Journal of Visualization, Vol. 4, No. 1 (2001) 99-107

Flow Visualization of Vortex Structure of an Excited Coaxial Jet

Kiwata, T.*, Okajima, A.* and Kimura, S.*

* Department of Mechanical Systems Engineering, Kanazawa University, 2-40-20 Kodatsuno, Kanazawa 920-8667, Japan.

Received 13 October 2000.
Revised 15 January 2001.

***Abstract*:** This paper describes the results of experimental and numerical studies concerning the near-field vortical structure and dynamics of a coaxial jet. The effect of excitation of annular and circular jets on the vortical structure in the inner and outer shear-layers was studied. The flow visualization and the measurements of mean and fluctuating velocities, by a hot-film probe and the particle image velocimetry (PIV) technique, were carried out in an open water tank. The results of flow visualization and numerical simulation are in good agreement. With the excitation of a half of the initial vortex frequency, it is found that the vortex-pairing event is promoted by the forced excitation and it results in the rapid expansion of the jet width and the increase of velocity fluctuation and the entrainment rate. For the velocity ratio near unity, the dominant peak frequency coincides with the initial vortex frequency, i.e., the lip wake vortex frequency, independent of the forced excitation frequency.

***Keywords*:** coaxial jet, excited jet, flow control, vortex pairing, particle image velocimetry.

1. Introduction

The near-field structure of a coaxial jet configuration is considerably complex. The mixing between the jet streams is critically controlled by the dynamics and interactions of the vortical structures in shear-layers developed between the two jets, and also between the outer jet and the ambient fluid. The coaxial jet discharging into still fluid without artificial excitation has been studied by a number of researchers. The work on the flow structures of the coaxial jet was reported by Chigier and Beer (1964), Williams et al. (1969), Champagne and Wygnanski (1971) and others. Their results showed that the mean velocity ratio U_i/U_o, where U_i is the flow velocity of the inner circular jet and U_o is that of the outer annular jet, dominates the development of vortical structure of the coaxial jet. Ko and Au (1985), Au and Ko (1987), Buresti et al. (1994) and Rehab et al. (1997) carried out detailed studies on the coaxial jet of mean velocity ratios less than unity, i.e., $U_i/U_o < 1$. The axisymmetric and azimuthal structures within the initial region of coaxial jet of mean velocity ratio of 0.3 were reported by Tang and Ko (1994). Dahm et al. (1992) gave a detailed flow visualization of the vortex dynamics of the near field in the coaxial water jet. The previous work of the authors (Okajima et al., 1994; Kiwata et al., 1997) indicated the existence of a recirculating region along the axis of the jet and the visual configurations of the coherent structure in the inner and outer mixing regions of an unexcited coaxial jet.

On the other hand, the responses of the coaxial jet upon acoustic excitation were studied by Lepicovsky et al. (1985), Tang and Ko (1993;1994) and Wicker and Eaton (1994). Tang and Ko (1994) also observed the flow structure in the initial region of an excited coaxial jet with the mean velocity ratio of 0.3. Wicker and Eaton (1994) found that the excitation of the inner jet produces periodic structures in the inner layer, but it does not have a significant effect on the evolution of the outer layer.

The aim of the present paper is to clarify the effects of excitation of outer and inner jets on the vortical structure of coaxial jet for the low Reynolds number. The velocity, turbulent intensity distributions and the power spectra of the fluctuating velocity of the jets for various velocity ratios have been measured by the hot-film velocity measurement technique, the flow visualization and the particle image velocimetry (PIV) technique. We also carried out a series of numerical simulations by the finite difference method under the same conditions as the experiments.

2. Apparatus and Techniques

2.1 Experimental Setup

The experimental setup consists of coaxial axisymmetric water jet discharging into an open water tank (435 mm × 435 mm × 1000 mm) where the fluid (water) is at rest. A schematic diagram of the nozzle is shown in Fig. 1. The annular and central nozzles are made of acrylic resin. The outer nozzle, i.e., an annular nozzle, has an outer diameter D_o of 40 mm and an inner diameter of 24 mm. The inner nozzle has an inner diameter D_i of 16 mm with a straight pipe of 1m long. The pipe is sufficiently long to yield fully developed velocity profiles at the exit plane of the inner jet. The pipe length of the outer nozzle L was also changed from $L/D_o = 0$ to 0.5. The experiments were run with the mean exit bulk velocity U_o of the outer annular jet, about 8.5 cm/s. The Reynolds number based on the outer diameter D_o and the mean velocity U_o of the annular jet was 3000. The mean velocity ratio was changed from $U_i/U_o = 0.1$ to 1.2, where U_i is the mean exit bulk velocity of the inner circular jet. The value of boundary layer displacement thickness at the inner side of outer jet was $d^* = 1.27 \sim 1.75$ mm.

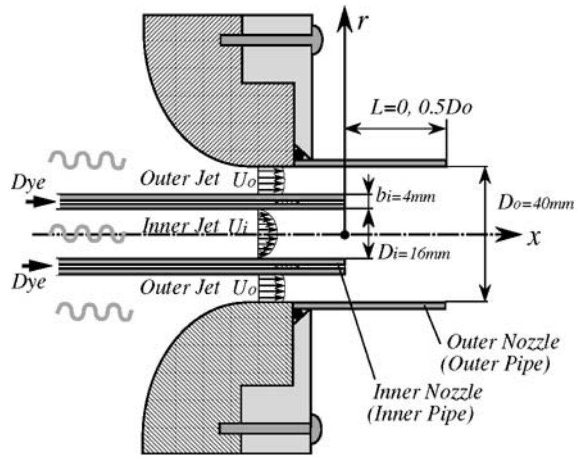


Fig. 1. Schematic diagram of the nozzles.

