VIBRATION OF MULTIPLE CIRCULAR CYLINDERS IN TANDEM ALIGNMENT

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There have been various attempts and investigations to capture wind energy through wind-induced vibration of some kind of structural elements. The wake galloping is one of the candidates due to its divergent nature, and the wake galloping of a single circular cylinder has been investigated in a couple of studies. However, if multiple cylinders can vibrate simultaneously, it would be favorable to capture more wind energy through the vibration. Based on this idea, a basic wind tunnel experiment has been conducted in the present study. In the present experiment, in the wake of a fixed circular cylinder, multiple circular cylinders of the same diameter as the fixed one are supported by coil springs and deployed in tandem alignment. The numbers of spring-supported cylinders are changed from 1 to 3, and the distance between their centers is another experimental parameter. As the results, two cylinders or even three cylinders vibrate together. It is worth to note that, in case that the distance between their centers is double of the cylinder diameter, the two or three cylinders vibrate in bigger amplitude than other wider distance cases though the single cylinder does not reveal wake galloping in such narrow spacing.

Keyword: Wake galloping, Multiple circular cylinders, Wind energy

1. INTRODUCTION

Machine devices to capture energy from wind mostly consist of a rotor with some number of blades. Large wind turbines usually have three blades to the horizontal axis rotor. Some small or middle size wind turbines have vertical axis rotor. As well known, wind turbines of these types can lead to quite rapid rotational motion if their cutout mechanism does not work. This is due to the self-excited process in which lift force to the blades accelerate the blade rotation.

As ordinary wind turbines utilize vigorous wind-induced motion, other types of devices which are equipped with some sort of self-excited wind-induced motion can capture wind energy. Various attempts have been made to develop new devices base on the knowledge of wind engineering. Matsumoto, et al. investigated the devices utilizing flutter of plate[1)]. Pimentel, et al.[2)] reported a device in which flutter of textile belts generates electricity. Meanwhile, Hiejima, et al.[3)] is working on wake galloping of a circular cylinder. They investigate a method to magnify the cylinder amplitude by oscillating the upstream cylinder. Jung, et al.[4)] also conducted a series of experiment to generate electricity from wake galloping of circular cylinder.

In the preceding works to utilize wake galloping[5,6)], the number of vibrating cylinder is one. If we can increase the number of vibrating cylinder, we may capture more wind energy. Based on this idea, we place multiple spring-supported circular cylinders in the wake of a fixed cylinder. The numbers of vibrating cylinder in the present study are one, two and three.

Wake galloping of circular cylindrical object is observed in transmission lines or stay cables of cable-stayed bridges. This phenomenon has been investigated in wind engineering, but in most cases number of circular cylinders are two and only one of the two vibrates. Although Nagao, et al.[7)] or Kubo, et al[8)] investigated three parallel cables of cable stayed bridge, only one of the three cables is allowed to vibrate in either study.

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2. WIND TUNNEL EXPERIMENT

(1) The experimental setup

Fig. 1 shows the schematic view of the experiment conducted in the present study. A circular cylinder of diameter d is fixed at the blowing outlet of the wind tunnel. In the wake of the fixed circular cylinder, circular cylinders of the same diameter d are suspended by coil springs. These circular cylinder are straightly aligned in the direction of the wind flow with an identical distance nd between the centers of cylinder, where n is an integer. Fig. 2(a) and 2(b) are the photographs of the present experiment. The wind tunnel of Fig. 2(a) has a square section of 22.5 cm by 22.5 cm. The fixed circular cylinder is made of wood and its diameter d is 2cm. The spring-supported circular cylinders are made of acrylic, of which length is 30 cm and mass is 113 g. As shown in Fig. 2(b), four coil springs are used to suspend each acrylic cylinder. These springs are outside of the air stream. No end plates are used.

