Flow Field for Merging of Four Vortex Rings in a Round Jet Acoustically Excited by a Sinusoidal Wave

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Abstract

Round jets roll up the shear layer near the nozzle exit and form vortex ring street. The vortex ring street then merge to form large vortex rings. Since the formation of vortex rings is a periodic phenomenon, acoustic excitation using periodic sound waves is highly effective for controlling vortex rings. Acoustic excitation can cause the regular merging of vortex rings, which occurs irregularly in the natural transition of jets. We have shown through experiments by flow visualization that four consecutive vortex rings can be merged by acoustic excitation with a single sinusoidal wave of a single frequency, and have shown the condition of *Re* and *St* of jets for the merging of four vortex rings. The streamwise distance between the vortex rings when the four vortex rings merge has been presented. Here, PIV measurements were conducted to investigate the advective velocity of the vortex rings in the above merging process.

Keyword: *Round jet, Vortex ring, Merging process, Advection velocity, Acoustic excitation*

1. Introduction

Since the characteristics of the jet (diffusion, mixing, and noise, etc.) are closely related to the behavior of vortices, it is possible to control the characteristics of the jet by controlling the vortices in the jet. In a round jet, the shear layer rolls up near the nozzle exit and a vortex ring street are formed in the initial region. The vortex ring street then merges to form large vortex rings. The large-scale vortex ring eventually breaks down and becomes disordered due to azimuthal instability of the vortex ring. Since the formation of vortex rings is a periodic phenomenon based on the instability of the shear layer, acoustic excitation, which is one of the active control methods using periodic sound waves, is suitable for controlling vortex rings. Several researchers have studied round jets using acoustic excitation, and have proposed the concept of a preferred mode [1], [2]. In naturally transitioning jets, the merging of vortex rings occurs irregularly, but acoustic excitation can induce regular merging.

It is said that the merging of N vortex rings is promoted by excitation at a frequency of f_v/N (where N is a natural number) when the frequency of the formation of the vortex rings is f_v [3]. It is also known that the merging of two consecutive vortex rings occurs by acoustic excitation at half the frequency of f_v. However, the upper limit of N has is still unknown. Inoue and Muramatsu [4]-[8] investigated the conditions and the number of vortex rings involved in merging using flow visualization techniques. They showed that four consecutive vortex rings can merge by using excitation at two frequencies (bimodal excitation) or excitation at a single frequency. The merging process of four vortex rings is illustrated in Fig. 1 [8]. The formation order of vortex rings is from (I) to (IV). The first two vortex rings (I) and (II) merge with each other, the later vortex rings (III) and (IV) merge with each other, and then the merged vortex rings (I) + (II) and (III) + (IV) merge with each other, resulting in the merging of four vortex rings. Note that the number of vortex rings that merge at one time is two. They showed that the dimensionless frequency (Strouhal number) *St* at which the merging of four consecutive vortex rings occurs for jets with a jet Reynolds number *Re* between 3000 and 7000 excited at a single frequency, and the distance in the streamwise direction between the vortex rings for the merging [8]. In addition, when four vortex rings merge, the breakdown of the jet is delayed than when the four vortex rings do not merge, and the initial region may extend further downstream. This phenomenon corresponds to the preferred mode concept presented by Crow and Champagne [1].

In this study, we present the results of PIV measurements conducted to investigate the advection velocity of the vortex rings in the merging process of the four vortex rings, as reported by Muramatsu and Inoue [8].

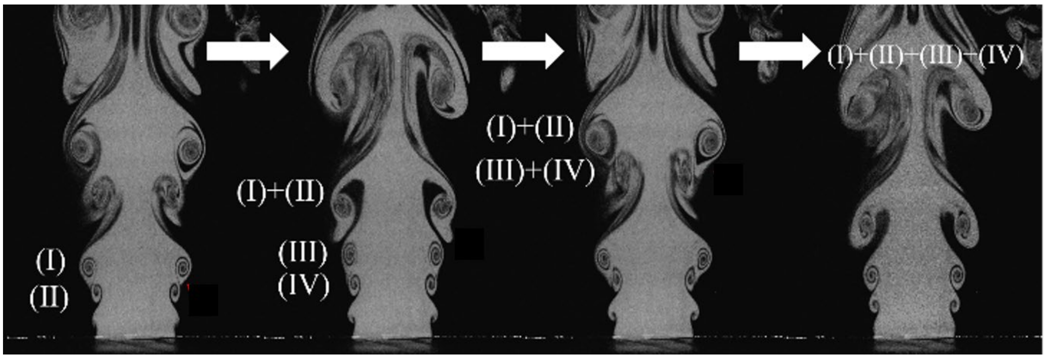

Fig. 1 Merging process of four vortex ring by excitation of a sinusoidal wave at a single frequency, $Re = 4000$, $St = 1.10$ [8].