To study the effects of controlled perturbation, the outer and inner jets were individually excited by two shakers. The sinusoidal motion of shaker which consists of a stepping motor and a crank actuated a piston in a cylinder containing water. In the case of the excitation of both jets, a computer with a pulse control board was used to supply two stepping motor drivers with the synchronized periodic waveform. The disturbance velocity with an amplitude of $a_f = 0.05 \sim 0.1U_o$ was added to the outer jet, and that with an amplitude of $a_f = 0.1U_i$ to the inner jet. The frequency f_e of forced excitation was changed from $0.5f_n$ to f_n, where f_n is the initial vortex frequency in the mixing layer (Kiwata et al., 1997).

2.2 Experimental Method

The vortex structure in the near field was visualized with a two-color planar laser-induced-fluorescence technique. The jet and the tank fluid were marked with two different laser-fluorescent dyes. For the particle image velocimetry technique, the fluid was seeded with 20 μm acrylonitrile spherical particles. A light sheet generated from a 4 W Argon ion laser illuminated the near field of jet. The laser sheet thickness was approximately 3 mm. The images were acquired at a 768(659) × 494 pixel resolution with a CCD video camera (SONY XC-009, NEC TI-150A) and stored on a digital video recorder (SONY DSR-40). At each condition 768 images were recorded at a frame rate of 30 Hz for a total time of 25.6 seconds.

During processing, each image was sub-sampled into smaller windows called interrogation zones and the velocity was measured within each zone by performing a cross-correlation with a zone in a subsequent image. The location of the cross-correlation peak with respect to the origin in correlation space determined the average particle displacement within the interrogation zone from one image to the next. Dividing by the time interval between images yielded the mean velocity. The video data from the video recorder were digitized onto a 512 × 512 pixel grid and transferred to a workstation. These images were processed to produce a 48 × 48 point grid of velocity measurements by an interrogation zone size of 16 × 16 pixels with a step size of 8 pixel. A spatial resolution was about 0.33 mm/pixel.

Measurements of mean and fluctuating velocities were made with single-wire probes and hot-film anemometers which were constant-temperature types with linearized output. The mean and turbulence quantities and the spectrum analyses were done using a workstation and FFT analyzer (ONO SOKKI CF-5210).

2.3 Computational Techniques

The Navier-Stokes equations, which are based on assumptions of unsteady, viscous, laminar, incompressible and axisymmetric flow, were solved to satisfy the continuity equation by the Poisson equation for pressure, following the algorithm of SIMPLE method. The governing equations were integrated over elementary control volumes, that is, the finite control volume method was employed. The QUICK scheme was applied to approximation of the convective terms, and all other terms in the Navier-Stokes equations were approximated by the second-order-centered differencing. For time marching, the Navier-Stokes equations discretized by the finite difference scheme were solved by the completely implicit scheme. The computational domain and the boundary conditions are shown in Fig. 2. Considering the stability of the calculation, the velocities of the upstream and upper boundaries were fixed at $0.01U_o$. The calculation was carried out at Re = 5000. The excitation amplitude at the outer nozzle exit was 5% of the mean exit velocity of the outer nozzle.

