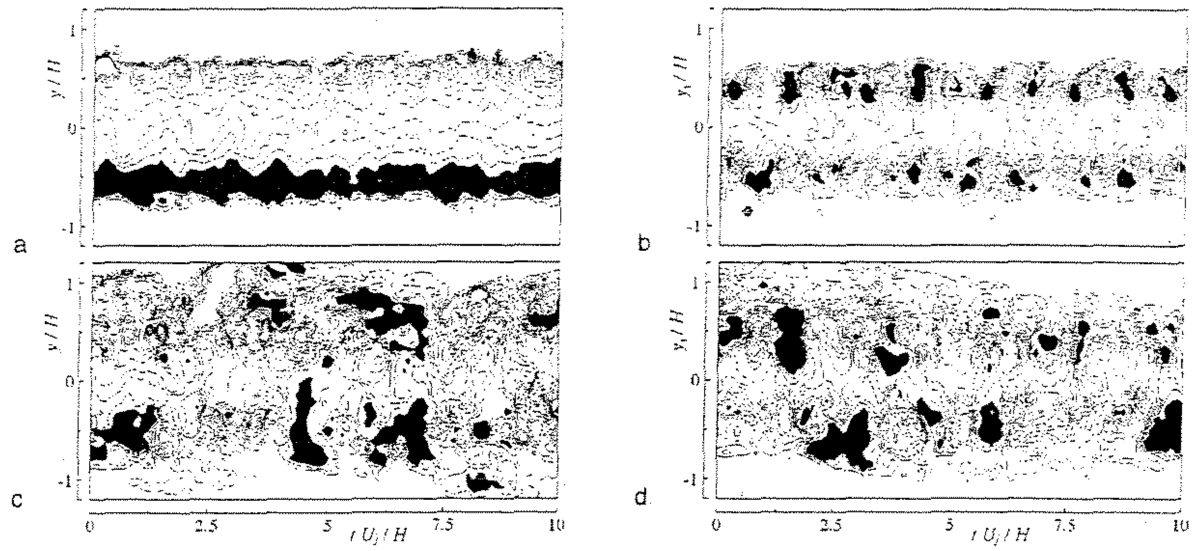

Fig. 4 Spatiotemporal velocity field in the lateral direction. **a** y-t plane at x/H =1, **b** y_1-t plane at x/H =1, **c** y-t plane at x/H =3, **d** y_1-t plane at x/H =3

organized pattern in each layer. In the downstream section of $x / H = 3$ shown in Figs. 4c-d, there is no remarkable difference between both directions, and the regions with various velocity and length scales are scattered spatiotemporally.

3.3 Power spectrum

Figure 5 shows power spectra of fluctuation velocity u at $y = 0$ and $z = 0.4\,H$. The spectrum is obtained by Fourier transforming a time-series data set of 512 points, and ensemble averaged values are shown. In the upstream sections of $x / H = 1$ to 2, there exist two spectral peaks at normalized frequencies of $St_H = f H / U_j = 0.80$ and 1.12. Also, the frequency corresponding to the jet column mode is $St_H \approx 0.41$ from the result on the jet axis. Figure 6 shows the streamwise distribution of power spectral density at these three frequencies. The values at $St_H = 0.41$ are outstanding in $x / H > 2$, and are relatively weakened in $x / H > 3.5$. The distribution related to $St_H = 0.80$ takes a peak at $x / H \approx 1.3$. The dimensionless frequency of 0.80 seems to be consistent with a time scale based on the advection of the vortex ring structure.

3.4 Coefficient of Wavelet transform

Figure 7 represents the wavelet transform of fluctuating velocity at $x / H = 1.5$ and 3. Only the positive value of the real part of the transformed results is shown. The wavelet for the analysis is Morlet wavelet [8], and k_ψ is a constant of 6. Here, a is the scale of the wavelet and b the translation on the time axis.

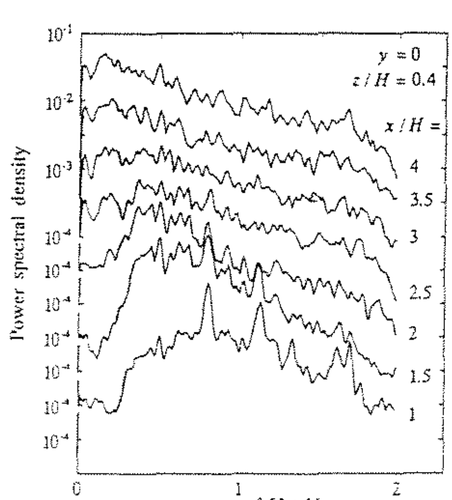

Fig. 5 Power spectrum at various streamwise-positions.