2. Experimental Device and Method

The experimental device shown in Fig. 2 is identical to that used by Inoue and Muramatsu [4]-[8]. A 20 cm full-range speaker (Fostex, FF225WX) is attached to the bottom of the device to introduce disturbances in the main flow direction of the jet. Air is introduced into the nozzle through the two inlets as shown in Fig.1, and then ejected vertically upward from a round nozzle into still air. The exit diameter of the round nozzle is $D_0 = 16$ mm, and the area contraction ratio is 17.0.

PIV measurements were performed using a laser sheet with approximately 1 mm thick and a high-speed camera at 10,000 fps, with the air jet and surrounding air mixed with fine particles. Experimental conditions were set up based on the Ref. [8]. The Reynolds number Re of the jet was set to 5000, where the characteristic velocity of Re is the issuing velocity at the center of the nozzle exit U_{c0}, and the characteristic length is the nozzle diameter D_0. A sine wave with frequency f_s was input to the loudspeaker, and the turbulence intensity at the nozzle exit center was set to 2%. The frequency f_s was set at a dimensionless frequency $St = f_s D_0/U_{c0}$, ranging from 1.00 to 1.40 in increments of 0.10. In the PIV analysis, the velocity and vorticity fields were computed using a PIV analysis software, DynamicStudio (Dantec Dynamics), which processed pairs of images with a time difference of 1/10,000 s, setting the interrogation area to 32 x 32 pixels and an overlap of 50%.

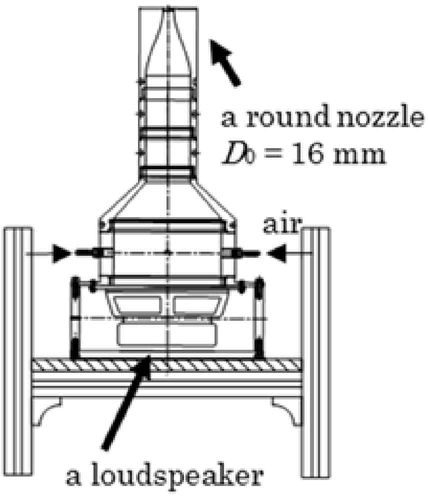

Fig. 2 A round nozzle with a loudspeaker.

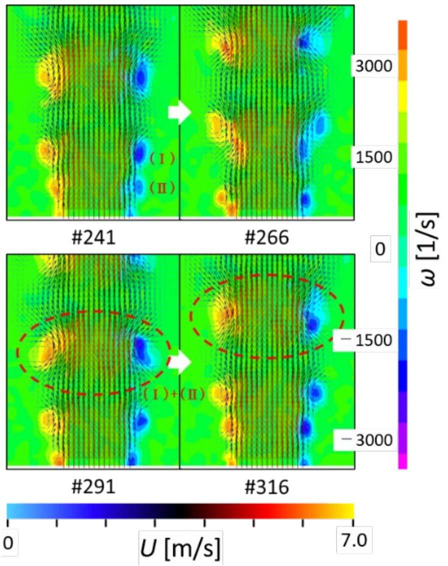

Fig. 3 Measured velocity and vorticity ($Re = 5000$, $St = 1.00$).

3. Experimental Results

Under the experimental conditions displayed here, three different cases are observed: no merging of vortex rings at all ($St = 1.40$), merging of two vortex rings ($St = 1.00$), and merging of four vortex rings ($St = 1.10$ to 1.30). Figure 3 shows the PIV measurement results, illustrating the merging process of two vortex rings.

Figure 3 is vorticity contours superimposed on velocity vector diagrams. The numbers with "#" in Fig. 3 indicate the frame number of the image. At frame #241, vortex rings (I) and (II) are visible in the order of their formation. At frame #266, the two vortex rings have approached each other, and at frame #291, they have merged, as indicated by the red dashed line. At frame #316, the merged vortex rings continue to move downstream. During the merging process, the red velocity vectors in the center of the jet increase, suggesting an increase in flow speed near the jet centerline during the merging.

