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Flow Visualization of Vortex Structure in a Pulsed Rectangular Jet

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Abstract : Pulsating jet is visualized using hydrogen bubble method to clarify the vortex nature in the near field of the jet. This study focused on the development in space and time of vortex structures evolution in low aspect-ratio rectangular jet with pulsation. Pulsation means large-amplitude, low-frequency excitation which is expected to increase the mixing and spreading of the jet and to accelerate its transition from a rectangular form to an axisymmetric form. It was deemed appropriate to investigate whether jet characteristics of a pulsating, submerged jet flow can be altered by including pulsations. The difference of the vortex deformation process is discussed in relation to pulsating conditions. Consequently, the pulsation leads to the formation of vortices at regular intervals, which are larger than those occurring in a steady jet. The results show that the streamwise interaction, between leading vortex and trailing vortex rolled up at nozzle lips, strengthens with increasing pulsating frequency. The spanwise drift of the vortex becomes strongly apparent at large amplitude and high frequency conditions. The drifting start position does not change regardless of pulsating condition. The convection velocity of vortex increases at lower frequency and larger amplitude.

Keywords : Rectangular jet, Vortex visualization, Flow pulsation, Hydrogen bubble method.

1. Introduction

The development of a large vortex structure in fluid flow is responsible for some of the most fascinating aspects of fluid dynamics such as mixing, transport and instability. Since the pioneering work on coherent structures in turbulent flow by Crow and Champagne (1971), and Brown and Roshko (1974), a lot of research has been carried out concerning the mechanism and role of coherent structures in jet flows (Hussain and Husain, 1989; Toyoda et al., 1999; Ramesh et al., 2006). The pulsating jet also has been extensively investigated in previous works by the authors (Yellin and Peskin, 1975; Young, 1979; Yokota et al., 1986; Seno et al., 1987; Iguchi et al., 1990; Rade et al., 2005) in the fields of engineering, medical science, physiology and many others. Although the previous studies give us useful information, the effect of pulsation, large amplitude and low frequency, on the vortex structure in rectangular jet is still unclear.

The authors have already examined a series of studies of pulsating jet. Recently, pulsating jet dynamics were examined with a particular emphasis on vortex formation and behavior. Flow visualization was conducted to clarify the vortex behavior in the shear layer of a pulsating jet emanating from a rectangular nozzle with a short parallel section at the nozzle exit (Ikeda et al., 1997). This flow was then compared with that of a steady jet. The results revealed that the frequency of the vortex formation in the shear layer was in synchronizing with that of jet pulsation, regardless of the amplitude ratio of the pulsating velocity. In the case of pulsating jets, the formation and growth of vortices occurred in the upstream position unlike those in the case of steady jets. Numerical studies on pulsating jets in a shear layer were conducted solving the two-dimensional Navier-Stokes equation in order to estimate effects of pulsating frequencies, amplitude ratio, and Reynolds number on the vortex behavior (Ishikawa et al., 1998). The results of the calculation were in good agreement with the experimental results obtained by Ikeda et al. (1997). In the report by Ikeda et al. (2000), the influence of the jet exit geometry on the vortex formation of pulsating jets was clarified. The experiments were made on three exit conditions of two nozzles and a rectangular orifice. One of these nozzles had a long parallel section upstream of the jet exit and the other had a short one. As a result, the flow patterns were strongly affected by the jet exit conditions. In the case of the nozzles, the frequency of vortex formation agreed with that of the jet pulsation. In the case of the orifice, several large scale vortices were formed due to the shear layer instability, and the vortices coalesced. The vortices of the orifice jet moved downstream faster than those of the nozzle jets. In the report by Yoshida et al. (1997), we investigated the pulsating jets from rectangular chokes. Subsequently, the relationship between the thickness of chokes and vortex behavior was confirmed. The jets issuing from the thin chokes produced symmetrical patterns of small vortices. Due to the strong acceleration of discharge velocity, the symmetrical vortex pair rolled up from the corner of the choke. In the case of the thick chokes, the vortex evolution was asymmetrical. Iio et al. (2006) studied the deformation process of vortex ring in the pulsating jet issuing from a rectangular nozzle.