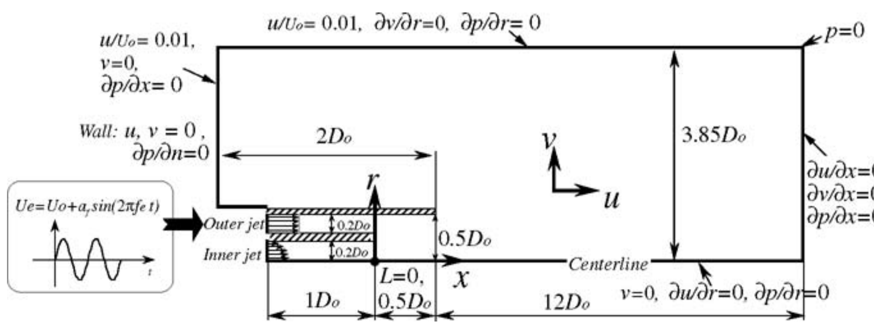


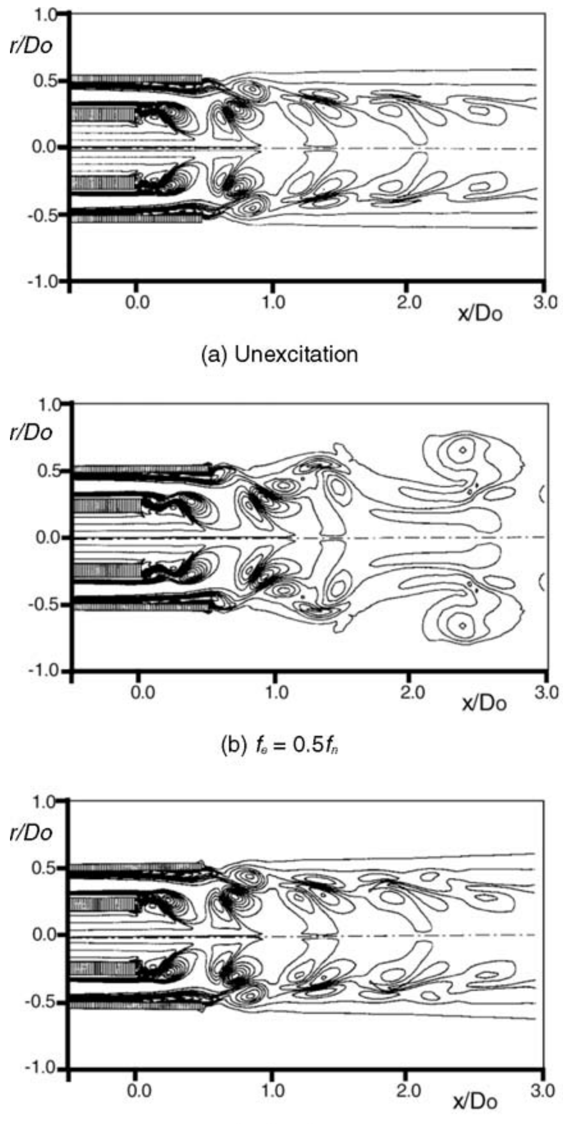
Fig. 2. Computational domain.

3. Results and Discussion

3.1 Effect of Excitation Frequency

3.1.1 Flow patterns

In order to examine the flow structure of the coaxial jets, we added the disturbance velocity with an amplitude of $a_f = 0.05U_o$ to the outer jet for the velocity ratio of $U_i/U_o = 0.6$ and the pipe length of $L/D_o = 0.5$. To visualize the flow, a fluorescent red dye, i.e., an aqueous solution of Rhodamine B, seeped through narrow slits along the lips of the inner nozzle perimeter, while the water in the tank was an aqueous solution of disodium fluorescein which fluoresces yellowish green. The fluid of the outer jet contained no dye and appears black in the photographs. The results of numerical simulation and flow visualization are in good agreement as shown in Figs. 3 and 4 for the unexcited jet and the ratios of forced/natural frequencies of Figs. 3(b) and 4(b)0.5 and Figs. 3(c) and 4(c)1.0. Figures 3(b) and 4(b) show the flow patterns of the vortex-pairing event for $f_e = 0.5f_n$. The forced excitation disturbance with frequency of $f_e = 0.5f_n$ appears to have a significant effect on the development of the vortical structure of the coaxial jet. The flow pattern of the jet of $L/D_o = 0$ with the excitation frequency of $f_e = 0.5f_n$ is similar to that of the jet of $L/D_o = 0.5$ (as shown in Fig.8).

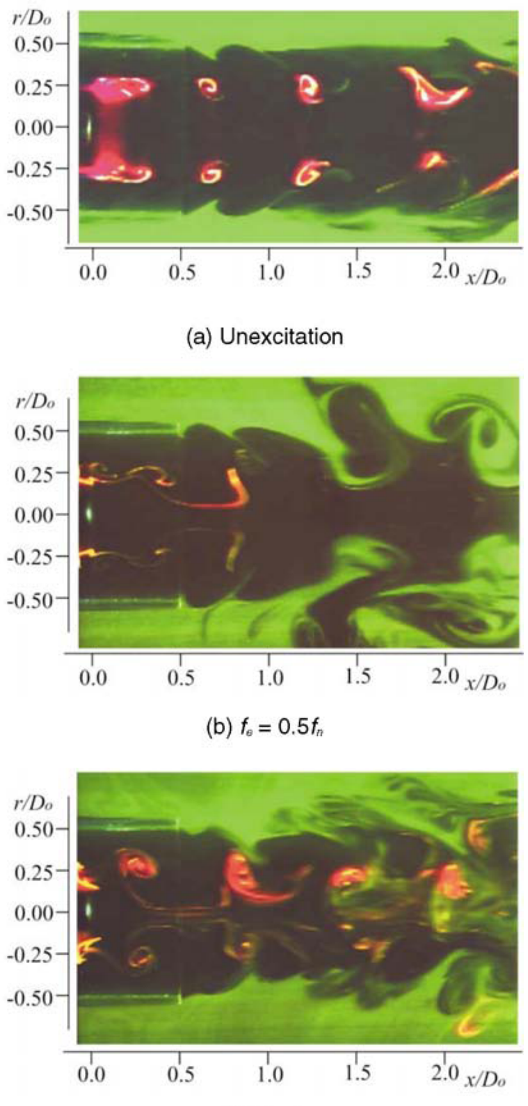


(a) Unexcitation

(b) $f_e = 0.5f_n$

(c) $f_e = f_n$

Fig. 3. Vorticity contours ($L/D_o = 0.5$, $U_i/U_o = 0.6$).