The merging processes of two vortex rings and four vortex rings are visualized using vorticity contour plots. Figure 4 shows a contour plot of vorticity at *St* = 1.00 when two vortex rings merge, while Fig. 5 displays a contour plot of vorticity at *St* = 1.20 when four vortex rings merge. Figures 4 and 5 show eight frames to easily compare the merging processes of vortex rings, and the numbers marked by "#" representing the frame numbers. In Fig. 4, two vortex rings formed in the lower half of frame #241 merge by frame #291. Similarly, the two vortex rings in the lower half of #316 merge by #366. However, as can be seen in the subsequent #391 and #416, the upstream merged vortex rings (III) + (IV) do not catch up with the downstream merged vortex rings (I) + (II) and continue to flow downstream. In Fig. 5, where *St* is larger than in Fig. 4, the interval between the initially formed vortex rings is shorter. The two vortex rings visible at the bottom of #189 in Fig. 4 merge by #241. Similarly, the two vortex rings visible upstream of #263 merge by #306, and then the merged vortex rings (III) + (IV) catch up with the merged vortex rings (I) + (II) on the downstream side, combining into a total of four vortex rings at #372.

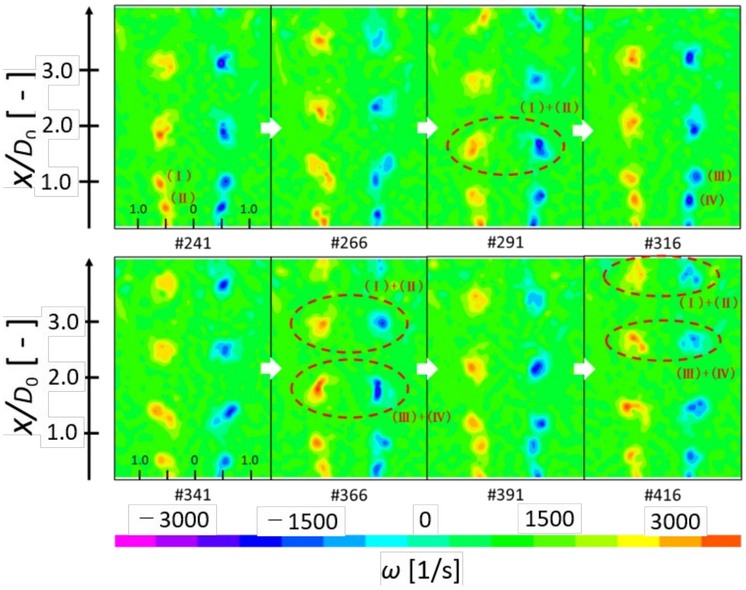

Fig. 4 Pairing process of two vortex rings (*Re* = 5000, *St* =1.00).

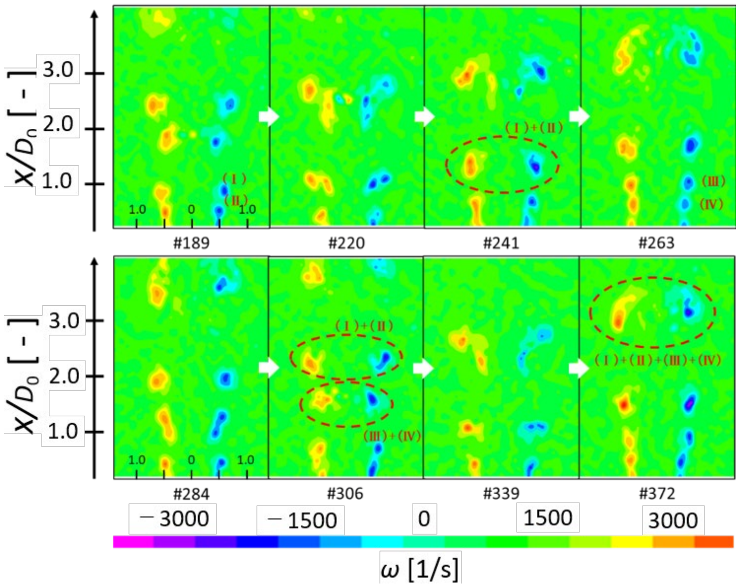

Fig. 5 Merging process of four vortex rings (*Re* = 5000, *St* =1.20).