The cylinder-spring system has two modes of vertical vibration as shown in Fig. 3(a) and 3(b), that is, the translational mode of Fig. 3(a) and the rotational mode of Fig. 3(b) both in the vertical plane perpendicular to the air stream. In addition, since there is no restriction against the horizontal motions of the cylinder, the horizontal translational motion and the horizontal rotational motion are possible. Table 1 summarizes the natural frequencies of these four modes. The damping coefficients of the two cases shown in Fig.3 are: 0.3% for the vertical translational mode of Fig. 3(a), and 0.4% for the vertical rotational mode of Fig. 3(b), respectively.

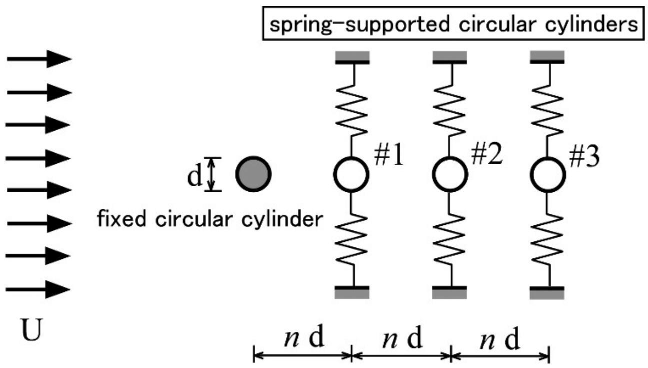


Figure 1: Schematic view of the experimental setup.

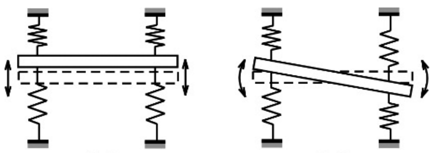
Figure 2: (a) Overall view of the present experiment; (b) the cylinders.

(2) The experimental conditions and procedures

As summarized in Table 2, number of the vibrating circular cylinders and the spacing between the cylinders are changed. Consequently, the combination of these two parameters results in 9 cases. For each case, the wind speed U is increased from 1 m/s to 13 m/s by the increment 1 m/s. At each wind speed, the vibration amplitude and the frequency are measured from the video images. The referential wind speeds are measured by removing all cylinders including the fixed one. The location of the measurement is that the fixed cylinder will be located.

Table 1: Captions should be centered above tables.

Vibration modes	Natural frequency (Hz)
Vertical translation	$f_{\mathrm{VT}} = 2.3$
Vertical rotation	$f_{\mathrm{VR}} = 3.3$
Horizontal translation	$f_{\mathrm{HT}} = 2.0$
Horizontal rotation	$f_{\mathrm{HR}} = 3.0$



(a) (b)

Figure 3: Vibration modes of the spring-cylinder system:
(a) the vertical translational mode; (b) the vertical rotational mode.

Table 2: Experimental cases.

Number of spring-supported cylinders	1, 2, 3
Distance between the center of the circular cylinders	2d, 3d, 4d

As noted above, horizontal motions of the cylinders are allowed in the present experiment. Therefore, horizontal motion like swaying occurs in some experimental cases, in some experimental cases. In such cases, in order to restrict cylinder vibration to vertical ones, those cylinders are displaced vertically by human hands and then released to let them vibrate vertically.

3. EXPERIMENTAL RESULTS

(1) Preliminary remarks

Figures 4, 6 and 8 below show the experimental results of cylinder vibration and frequency against wind speed for different numbers of vibrating cylinders.

[1] In case of vertical rotational vibration, the amount of the amplitudes plotted by a symbol mark is the amplitude of the end of the cylinder. Based on a rough and simple calculation, the kinematic energy of the rotational motion is about 80% of that of the translational motion if the end displacements of both modes are same.

[2] The amplitude of the vertical translational vibration is plotted by black solid marks while the amplitude of the vertical rotational vibration is plotted by white marks.

[3] In these figures of amplitude, if the cylinder motion is small and ambiguous or not clear, no symbol mark is plotted.

[4] Static horizontal displacement occurs to each circular cylinder. The amounts are about $d/5$ at wind speed 7 m/s, $d/4$ at 9 m/s and $d/3 \sim d/2$ at 11 m/s.

[5] When the cylinder vibrates vertically at considerably large amplitude, horizontal vibration is quite small.