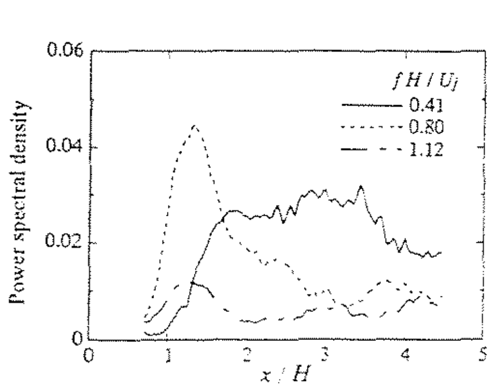

Fig. 6 Streamwise distribution of power spectral density at various frequencies.

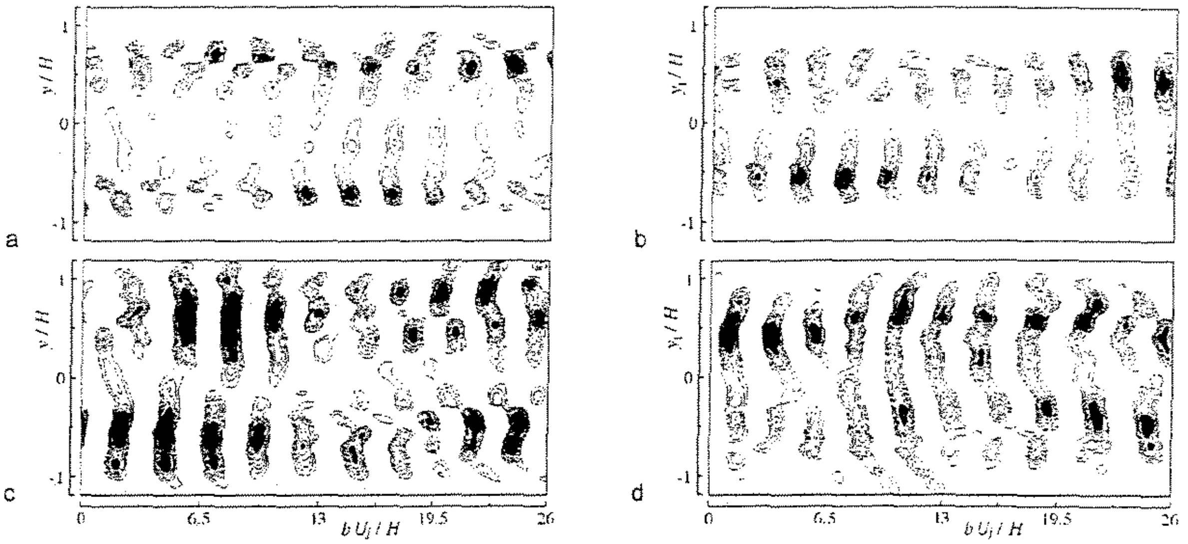

Fig. 7 Spatiotemporal map of wavelet transform with a scale of $a\,U_j/H = 2.4$. **a** y-b plane at $x/H = 1.5$, **b** y_1-b plane at $x/H = 1.5$, **c** y-b plane at $x/H = 3$, **d** y_1-b plane at $x/H = 3$

Wavelet coefficients of the velocity component normal to the jet axis are shown in Figs. 7a-d at $x / H = 1.5$ and 3. The dimensionless scale of the wavelet is fixed at $a\ U_j / H = 2.4$, which is nearly equal to a time scale of the jet column instability. Figures 7a-b in the upstream section show that the velocity perturbations with this scale occur in the mixing layers about $|y| = 0.6\,H$ and $|y_1| = 0.4\ H$, respectively. On the other hand, at $x / H = 3$ (Figs. 7c-d), the velocity fluctuations by the jet column mode are developed across the jet. The aspect of the flow field is educed by the wavelet transform, which cannot been seen clearly in spatiotemporal contour maps of the instantaneous velocity component (Figs. 4c-d). In addition, the spatiotemporal instability of the column mode can be found.

4. Concluding remarks

The spatiotemporal flow structure in the near-field of a square jet were investigated by UVP monitor. Mean flow pattern were given for the contour maps of mean velocity in the streamwise direction and in the lateral direction. Instantaneous flow pattern, power spectral density of fluctuation velocity and the wavelet transform of fluctuating velocity were analyzed from data set measured by the UVP monitor. These quantities made clear the structural properties in the near-field of a square jet.

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