Merging of Four Vortex Rings in a Round Jet Using a Sinusoidal Sound Wave

Akinori Muramatsu and Naho Inoue

Abstract In the initial region of a round jet, there are periodic vortex rings, which merge to form a large-scale vortex ring that subsequently collapses and becomes turbulent. This study focuses on the merging of vortex rings in a round jet, and aims to clarify the conditions for the regular merging of vortex rings. Acoustic excitation using a sinusoidal wave was used to facilitate the regular merging of the vortex rings. To investigate the merging process of vortex rings, the streamwise cross-section of the excited jets with varying Reynolds numbers was visualized using a laser-light sheet. As a result, it was found that there is a specific range of Strouhal number within which four vortex rings merge. There is a suitable frequency for the merging by acoustic excitation. The reason is discussed for this phenomenon and it is found there is a suitable distance between vortex rings for successful merging.

Keywords Round Jet · Vortex ring · Merging process · Preferred mode

1 Introduction

Periodic vortex rings exist in the initial region of a round jet, and they merge to form a large-scale vortex ring before collapsing and becoming turbulent. The characteristics of jets are primarily governed by the vortical structure in the initial region. The formation of vortex rings is a periodic phenomenon based on the instability of the jet shear layer, making it easy to control using acoustic excitation with sound waves. Many researchers have studied round jets using acoustic excitation and proposed the concept of a preferred mode [1–3]. Since the vortex rings in a round jet may irregularly merge in the natural transition, they were regularly merged using acoustic excitation [4]. Acoustic excitation at the frequency of vortex ring formation confirmed the

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regular merging of four vortex rings in the range of jet Reynolds number, *Re* from 3000 to 6000 [5]. Regular merging of two vortex rings was observed in jets with *Re* of 2000 and 7000, where vortex rings do not merge naturally [6]. To investigate the frequency range where four vortex rings merge, visualization experiments were conducted using a dimensionless frequency, namely Strouhal number *St*, as a parameter. By obtaining the formation and collapse positions, and the formation interval of vortex rings from visualized images, we discussed the conditions under which four vortex rings merge.

2 Experimental Device and Method

A round nozzle with a loudspeaker attached to the bottom was used to introduce a disturbance in the streamwise direction of a jet [4–6]. The outlet diameter of the round nozzle is $D_0 = 16$ mm, and the area contraction ratio is 17.0. Air was ejected vertically upward from the round nozzle into still air by giving it a periodic disturbance generated by the loudspeaker. Flow visualization was conducted using Mie scattering to investigate the merging of vortex rings in the round jets. Fine particles were mixed into the air jet, and a laser-light sheet with a thickness of about 1 mm was irradiated on the jet centerline. The images of streamwise cross-section of the jets were recorded using a high-speed camera.

First, the merging processes of vortex rings were visualized in the natural transition. The jet Reynolds number *Re* was set in the range of 1000 to 10,000 in increments of 1000. The *Re* is defined by the velocity on the center at the nozzle exit U_{c0} and the diameter at the nozzle exit D_0. Next, vortex rings were regularly merged using acoustic excitation. The *Re* was set to 2000–7000, based on the range where vortex rings were formed in the natural transition. Dimensionless frequency *St* was set to 1.00 to 1.40, which is close to *St* obtained from the formation frequency of vortex rings in the range of *Re* from 3000 to 7000 in the natural transition. The excitation frequency f_s of the jet was determined from $St = f_s\, D_0/U_{c0}$. The signal waveform input to a loudspeaker was sinusoidal, and the voltage was adjusted by an amplifier so that the turbulent intensity of the velocity fluctuation at the center of the nozzle exit was 2%. The turbulent intensity was measured using a hot-wire anemometer.