[6] At wind speed 12 m/s or 13 m/s, it occurs large motion which is a combination of vertical vibration and horizontal one. In such cases a symbol $\times$ is plotted in the amplitude figures.

(2) The cases of single vibrating circular cylinder

Fig. 4 shows the amplitude and the frequency against the wind speed in the cases of single

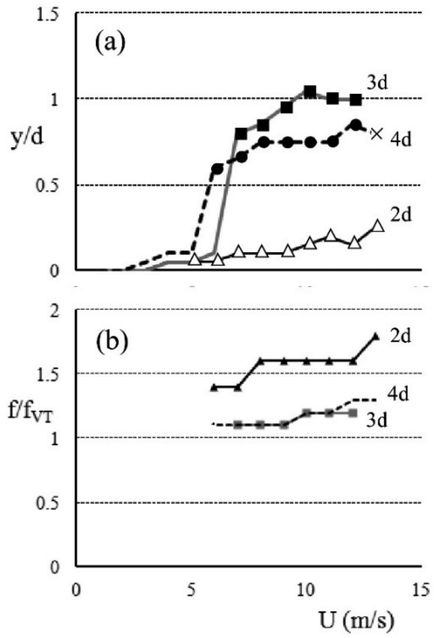


Fig. 4 Experimental results of single vibration circular cylinder in the wake of the fixed cylinder (2d, 3d and 4d denote the center distance between cylinders): (a) non-dimensional amplitude (white symbols are vertical rotational vibration, black symbols are vertical translational vibration, × indicates combination of vertical and horizontal motion) ; (b) non-dimensional frequency (the ratio to the natural frequency of the vertical translational vibration mode f_{VT})

(a) (b)

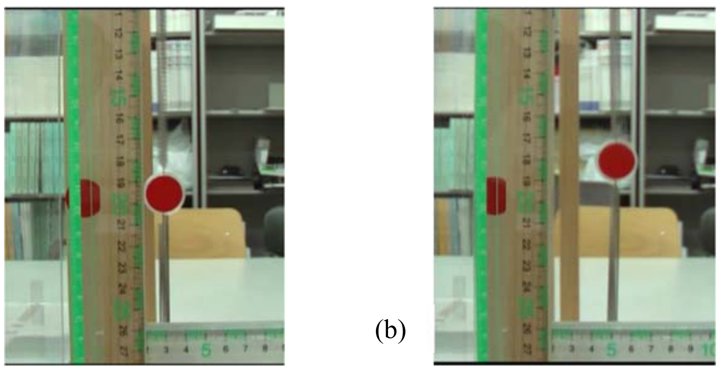


Fig. 5 Snapshots of the cylinder vibration of the cases of single spring-supported cylinder: (a) the center distance 2d at wind speed 8 m/s; (b) the center distance 3d at wind speed 8 m/s.

spring-supported circular cylinder for three cases of the cylinder distance from the fixed cylinder. As shown in Fig. 4(a), at the distance 2d, the cylinder vibrates rotationally but the amplitude is small. See also the snapshot of experiment Fig. 5(a). On the contrary, at the distance 3d and 4d, the amplitude of vertical translational vibration increases at wind speed 5 m/s. The case of the distance 3d reached the largest amplitude. See also the snapshot of Fig. 5(b). Shiraishi, et al.[6] indicated that the wake galloping of circular cylinder occurs when the distance is 3d. Jung, et al[4] showed in their experiments that wake galloping occurs from 3d to 6d though they did not conduct the case of 2d. Our results shown in Fig. 4 consist with these observations.