(a) Unexcitation

(b) $f_e = 0.5f_n$

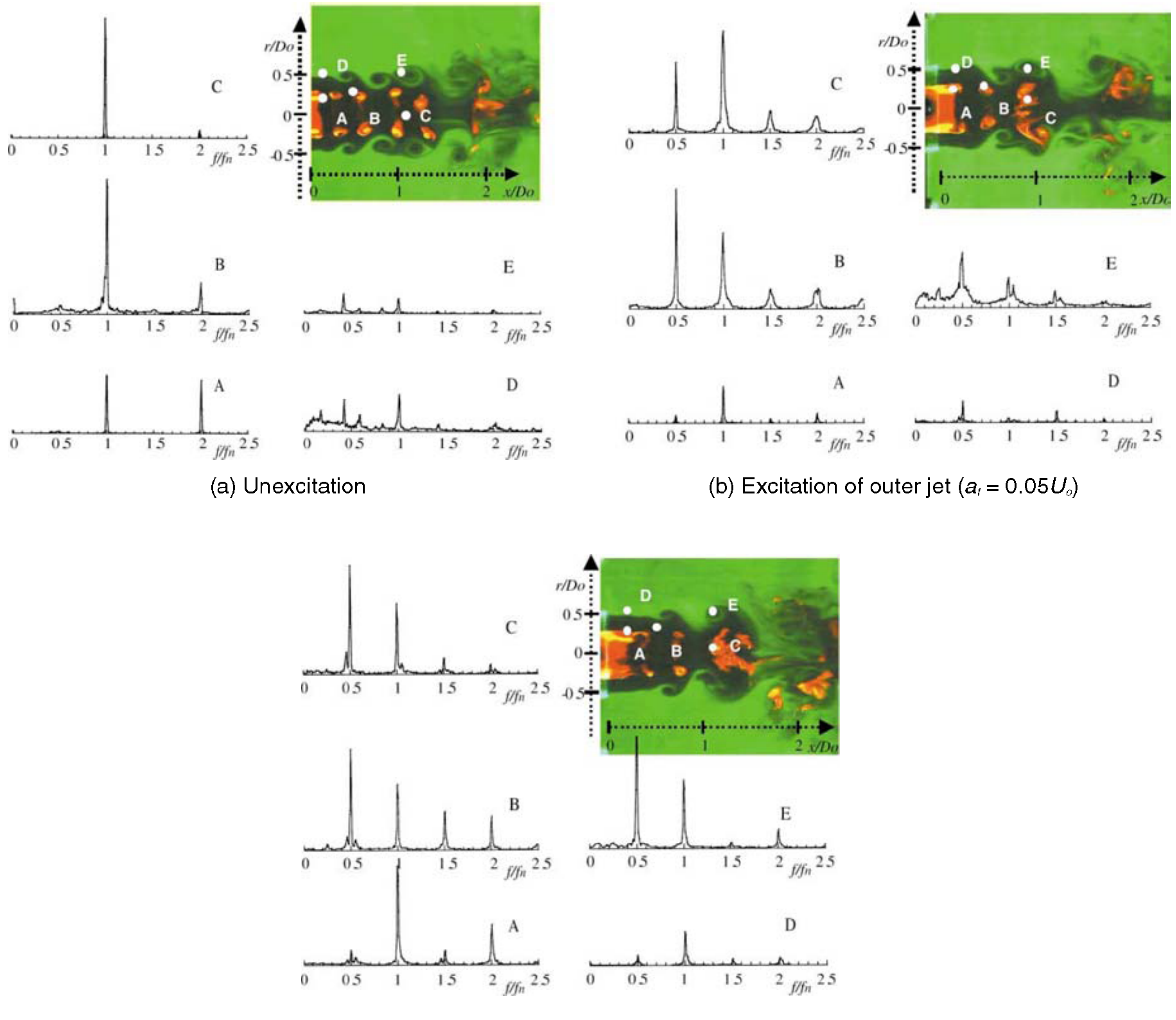
(c) $f_e = f_n$

Fig. 4. Visualized flow patterns ($L/D_o = 0.5$, $U_i/U_o = 0.6$).

3.1.2 Spectra of the velocity fluctuations

Spectral analysis of the velocity fluctuations in the near field of coaxial jet was carried out. Figure 5 shows the streamwise variations of spectra of u' signal in the shear-layers for the velocity ratio of $U_i/U_o = 0.6$, and the probe locations are shown in the inset in Fig. 5, respectively. For the unexcited jet, as shown in Fig. 5(a), the fundamental component ($f_n \approx 2.7$ Hz) remains at $x/D_o = 1$, and the subharmonic component of $f/f_n = 0.5$ does not appear. With the excitation frequency of $f_e = 0.5f_n$ in the outer or inner jet, the subharmonic component, which is associated with the vortex-pairing, is mainly observed at $x/D_o > 0.5$. In particular, for the excitation of the outer jet, the fundamental component f_n becomes dominant near the axis of the jet (shown at point C in Fig. 5(b)). Figure 6 shows the numerically predicted frequency St_{D_o}, which is normalized by the outer diameter D_o and the mean velocity U_o, at various axial locations in the inner shear layer. As can be seen in this figure, the subharmonic component becomes dominant with the increase of a distance in the x direction. For velocity ratios of $U_i/U_o = 1$, the subharmonic component growth rate is smaller than that of $U_i/U_o = 0.6$. These observations are in accord with the experimental results in Figs. 5 and 7.