3 Experimental Results and Discussion

3.1 Merging of Vortex Rings in the Natural Transition

In the natural transition, the merging of vortex rings is observed in the range of *Re* from 3000 to 6000. Only two vortex rings can merge at the same time, and no more than two vortex rings merge simultaneously. The jet with *Re* of 1000 is laminar and

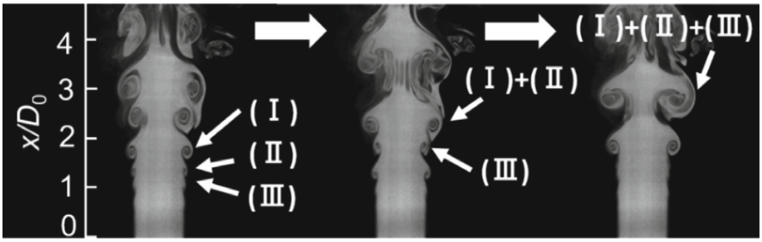

Fig. 1 An example of merging process of 3 vortex rings in the natural transition ($Re = 5000$)

has only constrictions in the shear layer. At *Re* of 2000, vortex rings form but do not merge. The dimensionless formation frequency *St* of vortex rings when *Re* is between 2000 and 7000 is greater than 1.00 except for the jet with *Re* of 2000. The *St* has maximum when *Re* is 5000. Hussain et al. [2] reported *St* ranges from 0.6 to 1.6 for the column mode in the pairing of vortex rings. The *St* calculated from the formation frequency of vortex rings f_v obtained from visualized images is in this range except when *Re* is 2000.

At *Re* of 5000, the merging process of vortex rings has various types, with merging observed for two, three, or four vortex rings. The merging processes of three vortex rings consists of two types and one of which is illustrated in Fig. 1. The dimensionless coordinate x/D_0 is indicated in Fig. 1, where *x* represents the streamwise coordinate from the nozzle exit and D_0 is the nozzle diameter. The formation order of continuously forming vortex rings is from (I) to (III). One is that the first vortex ring (I) and second vortex ring (II) merge and then the merged vortex ring (I) + (II) merges with the third vortex ring (III), as shown in Fig. 1. The other is that the second vortex ring (II) and third vortex ring (III) merge first and then the merged vortex ring (II) + (III) merges with the first vortex ring (I). The difference between these two merging processes is thought to be caused by a slight deviation in the timing of the vortex ring formation. Similarly, the merging of two vortex rings and the merging of four vortex rings are also presumed to be influenced by slight deviations in the timing of vortex ring formation. Therefore, it is considered important to investigate the merging process of vortex rings under regular formation conditions.

3.2 Merging of Vortex Rings by Acoustic Excitation

Two or four vortex rings merge due to acoustic excitation. The merging process of four vortex rings is illustrated in Fig. 2. The formation order of vortex rings is from (I) to (IV). The first (I) and second vortex ring (II) merge, and then the third (III) and forth vortex ring (IV) merge in a similar manner. Subsequently, the vortex rings (III) + (IV) are drawn into the vortex rings (I) + (II) from the inside, and then the four vortex rings merge. It can be observed that in each merging process, a flow structure (predicted as a vortex sheet) hanging from the downstream vortex ring extends outward the upstream vortex ring, as indicated by the red arrows in Fig. 2. It is presumed that this structure suppresses the radial growth of the upstream vortex ring and enhances its suction into the downstream vortex ring.

Table 1 presents the experimental results of acoustic excitation with various *St* and *Re*. The merging of four vortex rings is denoted with an open circle, the merging of two vortex rings is indicated as "pairing", and "x" denotes no merging. At *Re* of 2000, two vortex rings merge at only *St* of 1.00, whereas four vortex rings do not merge. For the jets of *Re* other than 2000, the number of vortex rings for merging increases from two to four as *St* increases, and then no merging forms. The range of *St* when four vortex rings merge widens as *Re* increases. For *St* greater than 1.15, the merging of four vortex rings occurs even in the jet with *Re* of 7000, where vortex rings do not merge in the natural transition. When *St* is increased in jets with *Re* from 3000 to 6000, the arrangement of vortex ring is asymmetric with respect to the jet centerline if the merging of four vortex rings does not occur. There are upper and lower limits of *St* for the merging of four vortex rings.