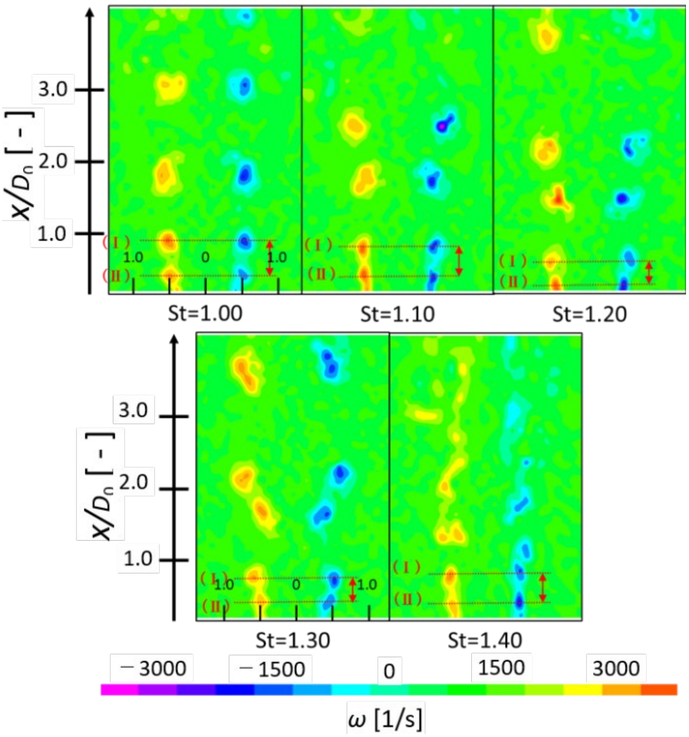

Fig. 6 Vorticity contours when vortex ring II forms (Re = 5000).

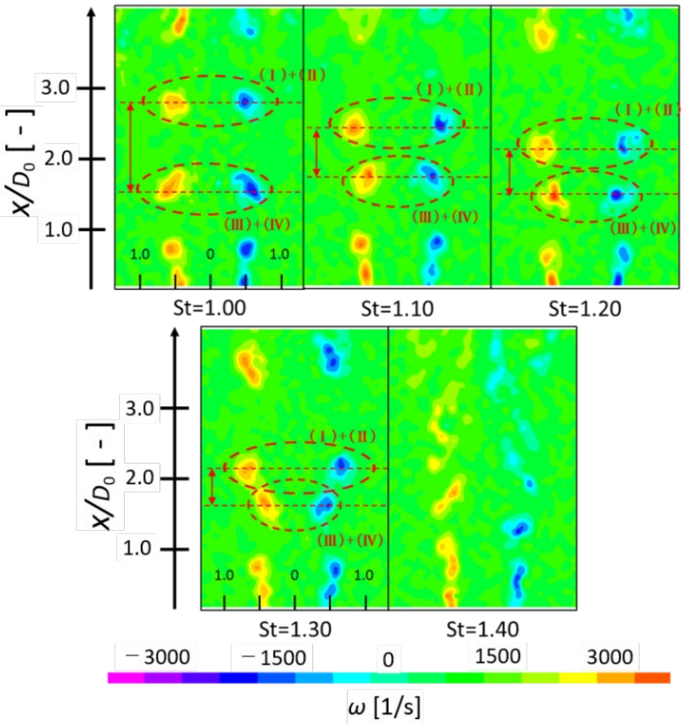

Fig. 7 Vorticity contours when vortex rings III and IV merge (Re = 5000).

Figure 6 shows the vorticity contours for each St immediately after the formation of vortex ring (II), and Fig.7 shows the vorticity contours immediately after the vortex rings (III) and (IV) merge. Figure 6 shows that the streamwise distance between vortex rings (I) and (II) decreases with increasing St, but the distance increases at St = 1.40, where vortex rings do not merge. The dimensionless streamwise distance, non-dimensionalized by D_0, is 0.446 for St = 1.00, 0.311 for St = 1.30, and 0.345 for St = 1.40. Table 1 shows the values of the velocity in the streamwise direction (advection velocity), velocity difference, and velocity ratio at the center of each vortex ring in Fig. 6. Except for St = 1.40, where vortex rings do not merge, the flow velocities of vortex ring (II) are slightly faster than those of vortex ring (I), and the ratio of the velocity of vortex ring (II) divide by the velocity of vortex ring (I) are 1.05 to 1.08.