Instead of presenting the spectra distribution in detail, the dominant peak frequencies f of fluctuating velocity u' in the initial region ($x/D_o = 1$) are plotted in Fig. 7 as a function of the mean velocity ratio, U_i/U_o. The frequencies of the first and second spectrum strength are chosen. For velocity ratios of $U_i/U_o \leq 0.6$, the velocity

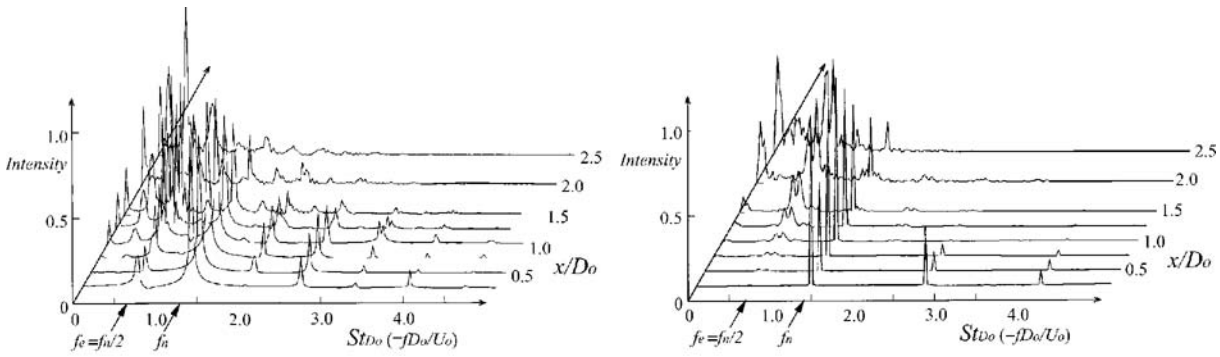


(a) Unexcitation

(b) Excitation of outer jet ($a_o = 0.05U_o$)

(c) Excitation of inner jet ($a_i = 0.1U_i$)

Fig. 5. Streamwise variation of spectra of velocity fluctuation signal ($L/D_o = 0$, $U_i/U_o = 0.6$, $f_e = 0.5f_n$).



(a) $U_i/U_o = 0.6$

(b) $U_i/U_o = 1$

Fig. 6. Spectra of velocity fluctuation signal ($L/D_o = 0.5$, $f_e = 0.5f_n$, $a_o = 0.05U_o$).

fluctuation frequency is influenced by the excitation frequency, and the dominant peak frequency f becomes the fundamental component of the excitation frequency f_e or the initial vortex frequency f_n. At velocity ratios near

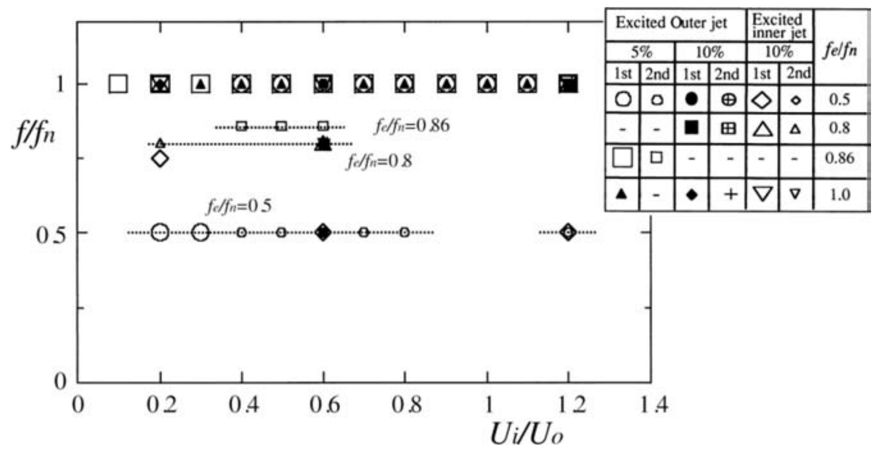


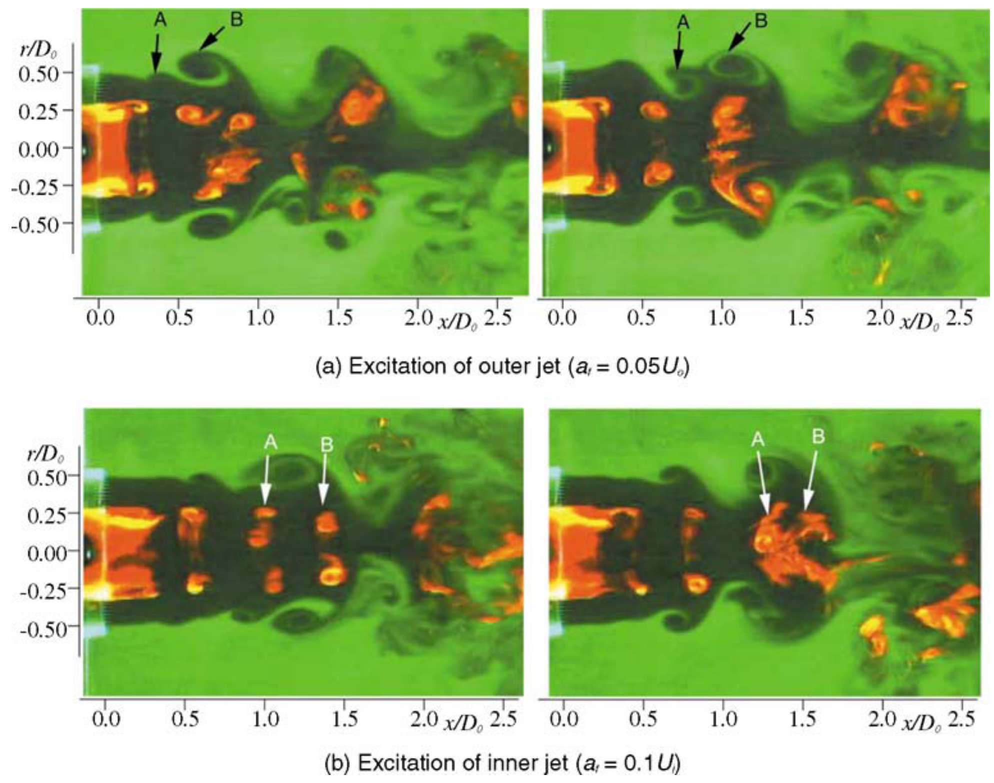
Fig. 7. Variation of the predominant frequency of the fluctuating velocity vs. the velocity ratios in the inner shear-layer ($L/D_o = 0$).