Distribution maps of the center positions of the merged vortex rings were created from visualized images for 0.5 s. Figure 4 illustrates the distribution map at *Re* from 3000 to 6000, comparing the jets under acoustic excitation with those in the natural transition. The origin of the coordinate system is the center of the nozzle exit, the x-axis is in the streamwise direction, and the r-axis is in the radial direction. Both axes

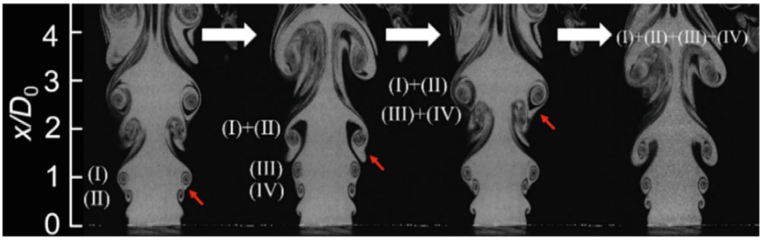

Fig. 2 Merging process of 4 vortex rings by acoustic excitation ($Re = 4000$ and $St = 1.20$)

Table 1 Range of *St* for 4 vortex rings merge

	$Re = 2000$	$Re = 3000$	$Re = 4000$	$Re = 5000$	$Re = 6000$	$Re = 7000$
$St = 1.00$	Pairing	Pairing	Pairing	Pairing	Pairing	Pairing
$St = 1.05$	×	Pairing	Pairing	Pairing	Pairing	Pairing
$St = 1.10$	×	○	○	○	○	Pairing
$St = 1.15$	×	○	○	○	○	○
$St = 1.20$	×	×	○	○	○	○
$St = 1.25$	×	×	×	○	○	○
$St = 1.30$	×	×	×	○	○	○
$St = 1.35$	×	×	×	○	○	○
$St = 1.40$	×	×	×	×	×	○

×: no merging of vortex rings, pairing: merging of 2 vortex rings, ○: merging of 4 vortex rings.

are dimensionless, scaled by the nozzle diameter D_0. Red lines in Fig. 4 indicate the formation position of the vortex ring. The merging of two vortex rings, three vortex rings, and four vortex rings are respectively denoted in black, red, and blue. Since only two vortices can merge at a time, the maps also include the merging of two vortex rings preceding the merging of three or more. The upper panel displays the results in the natural transition, while the lower panel shows the results of acoustic excitation at *St* of 1.10. Comparing the upper and lower results, it is evident that the merging positions of the vortex rings, which vary in the natural transition, are almost constant in the acoustically excited jets. In the excited jets, the merging positions of two vortex rings separate into two regions: the upstream side consists of the merging positions of vortex ring (I) and (II), while the downstream side is the merging positions of (III) and (IV) as shown in Fig. 2. The formation positions of vortex ring, indicated by the red line, are also upstream compared to the cases in the natural transition. Due to the excitation, the formation and coalescence of vortex rings occur upstream, allowing four continuous vortex rings to merge before they are broken. The merging of the three vortex rings observed at *Re* of 3000 and 5000 in the natural transition is not observed under the excitation. This is attributed to the fact that the formation positions of the vortex rings are fixed upstream by acoustic excitation, causing the merging positions of two vortex rings to also shift and become fixed upstream compared to the naturally transitional jets.

The merging positions for the excitation at *St* of 1.20 and 1.40 at *Re* of 7000 were plotted (not shown here). Comparing at the same *Re*, the merging positions in the jet excited at *St* of 1.40 are located farther upstream than those in the jet excited at *St* of 1.20. This suggests that the higher the excitation frequency (i.e., the higher *St*), the more the merging positions of vortex rings move upstream and the greater the number of merging, but there is an upper limit to the frequency.

