Effect of stroke on structure of vortex ring array in circular synthetic jets

Toru KOSO*, Shingo MATSUDA**, Hiroto MASUDA*** and Tomoya AKAHOSHI****

* Department of Energy and Environmental Engineering, Kyushu University
Kasuga-koen 6-1, Kasuga-shi, Fukuoka, 816-8580 Japan
E-mail: koso@cm.kyushu-u.ac.jp
** Present affiliation: Sanyo Electric Co., Ltd.
222-1, Kaminaizen, Sumoto City, Hyogo, 656-8555, Japan
*** Present affiliation: Hydraulic & Energy Department, Mitsubishi Heavy Industries Ltd.
2-1-1 Shinhama Arai-cho Takasago, Hyogo, 676-8686, Japan
**** Present affiliation: Fukuoka City Municipal Office
1-8-1, Tenjin, Chuo-ku Fukuoka-shi, Fukuoka, 810-0001, Japan

Received 31 March 2014

Abstract
Array of vortex rings in circular synthetic jets was investigated experimentally by instantaneous velocity measurements using a hot-wire anemometer. The ensemble averaged velocities were derived by referencing the oscillatory flow in a circular orifice. The contours of the ensemble averaged velocity showed that the elliptical shaped high-velocity regions were generated per a cycle of the oscillatory flow. These high-velocity regions were caused by vortex rings, consequently their travelling and disappearance in the downstream indicated the convection and collapse of the vortex rings. The structures of vortex array were examined for seven dimensionless strokes of the oscillatory flow range of \(L/d=0.712-7.10\), where the stroke \(L\) was the length of the fluid ejected in an oscillatory cycle and \(d\) is the diameter of the orifice. It was found that vortex rings with nearly equal intervals along the jet axis travelled downstream, and collapsed in a further downstream location. In the process of vortex collapse, no direct interactions with the neighbouring vortices were observed. For the dimensionless strokes larger than 3.6, it was observed the vortex ring accompanied weak and small trailing vortex rings. It was also found that dimensionless convection velocities of vortex ring were independent of the stroke, but the spatial intervals of vortex rings increased as the stroke was increased. As the stroke was increased, the location of the vortex collapse moved downstream. The correlation between the location of the vortex collapse and the starting point of jet width growth was good. The effect of the stroke on the jet evolution was attributed to the change in the location of the vortex collapse.

Keywords: Synthetic jet, Ensemble average, Stroke, Vortex ring, Trailing vortex, Vortex collapse

1. Introduction

A synthetic jet is a mean flow produced by an oscillatory flow through an orifice or a slit (Glezer and Amitay, 2002). A typical synthetic jet actuator consists of an orifice, a cavity, and a vibrating boundary such as a piezoelectric diaphragm disk, as illustrated in Fig. 1. The oscillatory flow through the orifice has no net-mass-flux but can generate a mean jet flow. As the disk vibrates, the volume of the cavity changes, and an oscillatory flow through the orifice is generated. In case the amplitude of the oscillatory flow is larger than a critical value, a vortex ring detaches from the orifice and moves away from the orifice by the self-induced velocity of the vortex ring. As the cycle is repeated, an array of vortex rings is formed outside the orifice and induces a mean jet flow called "synthetic jet", in a sense being synthesised from the surrounding fluids.

The synthetic jet actuator requires no fluid source and converts the electric energy directly to fluid momentum. Thus, synthetic jets have attracted much attention in recent years because of their potential for flow separation control.
(Gilarranz and Rediniotis, 2001), flow vectoring (Smith and Glezer, 2002), and mixing enhancement (Davis and Glezer, 1999; Koso, 2005; Koso and Kinoshita, 2008).

There have been many studies on the flow control applications of synthetic jets, however, studies on the flow characteristics and vortex structures of synthetic jets are relatively few. Shuster and Smith (2007) examined circular synthetic jets and showed that the flow near the orifice is dominated by the vortex rings formed during the expulsion phase, and for distances from the orifice greater than a stroke, the flow resembles a round turbulent jet with a faster spreading rate. Koso et al. (2008) compared circular synthetic jets and a continuous jet for identical orifices with matching jet momentums and found that the synthetic jets had the same self-similar profiles as the continuous jet but their spreading rates were much larger than that of the continuous jet.