Experimental studies of large vortex structure in rectangular jet are investigated here. Visualization measurement using hydrogen bubble method is conducted. From this measurement, the relation between the behavior of the vortex structure and the pulsating condition is clarified. Specific objectives of this work are to examine the vortex deformation processes and interactions between vortices, as a function of pulsating frequency and pulsating amplitude.

2. Experimental Apparatus and Procedure

Figure 1 illustrates the experimental set-up. Water in a head tank with an over flow system goes through the pulsating device, enters the settling chamber and emerges in the test section through the nozzle. Figure 2 shows the geometry of the nozzle. The nozzle exit is rectangular, the width, *w*, is 20 mm, the depth, *h*, is 100 mm, and the aspect ratio, *h/w*, is 5. The nozzle is composed of two circular arcs, and a parallel part connects the edge of one of the arcs. The velocity profile at the nozzle exit is uniform, except for the thin boundary layers on the nozzle walls (Horikoshi et al., 1986). The timeline markers in the immediate vicinity of the nozzle exit show that the velocity profiles at the exit are essentially uniform with a small boundary thickness as described later (see in Fig. 4(a) for natural jet). The coordinate system is fixed at the nozzle center, *x*-axis aligned with the flow direction, the *y*-axis in the span-wise direction, and the *z*-axis in the vertical direction which is also perpendicular to the flow as shown in Fig. 2. The pulsating device consisted of a Scotch-yoke mechanism. The pulsating flow is generated by the reciprocating motion of a piston in a cylinder

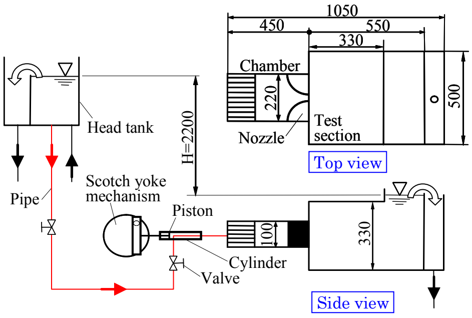

Fig. 1. Experimental apparatus.

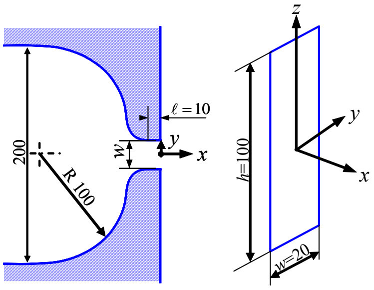

Fig. 2. Nozzle sketch.

inserted in the water-supplying pipe. The inner diameter of the pipe is 50 mm. The length of the cylinder is 280 mm and inner diameter, D, is 20 mm. The amplitude of pulsation and the frequency of pulsation are easily changeable by the rotation radius, R, of the crank pin and the rotational speed of a crank. The sinusoidal change of the displacement volume, Q_{vth}, is obtained from Eq. (1). The pulsating amplitude is defined as flow amplitude ratio $\beta = (Q_{max} - Q_{min})/(2 \cdot \overline{Q})$. The frequency of pulsation is defined as f_m. Experimental conditions are listed in Table 1. The notation concerning the flow rate, Q $(= \overline{Q} + Q_{vth})$, is shown in Fig. 3. The acceleration reaches a maximum at $t = 0$ and T, and reaches minimum at $t = 2T/4$.

$$Q_{vth} = \left(\pi^2 D^2 R f_m / 2\right) \cdot \sin 2\pi f_m t \qquad (1)$$

The jet exit velocity u_m $(= \overline{Q} / wh)$ of the steady jet is kept constant at 8 cm/s by regulating a valve that is upstream of the pulsating flow generator. The Reynolds number is Re $(= u_m w / \nu) = 1300$ and ν is the kinematic viscosity of water. Throughout this investigation the hydrogen bubble technique was employed to clarify the complex formation of the vortices. Platinum-wire electrode is mounted horizontally (parallel to the y-axis) or vertically (parallel to the z-axis) at the nozzle exit. The diameter of platinum-wire is 50 µm. Two types of bubble production were used. Application of a fixed value of DC voltage (≈ 40~50 volts) produced a uniform sheet of hydrogen bubbles with a clearly defined boundary between the edge of the jet and the ambient water. The pulsed technique of producing timelines was employed with a voltage of 300 volts, a square wave of duty ratio 0.25 at 25 Hz. The photographs to be shown here were captured from movies recorded via high speed digital video camera (DITECT, K-Ⅱ, 640 × 480 pixel, 0.42 mm/pixel) at a frame rate of 200 Hz for a total time of 10 seconds. The light source (400 watt bulb) was placed at an angle of about 90 deg. with respect to the photographing direction.