As noted above, the vibration at the distance 2d is vertical rotational vibration. As shown in Fig. 4(b),

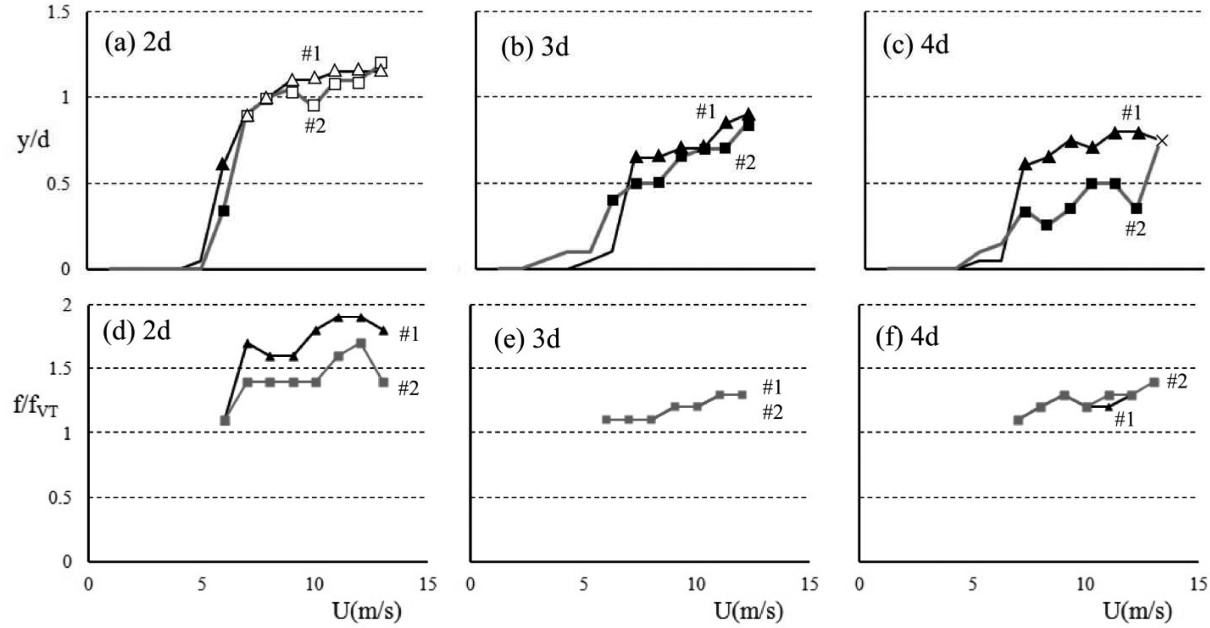


Fig. 6 Experimental results of two vibration circular cylinders in the wake of the fixed cylinder (#1 and #2 are the cylinder number from counted from the fixed cylinder) : (a) non-dimensional amplitude of the cylinder distance 2d; (b) non-dimensional amplitude of the cylinder distance 3d; (c) non-dimensional amplitude of the cylinder distance 3d; (d) non-dimensional frequency of the cylinder distance 2d; (e) non-dimensional frequency of the cylinder distance 3d; (f) non-dimensional frequency of the cylinder distance 4d (colors of the symbols in Fig. 6(a)～(c) have the same meaning as in Fig. 4).

the observed frequencies of 2d are larger than those of 3d and 4d and the ratio to the natural frequency of vertical translational vibration f_{VT} is 1.5 to 1.6. This is corresponding to the natural frequency of vertical rotational vibration f_{VR}.

(3) The cases of two vibrating circular cylinders

Fig. 6 shows the amplitude and the frequency against the wind speed in the cases of two spring-supported circular cylinders for three cases of the cylinder distances. As shown in Fig. 6(a), at the distance 2d, both of the cylinders vibrate at fairly large amplitude of vertical rotational vibration after vertical translational vibration at first. These two cylinders rotate at almost opposite phases as shown in a snapshot of Fig. 7(a). Since the second cylinder (the downward cylinder) revealed an intermittent fluctuation, the vibration frequencies of these two cylinders are a little different.

The cylinders at the distances 3d and 4d revealed vertical translational vibration as shown in a snapshot of Fig. 7(b). The case of 4d, the amplitude of the second cylinder is relatively small. Consequently, in the cases of the distance 2d, the largest amplitudes are observed. Although the vibration mode of 2d is different from 3d or 4d, the kinematic energy of the vibration of 2d is the largest based on the energy evaluation described in the item [1] of 3.1(1).