The effect of the oscillatory flow conditions on the synthetic jet flow has been studied. Utturkar, et al. (2003) and Holman, et al. (2005) studied the formation criteria for synthetic jets and showed that to form a synthetic jet, the Strouhal number of the oscillatory flow should be greater than a threshold value. In other words, the stroke of the oscillatory flow should exceed half of the orifice diameter to form a synthetic jet. Di Cicca and Iuso (2007) found that the Reynolds number had no effects on the streamwise variation of the jet width. Krishnan and Mohseni (2009) showed that the streamwise decay of the centreline velocity depends on the stroke.

Koso and Morita (2010, 2014) investigated circular synthetic jets experimentally for a dimensionless stroke range of $L/d = 0.6$–2.40 and showed that the dimensionless stroke had a remarkable effect on the streamwise variation of the velocity decay and the jet width, although the Reynolds number had no significant effects on the jet flows. The spreading rate of the jet width showed a strong streamwise variation, despite of the constant spreading in a continuous jet. The jet width was found to maintain its initial value for a while, and then started to grow at some distance from the orifice. Once the jet started to grow, the spreading rate of the jet width became much larger than that of a continuous jet. After that region, the spreading rates decreased and converged to the value of a fully developed turbulent jet. As the stroke was increased, the boundary of these regions moved downstream. This stroke dependency of streamwise evolution of synthetic jets was attributed to the change in the location where vortex ring collapse, because the collapsing vortex rings could mix the jet momentum and increase the jet width.

The vortex ring formation in synthetic jets was visualised by Crook and Wood (2001) and Cater and Soria (2002). Shuster and Smith (2007) showed that the spacing between successive vortex rings increases as the stroke is increased.

These studies have revealed that the vortex rings determine the flow structures of synthetic jets. However, characteristics of vortex array and their relationship to the mean velocity field have not been fully understood.

The purpose of this study is to examine the structures of vortex array in circular synthetic jets. The ensemble averages of velocity were derived from the measured instantaneous velocities by referencing the oscillatory flow in the orifice. Then, the contours of iso-velocity were plotted to visualise the special distributions of vortex rings and their evolution in time. The convection velocity and spatial interval of vortex rings were derived and their stroke dependencies were discussed. The location of vortex collapse was determined using the rms value of the ensemble averaged velocity in a cycle, and the effect of stroke and the relationship to the streamwise variation of jet width were discussed.

![Fig. 1 Schematic of synthetic jet actuator.](image)

### 2. Experimental apparatus

#### 2.1 Synthetic jet actuators

The experiments were carried out in ambient air. Figure 2 shows schematic views of two synthetic jet actuators...
used in this study. To cover a wide stroke range, two actuators with different vibration devices were used. Figure 2(a) shows an actuator with a piezo-disk and figure 2(b) shows an actuator with an electromagnet speaker. The circular orifices were identical for both actuators, and had a straight hole with a diameter $d$ of 5.0 mm in a 0.8-mm-thick stainless steel plate.

The piezo-disk (Murata 7NB-31R2-1) consisted of a circular piezoceramic patch bonded to a thin iron-nickel diaphragm. The diameter and thickness of the diaphragm were 31.2 mm and 0.1 mm, respectively. The electromagnet speaker (Kinyo D062) had a maximum output of 2 W and a diameter of 26.5 mm. These actuators were driven by a sinusoidal AC voltage. The resonance frequency of the actuators with a piezo-disk was 700 Hz, and that with a speaker was 250 Hz.

The streamwise coordinate $x$ was measured from the outer surface of the orifice plate, and the radial coordinate $y$ was measured from the centreline of the orifice, as shown in Fig. 2.

![Fig. 2 Circular synthetic jet actuators.](image)

**2.2 Velocity measurement and processing**

The velocities in the jets were measured using a single hot-wire probe and a constant temperature hot-wire anemometer. Figure 3 shows the velocity measuring system. A modified miniature probe (TSI 1260-T1.5) with a tungsten wire that had a diameter of 5 $\mu$m and a length of 1.0 mm was used to measure the streamwise velocity $u$. The velocity signal of the hot-wire anemometer was filtered using an anti-aliasing filter, and then sampled by a 16-bit AD converter at 24 kHz. The sample duration was 10 s. The measured signals were converted to instantaneous velocities using the calibration data. The ensemble average (phase average) of velocity was calculated to resolve the unsteady, periodic flows in the synthetic jets. A sync signal of the sinusoidal AC voltage applied on the actuator was used as a phase reference.