unity, i.e., $U_i/U_o \approx 1$, however, the peak frequency of velocity fluctuations is only composed of the frequency of the fundamental component of the initial vortex frequency, i.e., the lip wake vortex frequency (Kiwata et al., 1997), independent of the forced excitation frequency. With the excitation frequency of $f_e/f_n = 0.5$, except for $U_i/U_o = 0.8 \sim 1.2$, the dominant peak frequency f becomes the fundamental and subharmonic component of the initial vortex frequency. The flow pattern of the excitation amplitude of $a_f = 0.05U_o$ is similar to that of the excitation of $a_f = 0.1U_o$ (not shown here). So the excited amplitude of 10% does not seem to alter the dominant frequency of the velocity fluctuation.

3.2 Effect of Excitation of the Outer Jet, Inner Jet and Both Jets

3.2.1 Flow patterns of the vortex pairing

The vortex-structures in the near-field of the excited inner jet are compared with those of the excited outer jet in Fig. 8. This figure shows the flow visualization photographs of the vortex-pairing process. As can be seen, two



(a) Excitation of outer jet ($a_f = 0.05U_o$)

(b) Excitation of inner jet ($a_f = 0.1U_i$)

Fig. 8. Visualized flow patterns ($L/D_o = 0$, $U_i/U_o = 0.6$, $f_e = 0.5f_n$).

vortices (vortex A and B) approach each other and merge in the downstream at $x/D_o > 1$. For the excitation of the outer jet, the vortex-pairing event in the outer shear layer occurs closer to upstream than that in the inner shear layer, and then the merged vortices roll up in the downstream. On the other hand, for the excitation of the inner jet, the vortex-pairing event occurs nearer upstream in the inner shear layer than in the outer shear layer. Thus, the vortex-pairing event in the shear layer is affected by the excitation of the relevant jet.

3.2.2 Distributions of mean and fluctuating velocities

Streamwise mean velocity contours measured by PIV are shown in Fig. 9. Note that the spread of the velocity of the excitation of the inner jet is greater than that of the excitation of the outer jet. But, at $x/D_o > 1$, the centerline velocity of the excitation of the outer jet increases. The velocity contour of the excitation of the inner jet is similar

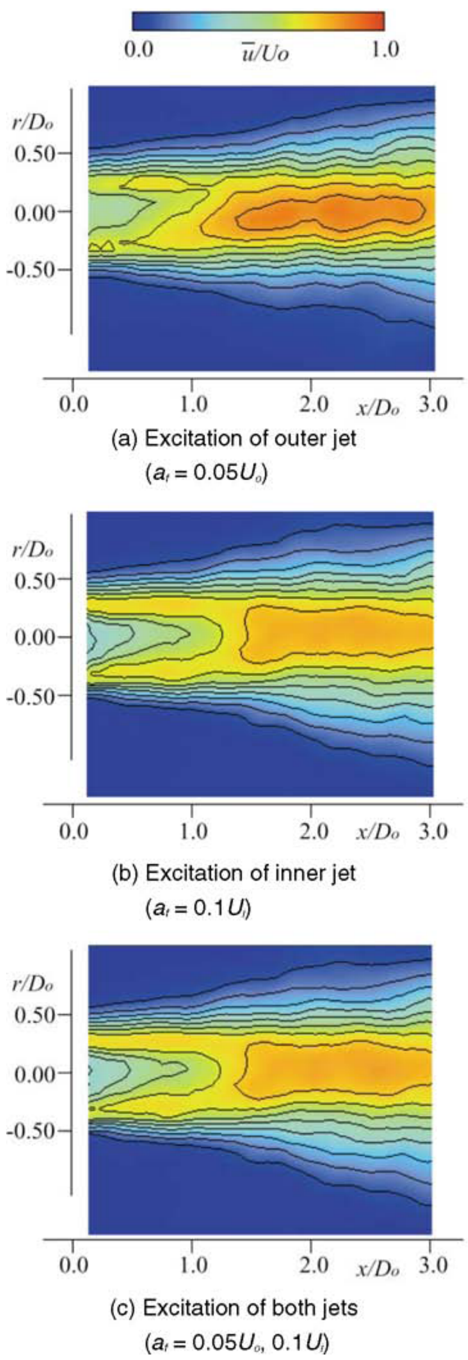


Fig. 9. Mean axial velocity contours ($L/D_o = 0$, $U_i/U_o = 0.6$, $f_e = 0.5f_n$).