Table 1. Pulsating condition.

Case	Pulsating frequency, f_m [Hz]	Flow amplitude ratio, β
1	0.93	0.17
2		0.40
3		0.60
4	1.5	0.28
5		0.65
6		0.96
7	2.0	0.37
8		0.86
9		1.28

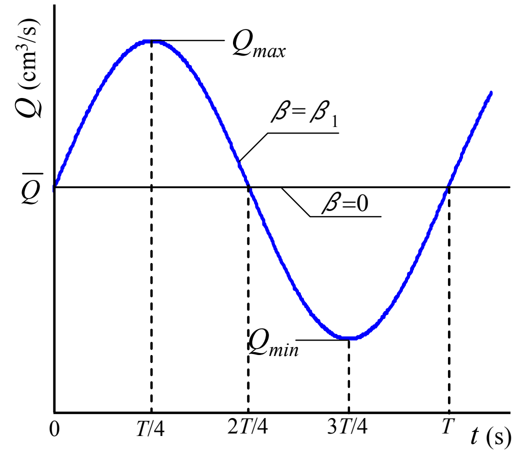

Fig. 3. Flow change model with pulsation.

3. Visualization of Vortex Formations

The typical vortex formations in the natural jet are shown in Figs. 4(a) and (b). The jet flows from the left to the right. In an inset bellow the photographing of Fig. 4 the camera views are represented by an arrow and the places, where the platinum-wire electrode mounted, are represented by dashed lines. Figure 4(a) shows flow pattern in x-y cross section. A laminar shear layer separates from the nozzle lip ($y/w = \pm 0.5$) and rolls up in to vortex at about $x/w = 2.5$ with regular spacing. The natural vortex shedding frequency, F, is 1.64 Hz (Strouhal number, $St = Fw/u_m$, is 0.41). In x-z cross section shown in Fig. 4(b), the structure looks like vortex filaments are formed in the shear layer, this structure flows downstream keeping own shape. Note that a vortex forms only in the shear layer of the nozzle long side as one of the notable features of the natural jet in this study.