The rms velocity $u_*$ of the oscillatory flow was measured using the hot-wire probe at the centre of the orifice, where the average velocity was zero. After the hot-wire anemometer provided the rectified velocity $|u|$ in the alternation flow, the rms velocity could be precisely derived from $u_* = \sqrt{\langle u^2 \rangle} = \sqrt{\langle |u|^2 \rangle}$ using the measured $|u|$.

The hot-wire probe was mounted on a two-axis automatic traversing mechanism. The velocity was measured at 61 streamwise locations: $0.1 \leq x/d \leq 20$ and at 21 radial locations.

![Fig. 3 Velocity measuring system.](image)
2.3 Experimental conditions

The whole flow field of a circular synthetic jet is governed by the characteristics of the oscillatory flow in the orifice. With a simple slug flow model wherein the oscillatory flow in the orifice is uniform and sinusoidal, the flow can be expressed in the form \( u = u_a \sin(2\pi f_s t) \), where \( u_a \) is the amplitude of the velocity and \( f_s \) is the oscillation frequency. This oscillatory flow can be represented by a velocity scale and a frequency \( f_s \). When the rms velocity \( u_s' = u_a/\sqrt{2} \) is used as a velocity scale instead of the amplitude \( u_a \), the synthetic jet flow is governed by the following four parameters:

- \( u_s' \): rms velocity of oscillatory flow
- \( f_s \): frequency of oscillatory flow
- \( d \): orifice diameter
- \( \nu \): kinematic viscosity of fluid

By analogy with vortex formation (Glezer and Amitay, 2002) and by the dimensional analysis (Koso and Morita, 2010, 2014), the dimensionless stroke and Reynolds number have been identified as the primary parameters of synthetic jet flows.

\[
L/d \quad \text{dimensionless stroke} \\
Re \quad \text{Reynolds number}
\]

The stroke \( L \) is defined as the length of a slug of fluid ejected during the expulsion phase in a cycle and calculated as \( L = \int_0^{T/2} u_s \sin(2\pi f_s t) \, dt = u_a/\left(4 \pi f_s \right) \), where \( T = 1/f_s \) is the time period of a cycle. The dimensionless stroke is expressed by \( L/d = (\sqrt{2}/\pi) \left( u_s'/f_s \right) d \) and is inversely proportional to the Strouhal number \( St = (f_s \cdot d)/u_s' \).

The Reynolds number \( Re = u_s' d/\nu \) is based on the rms velocity \( u_s' \) in the orifice, orifice diameter \( d \), and kinematic viscosity of fluid \( \nu \). The circulation \( \Gamma \) ejected during one cycle of the oscillation is calculated by \( \Gamma = (1/2) \int_0^{T/2} u_s \sin(2\pi f_s t) \, dt = (1/8) u_s'^2/f_s = (1/4) u_s'^2 f_s = (\sqrt{2}/8) \pi u_s' L \).

The actual flow in the orifice was not uniform, so the velocity measured in the centre of the orifice was used to represent the oscillatory flow.

Table 1 shows the experimental conditions studied. To examine the effect of the stroke, the dimensionless stroke \( L/d \) was varied from 0.712 to 7.10 with nearly constant Reynolds numbers of \( Re = 2500 \) and 2700. These strokes exceeded the critical stroke of \( L/d = 0.5 \) for synthetic jet formation. The rms velocities were kept nearly the same, and the frequencies were changed. The lower frequency range of \( f_s = 100-300 \) Hz was examined using the actuator with a speaker.

<table>
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<th>( f_s ) (Hz)</th>
<th>( u_s' ) (m/s)</th>
<th>( L/d )</th>
<th>( Re )</th>
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<tr>
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<td>7.10</td>
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3. Results and discussion
3.1 Mean velocity field and jet width

Figure 4 shows the mean velocity profiles with different strokes of \( L/d = 1.02 \) and 4.75. For both cases, typical jet flow profiles were formed and they resembled continuous turbulent jets. In these figures, the velocities just outside of the orifice are not presented because the flows in that region contain instantaneous reverse flows, and such velocities cannot be measured precisely using a hot-wire anemometer. The close comparison between two synthetic jets indicates...
that the synthetic jet with $L/d = 1.02$ near the orifice ($x = 10-25$ mm) had higher velocity than $L/d = 4.75$. Thus, the velocity distributions of two jets were different from each other, although they were driven by the same rms velocity.