3.3 Conditions for the Merging of Four Vortex Rings by Acoustic Excitation

The merging of four vortex rings observed here is all due to the merging of merged two vortex rings as shown in Figs. 2 and 3. The merging of four vortex rings requires that two vortex rings merge three times from their formation to their collapse. When the later merged vortex rings catch up with the earlier merged vortex rings, the four vortex rings merge. We consider the conditions for the merging of four vortex rings from three perspectives: the position of vortex ring formation, the position of vortex ring collapse, and the streamwise distance between vortex rings.

Table 2 shows the comparison of the formation and collapse positions of vortex rings between naturally transitional jets and acoustically excited jets. The formation positions of the vortex ring can be observed upstream due to compared to the natural transition, as shown in Fig. 3. The collapse position is defined as the point where the vortex ring deviates from the mainstream and the center of the vortex becomes

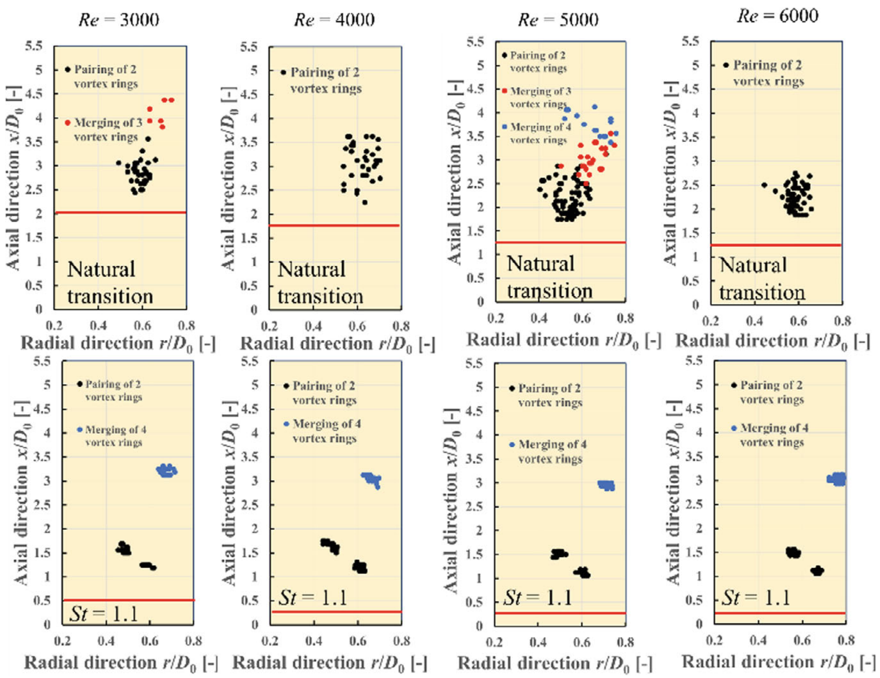

Fig. 3 Distribution maps of merged vortex rings

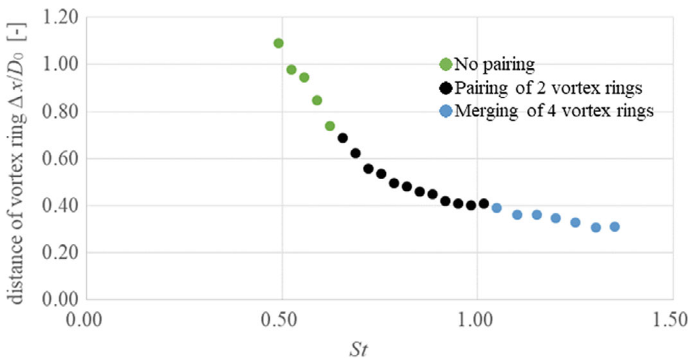

Fig. 4 Dimensionless streamwise distance between vortex rings at *Re* of 5000

obscure. Table 2 indicates that the collapse positions due to excitation are downstream of the natural transition except for $Re = 3000$. This suggests that acoustic excitation can increase the distance between vortex ring formation and collapse. It is believed that, for the jet at $Re = 7000$, which collapses before the vortex rings marge in natural transition, acoustic excitation extends the distance in which the vortex rings could exist, thus enabling the vortex rings to merge.