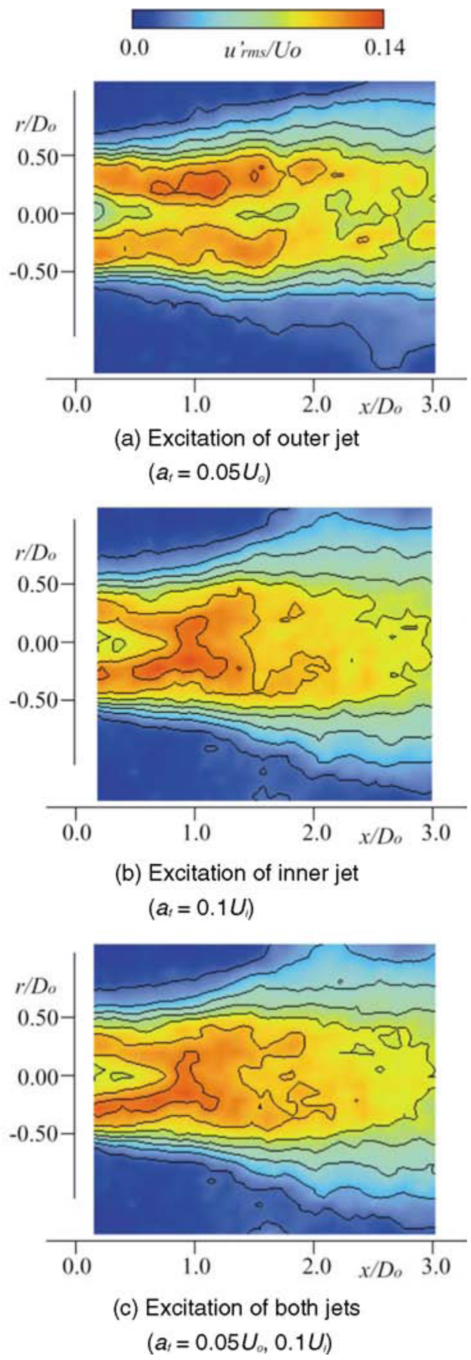


Fig. 10. r.m.s. values of streamwise velocity fluctuations contours ($L/D_o = 0$, $U_i/U_o = 0.6$, $f_e = 0.5f_n$).

to that of the excitation of the both jets.

Jet flow field intensity contour plots for streamwise velocity fluctuations are depicted in Fig. 10. Note that the fluctuation of the excitation of the outer jet is more intense within the shear layer than near the centerline, while the fluctuation intensity of the excitation of the inner jet and both jets increases within the inner mixing region near the axis of the jet. The increase of velocity fluctuation is mainly due to transverse displacement of interacting vortices by their amplified subharmonics formed during the merging process. It is found that the effect of excitation of either the inner jet or both jets on the vortex structure of the coaxial jet is different from that of excitation of the outer jet.

3.2.3 Entrainment rate

The axial distributions of the entrainment rate of fluid volume are plotted as $(Q - Q_o)/Q_o$, where Q_o is the flow rate at $x/D_o = 0.5$, against the non-dimensional distance x/D_o in Fig. 11. In the experiments, at $x/D_o \approx 0.75$ and 1.5, the entrainment rate exhibits the local maximum increase rate. These flow characteristics correspond to the vortex formation and the vortex-pairing, respectively. Moreover at $x/D_o \approx 1.0$, the entrainment rate ceases to increase until the merging process starts. The slope in the region of the vortex formation is the same as that of the vortex-pairing. These slopes seem to be independent of the excited conditions. After the merging process ($x/D_o > 2$), the slope of entrainment rate is slightly smaller. For the numerical result with the excitation frequency of $f_e = 0.5f_n$, the value of the entrainment rate increases near $x/D_o = 1$ by the vortex-pairing event (as shown in Fig. 3(b)). For the unexcited jet and in the downstream of the vortex-pairing event of the excited jet, the value of the entrainment rate hardly increases because the present numerical simulation cannot calculate the transition to the turbulent flow structure.

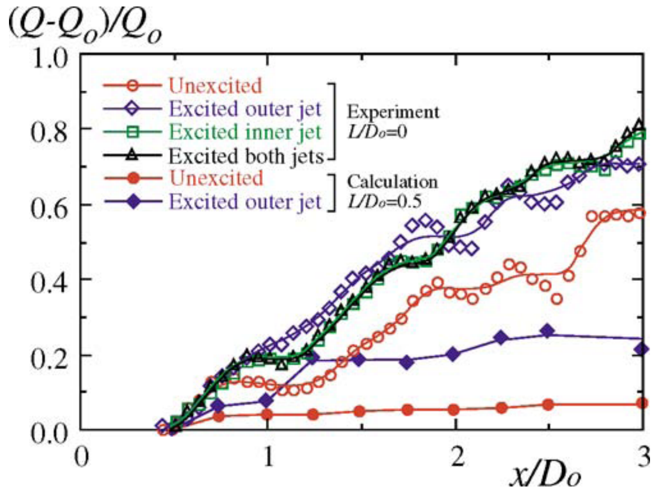


Fig. 11. Downstream development of entrainment rate in an excited coaxial jet.

The entrainment rate of the excitation of the inner jet is close to that of excitation of the both jets. It seems that, as shown by the above distributions of mean and fluctuating velocities, the flow structure of the excitation of the both jets is quite similar to that of the excitation of the inner jet. The entrainment rate of the excited jet increases faster at $x/D_o > 0.8$ than that of the unexcited jet. Thereby, it is verified that the vortex-pairing event by the forced excitation causes the rapid increase of the entrainment of coaxial jet.