Figure 5 shows the maximum velocity $\overline{u}_m$ and half-width $d_{0.5}$ along the jet axis. The maximum velocity in Fig. 5(a) was non-dimensionalised by the rms velocity $u'_s$, which was nearly the same for all the jets, with $u'_s = 7.9$ m/s. The decay curves of the maximum velocity depended strongly on the stroke. The decay of the maximum velocity for $L/d = 0.710$ started at the most upstream location. The streamwise location where the velocity started to decay moved downstream as the stroke was increased in the range of $L/d = 0.71-2.4$. For the longer stroke range of $L/d = 3.6-7.1$, the maximum velocities decayed gradually near the orifice.

The half-width $d_{0.5}$ in Fig. 5(b) was defined as a diameter. The width was non-dimensionalised by the orifice diameter $d$. The spreading rate of jet width varied along the jet axis. The half-width maintained nearly constant or grew gradually at first, and then started to grow suddenly at some distance from the orifice. This streamwise variation of jet width was different from that of the continuous jet (Koso et al., 2008) where the spreading rate of the jet width was constant. For the strokes of $L/d \leq 2.4$, the jet widths maintained nearly constant near the orifice, and started to grow at some distance from the orifice. These streamwise variations were observed in the previous study (Koso and Morita, 2010, 2014) and the sudden growth of the jet was attributed to the strong mixing by the collapsing vortex rings, based on the observed disappearance of the periodic velocity signal at the points. The collapsing vortex rings could cause the strong mixing, which resulted in the larger spreading rate of the jet width. For the strokes of $L/d = 3.6-7.1$, the jet width increased gradually near the orifice, and the increasing rate became large at some distance from the orifice. The gradual growth of the jet width correlated with the gradual decay of maximum velocity. These streamwise variations suggest that the flow structures near the orifice for $L/d \geq 3.6$ are different from those for $L/d \leq 2.4$.

![Figure 4 Mean velocity profiles](image)

(a) $L/d = 1.02$  
(b) $L/d = 4.75$

Fig. 4 Mean velocity profiles ($Re=2500, 2700, u'_s=7.9m/s$).

![Figure 5 Effect of stroke on maximum velocity and half-width of synthetic jets](image)

(a) decay of maximum velocity along jet axis  
(b) growth of half-width of jet

Fig. 5 Effect of stroke on maximum velocity and half-width of synthetic jets.

Figure 6 shows the starting point $x_s$ of jet width growth which was deduced from Fig. 5(b). The starting point showed a strong dependency of the stroke. The starting point moved downstream as the stroke was increased, but the points were nearly saturated for the larger strokes of $L/d \geq 3.6$. 

3.2 Ensemble averaged velocities

Figure 7 shows an example of calculated ensemble averaged velocity $\bar{u}$ on the jet axis in the case of $L/d = 1.02$. These are averages over a 7000 cycle period of the oscillation. The origin of time $t$ was set at an instant when the phase of the sinusoidal oscillatory flow in the orifice was zero, and the time $t$ was non-dimensionalised by the oscillation period $T$. In Fig. 7(a) $x/d = 0.1$, the peak velocity at $t/T = 0.25$ was the ejected velocity and the second peak at $t/T = 0.75$ was the suction velocity, but was displayed as positive due to the rectification of the hot-wire signals. In Fig. 7(b) $x/d = 0.8$, only the ejection velocity was observed, and the suction velocity disappeared. The rapid decay of the suction velocity can be explained that the suction flow is a potential flow which velocity is inversely proportional to the square of the distance from the orifice. In Fig. 7(c) $x/d = 4.0$, the peak velocity started to decay, and then in Fig. 7(d) $x/d = 7.0$ the velocity became nearly constant. These ensemble averaged velocities indicate that the flow was fully periodic near the orifice ($x/d \leq 4.0$), but became no correlation with the oscillatory flow in the further downstream locations.

Figure 8 shows the contours of ensemble averaged velocity $\bar{u}$ for the dimensionless stroke of $L/d = 1.02$. These contours were drawn from the ensemble averaged velocities measured at 51 times 21 points. It was observed that an elliptical shaped high-velocity region was ejected from the orifice at $t/T = 0.25$, and detached from the orifice at $t/T = 0.5$, and then moved downstream as shown at $t/T = 0.75$. At the time of $t/T = 0.75$ when the suction velocity was maximum, it was found that the suction velocity outside of the orifice was very small and restricted in the region of $x/d < 2$, due to the steep decay of the suction velocity. The high-velocity regions in the downstream locations were formed in the previous cycles. The intensity of the high-velocity region was decreased as they moved downstream. The high-velocity regions disappeared in the further downstream locations.