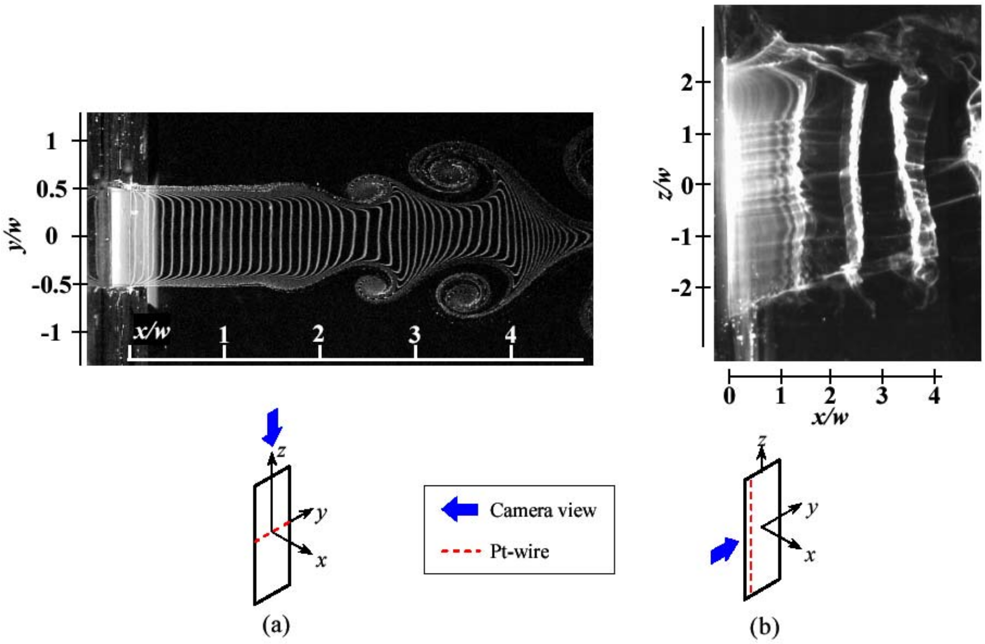

Fig. 4. Flow patterns of the natural jet: (a) *xy*-plane at *z*/*w* = 0, (b) *xz*-plane at *y*/*w* = -0.45.

The vortex formations in the pulsating jets are displayed in Figs. 5(a) and (b). Because we do not have enough space to describe everything about the vortex formations in all cases, we will introduce a few typical examples. The jet flows from the left to the right. The images were extracted at an interval one-fourth of the pulsation period T. The flow pattern images on xy-plane which platinum-wire located at $z/w = 0$ (on y-axis) shown in Fig. 5(a). The hydrogen bubble is generated intermittently. The pulsation leads to the formation of vortices at regular intervals, which are larger than those occurring in a steady jet. A vortex pair is formed at the interval of the pulsation period T in all pulsating conditions. A pair vortex generates near the nozzle exit at $t = 0$ keeps symmetric with respect to the jet axis and flows downstream with moving away from the jet centerline. The vena contracta between a pair vortex is observed clearly. For f_m = 1.5, 2.0, the vortex pair formed near the nozzle exit was drifted into one another which located downstream and coalescence each other, finally collapsed with passage of time. This tendency was more remarkable with higher pulsating frequency. In Fig. 5(b), the wire was set at $y/w = -0.45$ and parallel to the z-axis. The point to observe is that the roll vortex formed due to pulsation in the shear layer. It is clearly observed that the vortex pairs were generated in synchronization with the pulsation. A vortex tube (a part of the vortex ring) was generated near the nozzle exit parallel to the z-axis. With the passage of time, the vortex bent downstream, moved toward the jet axis, and collapsed further downstream. These self-deformation processes were the most stable in the case of $f_m = 0.93$ Hz. It is likely that the effect of each vortex deformation was independent in this observation area. On the other hand, for the case of $f_m > 0.93$, vortex ring connection occurred between each vortex and merged to a complicated vortex structure. The main results of these experiments are that the pulsating frequency and the flow amplitude ratio have significant effects on the interaction. As the pulsating frequency is higher, the position where the vortex tube generates is closer to the nozzle exit and the streamwise distances of the vortex pairs is shorter. The results show that the streamwise interaction, between leading vortex and trailing vortex rolled up at nozzle lips, strengthens with increasing pulsating frequency.

4. Evaluation of Vortex Behavior

To further understand the vortex behavior quantitatively, let us consider the behavior of the vortices