4. Conclusions

The results of experimental and numerical studies on the frequency of velocity fluctuation and the vortical structure in the excited coaxial jet for various values of the velocity ratio have been presented. The main results obtained are shown below.

(1) For velocity ratios of $U_i/U_o \leq 0.6$, the velocity fluctuation frequency is influenced by the excitation frequency, and the dominant peak frequency becomes the fundamental component of the excitation frequency.

(2) There is a good agreement between the results of flow visualization and numerical simulation. It is found that the vortex-pairing event is promoted by the forced excitation of a half of the initial vortex frequency. The rapid expansion of the jet width and the increase of the velocity fluctuation and the entrainment rate have been shown

to be associated with vortex pairing in the shear layer.

(3) For velocity ratios near unity, the dominant peak frequency becomes the initial vortex frequency, independent of the forced excitation frequency.

(4) It is verified that the vortex-pairing event in the shear-layer is affected by the excitation of the relevant jet, and the interaction of these structures governs the growth, entrainment and mixing of the coaxial jet.

References

Au, H. and Ko, N. W. M., Coaxial Jets of Different Mean Velocity Ratios Part 2, J. Sound Vib., 116(1987), 427-443.

Buresti, G., Talamelli, A. and Petagna, P., Experimental Characterization of the Velocity Field of a Coaxial Jet Configuration, Exp. Thermal and Fluid Sci., 9(1994), 135-146.

Champagne, F. H. and Wygnanski, I. J., An Experimental Investigation of Coaxial Turbulent Jets, Int. J. Heat Mass Transfer, 14(1971), 1445-1464.

Chigier, N. A. and Beer, J. M., The Flow Region Near the Nozzle in Double Concentric Jets, Trans. ASME, J. Basic Eng., 86(1964), 797-804.

Dahm, W. J. A., Frieler, C. E. and Tryggvason, G., Vortex Structure and Dynamics in the Near Field of a Coaxial Jet, J. Fluid Mech., 241(1992), 371-402.

Kiwata, T., Okajima, A., Ueno, H. and Kimura, S., Vortex Frequencies of Coaxial Jets, Proc. JSME Int. Conf. on Fluids Eng.(Tokyo), 1(1997), 111-116.

Ko, N. W. M. and Au, H., Coaxial Jets of Different Mean Velocity Ratios, J. Sound Vib., 100(1985), 211-232.

Lepicovsky, J., Ahuja, K. K. and Burrin, R. H., Tone Excited Jets, Part III: Flow Measurements, J. Sound Vib., 102(1985), 71-91.

Okajima, A., Kiwata, T. and Ueno, H., Experimental and Numerical Studies on Coaxial Jets, Proc. the 4th Triennial Int. Sympo. on FLUCOME(Toulouse), 1(1994), 191-196.

Rehab, H., Villermaux, E. and Hopfinger, E. J., Flow Regimes of Large-Velocity-Ratio Coaxial Jets, J. Fluid Mech., 345(1997), 357-381.

Tang, S. K. and Ko, N. W. M., Coherent Structure Interactions in Excited Coaxial Jet of Mean Velocity Ratio of 0.3, AIAA J., 31-8(1993), 1521-1524.

Tang, S. K. and Ko, N. W. M., Coherent Structure Interactions in an Unexcited Coaxial Jet, Exp. in Fluids, 17(1994), 147-157.

Tang, S. K. and Ko, N. W. M., Experimental Investigation of the Structure Interaction in an Excited Coaxial Jet, Exp. Thermal and Fluid Sci., 8-3(1994), 214-229.

Wicker, R. B. and Eaton, J. K., Near Field of a Coaxial Jet With and Without Axial Excitation, AIAA J., 32-3(1994), 542-546.

Williams, T. J., Ali, M. R. M. H. and Anderson, J. S., Noise and Flow Characteristics of Coaxial Jets, J. Mech. Eng. Sci., 11(1969), 133-142.

Author Profile

Takahiro Kiwata: He received his master's degree in Mechanical Engineering in 1987 from Kanazawa University. He also received his doctor's degree in engineering in 1996 from Kanazawa University. After the doctor course, he worked as Research Associate of Kanazawa University. In 1999 he became an Assistant Professor in Mechanical Systems Engineering at Kanazawa University. His research interests are vortical structure of jet and wake, PIV measurements and wind turbine.

Atsushi Okajima: He received the degree of D.Eng from the University of Tokyo in 1969. After the doctor course, he worked as Research Associate of the University of Tokyo, and Associate Professor of Kyusyu University. He is Professor in Mechanical Systems Engineering at Kanazawa University. The primary areas of his research interests are flow-induced vibration of structures, separated flow around bluff bodies, aerodynamics of structures in oscillatory flow, flow/collapsible-tube interactions in internal flow and wind turbine.

Shigeo Kimura: He received his degree in Mechanical Engineering in 1980 from the University of Colorado, and his Ph.D. degree in Mechanical Engineering in 1983 from the same university. After receiving his Ph.D., he worked as Researcher of Tohoku National Industrial Research Institute. Since 1996, he has been Professor in Mechanical Systems Engineering at Kanazawa University. His research interests are experimental and numerical studies of fluid mechanics and heat transfer, with special emphasis on conjugate natural convection, solidification and gas-liquid flows.