These high velocities can be caused by the induced velocity of a vortex rings (Lamb, 1932). Thus, the high-velocity region can be considered as an inner region of a vortex ring. Consequently, the travelling and disappearance of the regions indicate the convection and collapse of the vortex rings. Thus, it is possible to discuss the behaviors of the vortex rings from the contours of ensemble averaged velocities. The contours show that vortex rings with nearly equal intervals along the jet axis travelled downstream and collapsed in the further downstream locations. The coalescence of the vortices was not observed. It is interesting that no direct interactions with the neighbouring vortices were observed during the process of the collapse.

Figure 9 shows the ensemble averaged velocities for $L/d = 4.75$. A large high-velocity region was observed and it travelled downstream as well. The larger area can be caused by the larger circulation of the vortex ring. The circulation $\Gamma$ generated during the expulsion phase of a cycle is estimated by $\Gamma = (\sqrt{2}/8)n\pi u^2 L$, so the circulation increases as the stroke is increased. The spatial interval of vortex was longer than that of $L/d = 1.02$. It was also observed a small high-velocity region followed the leading vortex at $t/T = 0.5$. It is concluded the vortex ring accompanied a weak and small trailing vortex ring in the case of $L/d = 4.75$.

In the case of $L/d = 1.02$ (Fig. 8), the flow near the orifice ($x \leq 25$ mm) was induced by more than two vortex rings, but in case of $L/d = 4.75$ (Fig. 9), the flow near the orifice was induced by only one vortex ring due to the long vortex interval. This difference may have caused the difference in the mean velocity profiles in Fig. 5.
3.3 Effect of stroke

Figure 10 shows the contours and the streamwise profiles of the ensemble averaged velocity $\bar{u}$ for seven strokes of $L/d = 0.712$ to 7.10. The dimensionless time of these figures is $t/T = 0.5$, when the expulsion phase comes to an end and the formation of a vortex ring is completed. It is possible to examine the spatial distribution of vortex rings in the $\bar{u}$ contours and the intensity of induced velocity by vortex ring in the $\bar{u}$ profiles on the jet axis. It was observed that one vortex ring was generated in a cycle and travelled downstream for all the strokes. The peak of the induced velocity by the vortex ring became smaller as the vortex travelled downstream for example in Fig. 10(c). The peak velocity is the induced velocity by the vortex ring, so the decrease in the peak velocity suggests that the circulation of the vortex ring attenuated as the vortex moved downstream. It was also clarified that as the stroke was increased the spatial interval of vortex rings increased and the location of the vortex collapse moved downstream.

For the larger strokes of $L/d = 3.60, 4.75$, and 7.10, weak and small trailing vortex rings followed the leading vortex ring. These trailing vortices have been observed in impulsively started jets (Gharib, et al., 1998) driven by a piston for the dimensionless stroke over 3.6 to 4.5 depending on the ejection flow conditions. Thus, the present results indicate that the trailing vortex rings were formed with the similar criterion of stroke to the impulsively started jets.

The trailing vortex rings collapsed and diffused soon, as shown in Fig. 9(c) and (d). Therefore, the gradual increase
in the jet width near the orifice for $L/d \geq 3.6$ may have been caused by the collapse of trailing vortex ring.

(a) $L/d = 0.712$

(b) $L/d = 1.02$

(c) $L/d = 2.40$

(d) $L/d = 3.60$

(e) $L/d = 4.75$

(f) $L/d = 7.10$

Fig.10 Contours and streamwise profiles of ensemble averaged velocity at $t/T = 0.5$.

3.4 Characteristics of vortex ring array

Figure 11 shows the convective velocity $u_c$ of vortex ring along the jet axis. The velocities were derived from the temporal change in the $\vec{u}$ profile on the jet axis and normalized by $\sqrt{2} u'_c$, which is the maximum velocity of the oscillatory flow in the orifice. The results indicate that the convection velocities were the same for all the strokes and decreased as the vortices flowed downstream, although the some velocities showed the large scattering due to the low measurement accuracy.

The convection velocity is thought to be determined by the self-induced velocity of the vortex ring, because the neighbouring vortices induce little axial velocity on the vortex and the jet source is enough far not to affect the vortex ring, except just outside of the orifice. The self-induced velocity of a vortex ring is expressed as $u_c = (\Gamma/4\pi R)[\ln(8R/r_c)-1/4]$, where $R$ is a radius of vortex ring and $r_c$ is a radius of vortex core (Lamb, 1932). Therefore,
the decrease of the velocity $u_c$ in the downstream locations can be attributed to the decay in the circulation and the increase in the core size.