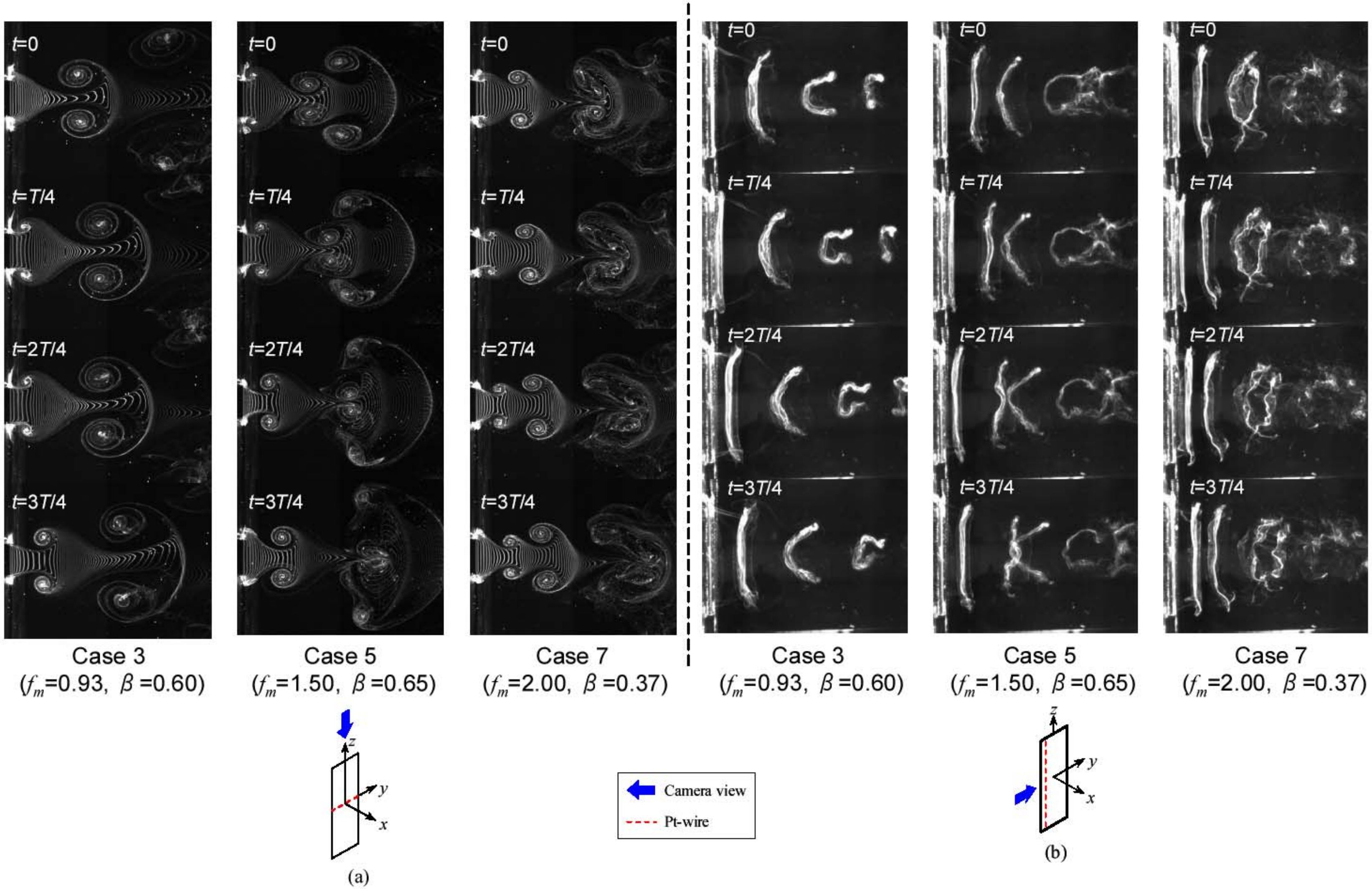

Fig. 5. Flow patterns of the pulsating jet: (left) *xy*-plane at *z/w* = 0, (right) *xz*-plane at *y/w* = -0.45.

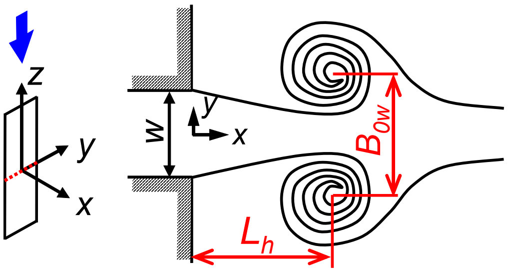

Fig. 6. Flow pattern model.

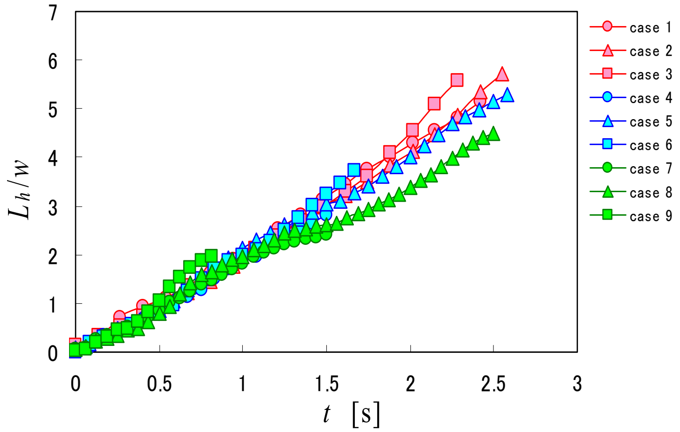

Fig. 7. The variation of L_h/w.