From Fig. 7, the streamwise distance between the merged vortex rings (I) + (II) and the merged vortex rings (III) + (IV), made dimensionless by D_0, is 1.27 at St = 1.00, when no merging of the four vortex rings occurs. However, this distance decreases to 0.788 at St = 1.10, 0.686 at St = 1.20, and 0.364 at St = 1.30. These measured distances align with the condition for the merging of four vortex rings, where the dimensionless distance between vortex rings must be 0.75 or less, as indicated by Muramatsu and Inoue [8]. The advection velocities of the merged vortex rings in the streamwise direction at the center of the merged vortex rings in Fig. 7 are shown in Table 2, as in Table 1. At St = 1.00, namely when the four vortex rings do not merge, the streamwise velocities of the merged vortex ring (I) + (II) and the merged vortex ring (III) + (IV) are almost the same. However, when the four vortex rings merge, the streamwise velocities of the merged vortex ring (III) + (IV) exceed than those of vortex ring (I) + (II) by a factor of 1.1 to 1.2. These differences in velocity is larger than those observed between vortex rings (I) and (II) immediately after the formation of vortex ring (II).

Table 1 Streamwise velocities of two vortex rings I and II (Re = 5000).

St	Vortex ring	U [m/s]	ΔU [m/s]	U_{II}/U_I
1.00	(I) (II)	4.556 4.901	0.345	1.076
1.10	(I) (II)	4.375 4.680	0.305	1.070
1.20	(I) (II)	4.379 4.663	0.284	1.065
1.30	(I) (II)	4.495 4.730	0.236	1.052
1.40	(I) (II)	4.753 4.560	− 0.193	0.9594

Table 2 Streamwise velocities of two merged vortex rings (Re = 5000).

St	Vortex ring	U [m/s]	ΔU [m/s]	U_{III+IV}/U_{I+II}
1.00	(I) + (II) (III) + (IV)	5.21 5.24	0.0302	1.006
1.10	(I) + (II) (III) + (IV)	4.70 5.21	0.505	1.109
1.20	(I) + (II) (III) + (IV)	4.51 5.40	0.897	1.197
1.30	(I) + (II) (III) + (IV)	5.18 5.64	0.463	1.089
1.40	(I) + (II) (III) + (IV)	– –	–	–

4. Conclusion

The streamwise distance between two merged vortex rings and the advection velocity of the merged vortex rings were investigated for both cases in which four consecutive vortex rings merge and in which only two vortex rings merge. A significant difference in both the distance and advection velocity was observed between these two scenarios.

References

[1] Crow, S. C. and Champagne, F. M., “Orderly Structure in Jet Turbulence”, *Journal of Fluid Mechanics*, Vol. 48 (1971), pp. 547-591.

[2] Zaman, K. B. M. Q. and Hussain, A. K. M. F., “Vortex Pairing in a Circular Jet under Controlled Excitation, Part 1. General Jet Response”, *Journal of Fluid Mechanics*, Vol. 101 (1980), pp.4 49-491.

[3] Toyoda K., “Vortices in jets”, *Journal of Japan Society of Fluid Mechanics “Nagare”*, Vol. 24, (2005), pp 151-160, (in Japanese).

[4] Inoue, N. and Muramatsu, A., “Control of merging process of vortex rings in a round jet”, *Proc. 48th Visualization*

Symposium of Japan, Online, (2020), pp. 1-5, (in Japanese).

[5] Inoue, N. and Muramatsu, A., "Merging of vortex rings in a round jet by acoustic excitation", *Proc. Mechanical Engineering Congress of JSME*, Chiba, S051-28, (2021), pp. 1-4, (in Japanese).

[6] Inoue, N. and Muramatsu, A., "The effect of Reynolds number on merging of vortex rings in a round jet", *Proc. Fluid Engineering Conference of JSME*, Online, OS03-06, (2021) pp. 1-4, (in Japanese).

[7] Inoue, N. and Muramatsu, A., "Merging Control of Vortex Rings in a Round Jet by Acoustic Excitation", *Proc. The 7th International Conference on Jets, Wakes and Separated Flows,* Tokyo, ICJWSE2022-E04, (2022), pp. 1-6.

[8] Muramatsu, A. and Inoue, N., "Merging of Four Vortex Rings in a Round Jet Using a Sinusoidal Sound Wave", *Proc. The 6th Symposium on Fluid-Structure-Sound Interactions and Control,* Busan, (2023) pp. 1-5.