Table 2 Formation and collapse positions of vortex rings

	Natural transition		$St = 1.10$		$St = 1.20$	
	Formation x/D_0	Collapse x/D_0	Formation x/D_0	Collapse x/D_0	Formation x/D_0	Collapse x/D_0
$Re = 2000$	3.13	-	0.500	-	0.500	-
$Re = 3000$	1.88	5.63	0.375	4.69	0.313	5.31
$Re = 4000$	1.88	4.38	0.313	5.00	0.313	5.00
$Re = 5000$	1.25	3.75	0.250	4.38	0.250	5.00
$Re = 6000$	1.25	2.81	0.250	4.38	0.250	5.00
$Re = 7000$	1.25	2.19	0.250	3.75	0.250	5.00

Next, the streamwise distances between merging vortex rings were investigated from the visual images. Since the interval between vortex rings determined by the frequency of acoustic excitation, the higher the excitation frequency f_s, the shorter the interval between vortex rings. Moreover, the higher the fs, the shorter the distance from the nozzle exit where vortex rings form. Figure 4 illustrates the dimensionless distance $\Delta x/D_0$ of vortex rings when acoustic excitation is applied to the jets at $Re = 5000$ in the range of $St = 0.492$ to 1.35. Here, Δx represents the streamwise distance between two continuously formed vortex rings (the distance between the vortex rings (I) and (II)). It is found that the distance between vortex rings decreases as St increases from Fig. 4. The cases of the merging of two vortex rings, of the merging of four vortex rings, and of no merging are respectively shown in black, blue, and green in Fig. 4. The merging of two vortices occurs when the dimensionless distance between the vortices $\Delta x/D_0$ is less than 0.750, and the merging of four vortices occurs at approximately half that distance.

Table 3 displays the dimensionless distance between vortex rings $\Delta x/D_0$ at various *Re*. Table 3 corresponds to Table 1, with the yellow columns indicating the distances between the vortex rings (I) + (II) and (III) + (IV) when the four vortex rings merge. It is confirmed that two vortex rings (I) + (II) and (III) + (IV) merge when the distance between the vortex rings is less than $\Delta x/D_0 = 0.750$, similar as when vortex rings (I) and (II) merge. At *Re* of 7000 and *St* of 1.10, the radial extent of the two vortex rings before merging is almost the same, and the radial growth of the upstream vortex ring is not suppressed by the vortex sheet extending from the downstream vortex ring. This suggests that the distance between vortex rings needs to be short to suppress the growth of the upstream vortex ring by the vortex sheet extending upstream from the vortex ring. Therefore, the condition for the merging of many vortex rings by acoustic excitation is to excite at a frequency that increases the distance over which the vortex rings remain and shortens the distance between them.

Table 3 Dimensionless streamwise distance between vortex rings

	$Re = 2000$	$Re = 3000$	$Re = 4000$	$Re = 5000$	$Re = 6000$	$Re = 7000$
$St = 1.00$	1.18	1.14	1.06	1.05	1.05	1.06
$St = 1.05$	×	0.825	0.850	1.01	1.04	1.02
$St = 1.10$	×	0.694	0.669	0.688	0.731	1.01
$St = 1.15$	×	0.688	0.591	0.663	0.681	0.656
$St = 1.20$	×	×	0.541	0.613	0.571	0.608
$St = 1.25$	×	×	×	0.544	0.527	0.575
$St = 1.30$	×	×	×	0.465	0.490	0.465
$St = 1.35$	×	×	×	0.428	0.383	0.338
$St = 1.40$	×	×	×	×	×	0.336

×: no merging of vortex rings, yellow: merging of 4 vortex rings, white: pairing of 2 vortex rings.

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