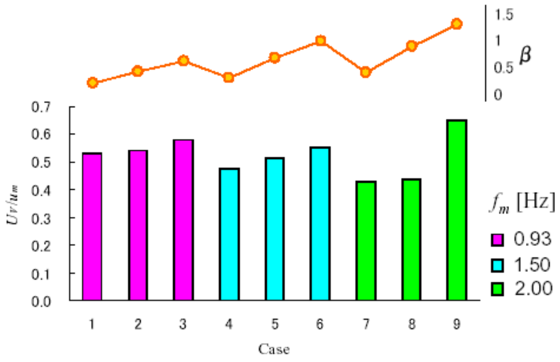

Fig. 8. Vortex convection velocity.

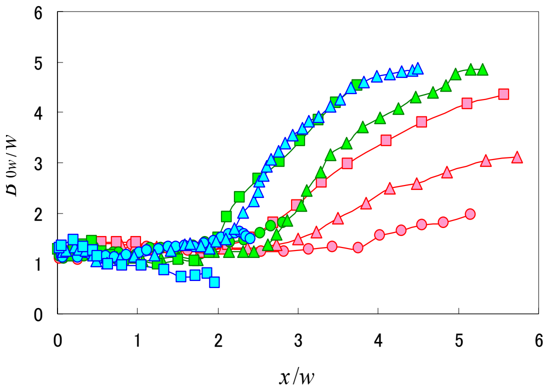

Fig. 9. The variation of B_{0w}/w.

that are formed in the shear layers. The model of the flow pattern in *xy*-section induced by pulsation is depicted in Fig. 6. Two values of the stream distances, L_h, and the distances between the vortices, B_{0w}, are defined in Fig. 6. The streamwise position of B_{0w} is defined as L_h. The locations where hydrogen bubbles are concentrated are regarded as the location of the vorticity concentration. Since these events occur near the location of the hydrogen bubble generation and have only a short travel time, the concentrations of the vorticity and hydrogen bubbles cannot be noticeably distinguished; of course, further downstream, the correspondence weakens because of three dimensional motions.

The variation of L_h/w against the pulsating time t is plotted in Fig. 7. L_h/w increases almost linearly, but the gradient is low in case of $f_m = 2.0$ (case 7-9) between $1.3 < t < 1.6$. Figure 8 shows the convection velocity of the vortices, U_V, normalized by the mean flow velocity u_m. It is clearly observed that the convection velocity is high when a pulsating frequency is low and the flow amplitude ratio is large. The difference in the convection velocity could be due to the difference in the self-induced velocity of the each vortex. The variation of B_{0w}/w against the location x is plotted in Fig. 9. Consequently, as the both of the pulsating frequency and the flow amplitude ratio increases, this value increases rapidly. It depends on the progresses of a vortex ring deformation (Iio et al., 2006). The pair vortex begins to move away from the jet axis at the same position $x/w \approx 2$, there is no dependence on the pulsating conditions.

5. Conclusion

Pulsating jet is visualized using hydrogen bubble method to clarify the vortex nature in the near field of the jet. This study focused on the development in space and time of vortex structures evolution in low aspect-ratio rectangular jet with pulsation. It is clarified that the vortex form and deformation process are greatly affected by the pulsating condition by visualization with hydrogen bubble method. The main results of this study are that the pulsating frequency and the flow amplitude ratio have significant effects on the vortex structures. As the pulsating frequency is higher, the position where the vortex tube generates is closer to the nozzle exit and the streamwise interval between vortex rings is shorter. So the streamwise interaction between leading vortex and trailing vortex strengthens with increasing pulsating frequency. As the both of the pulsating frequency and the flow amplitude ratio increases, the jet spreads rapidly. It depends on the progresses of a vortex ring deformation.

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