Figure 12 shows the spatial interval $\Delta x$ of vortex rings. The intervals were calculated as a distance to the preceding vortex from a vortex, for the completed vortices after $t/T = 0.5$. The vortex intervals increased as the stroke was increased. The vortex intervals decreased in the downstream locations for all the strokes due to the decrease in the convection velocity. The slowdown of the preceding vortex makes the shorter distance from the following vortex. So the streamwise decrease of the convection velocity and the streamwise decrease of the spatial interval of the vortex are caused by a single phenomenon. Figure 12 also shows the spatial interval $\Delta x$ increased as the stroke was increased.

![Fig.11 Convection velocity of vortex ring.](image1)

![Fig.12 Spatial interval of vortex rings.](image2)

Figure 13 shows the initial interval $\Delta x_0$ of the vortex rings at $t/T = 0.5$. The initial interval increased proportionally to the stroke, and can be expressed by $\Delta x_0 = 1.8L$ for $L/d \leq 4$, but the increasing rate was decreased for the larger strokes. This can be explained again by the streamwise decrease of the convection velocity of the vortex. In the case of long stroke, e.g. $L/d = 4.75$, the preceding vortex was located at $x/d = 11.5$ where the convection velocity was decreased as shown in Fig. 11, so the spatial interval $\Delta x$ became smaller.

Figure 14 shows the location of vortex collapse. The location of the vortex collapse was determined as a location where the rms value of the ensemble averaged velocity in a cycle became zero. In this study, a small threshold value of $\tilde{u}'/u_c = 0.003$ was used to determine the location. This value was nearly zero but high enough above the noise level of the calculated $\tilde{u}'$. The location of the vortex collapse moved downstream as the stroke was increased, but the increasing rate became smaller for the larger strokes.

The collapsing vortex could cause the strong momentum mixing in the jet, so the locations of vortex collapse were compared with the starting points of the jet width growth of Figure 6. Figure 15 shows the comparison between them. The starting point of the jet width growth was smaller than the location of vortex collapse, because the starting point of the jet width growth corresponded to the beginning of the vortex collapse, but the locations of vortex collapse corresponded to the end of the vortex collapse. The figure shows the correlation was good, thus it suggests that the

![Fig.13 Effect of stroke on initial interval of vortex rings.](image3)

![Fig.14 Effect of stroke on location of vortex collapse.](image4)
expansion of jet width was caused by the collapsing vortex rings. Consequently, the effect of the stroke on the jet evolution can be attributed to the change in the location of the vortex collapse.

4. Conclusions

The ensemble averaged velocities in circular synthetic jets were measured and the effect of the stroke on the structures of vortex array was examined. The array of vortex ring and its evolution were visualised successfully on the two-dimensional contour graphs of the ensemble averaged velocity. The convection velocity and spatial interval of the vortex rings, and the location of vortex collapse were deduced.

It was found that a vortex ring was generated in a cycle of the oscillatory flow for all the stroke range of \( L/d = 0.712-7.10 \). The vortex rings with nearly equal intervals along the jet axis travelled downstream and collapsed in the further downstream locations. As the vortex ring moved downstream, the convection velocity of vortex ring was decreased, consequently the spatial interval of vortex rings was decreased. The coalescence of the vortex rings was not observed. No direct interactions with the neighbouring vortex rings were observed during the process of the vortex collapse.

As the stroke was increased, the spatial intervals of vortex rings increased but the convection velocities of vortex ring were independent of the stroke. As the stroke was increased, the location of vortex collapse moved downstream. The correlation between the location of vortex collapse and the starting point of jet width growth was good. The collapsing vortex rings could have caused the strong momentum mixing of the jet that results the larger spreading rate of the jet width. Consequently, the effect of the stroke on the jet evolution can be attributed to the change in the location of the vortex collapse.

For the larger strokes of \( L/d \geq 3.6 \), the vortex ring accompanied weak and small trailing vortex rings. These trailing vortex rings were formed with the similar criterion of stroke to the impulsively started jets. The trailing vortex rings collapsed and diffused soon, therefore the gradual increase in the jet width near the orifice for \( L/d \geq 3.6 \) may have been caused by the collapse of trailing vortex rings.

Acknowledgements

This study was supported in part by Grants-in-Aid for Scientific Research (No.23560197) from Japan Society for the Promotion of Science (JSPS) and by Grants-in-Aid for Fluids Engineering Research from Harada Memorial Foundation.

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