It may be curious that the vibration is more excited in the case of 2d than the cases of 3d or 4d because this is different from the case of single vibrating cylinder of Fig. 4. It can be said that the vibration of the downward cylinder may affects the vibration of the upward cylinder in some way and these two cylinders synchronize to each other together with surrounding air stream. This should be clarified by flow visualization or simulation in future.

(a) 

(b) 

Fig. 7 Snapshots of the cylinder vibration of the cases of two spring-supported cylinders: (a) the center distance 2d at wind speed 9 m/s (vertical rotational vibration); (b) the center distance 3d at wind speed 9 m/s (vertical translational vibration).

(4) The cases of three vibrating circular cylinders

Fig. 8 shows the amplitude and the frequency against the wind speed in the cases of three spring-supported circular cylinders for three cases of the cylinder distances. As shown in Fig. 8, the vibration amplitude of the case of distance 2d is larger than the cases of 3d or 4d. The vibration mode up to 10 m/s is generally vertical translational vibration and the phase of cylinders are opposite for each pair of succeeding two cylinders as shown in the snapshots of Fig. 9(a) and 9(b). At higher wind speeds, the cylinder motions are complicated with intermittent motion or horizontal motion.

By comparing Fig. 8(b) and Fig. 8(b), in the case of distance 4d, the vibration initiates at higher wind speed and the amplitudes are smaller than the case of 3d. Even in case of two vibration cylinders, as shown in

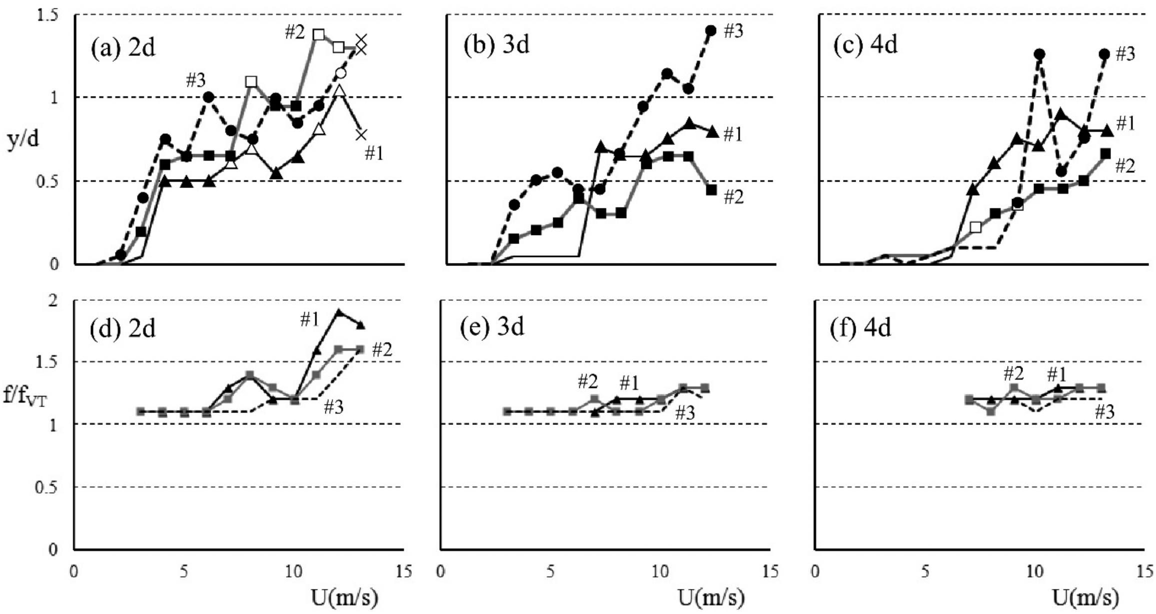


Fig. 8 Experimental results of three vibration circular cylinders in the wake of the fixed cylinder (#1, #2 and #3 are the cylinder number from counted from the fixed cylinder) : (a) non-dimensional amplitude of the cylinder distance 2d; (b) non-dimensional amplitude of the cylinder distance 3d; (c) non-dimensional amplitude of the cylinder distance 3d; (d) non-dimensional frequency of the cylinder distance 2d; (e) non-dimensional frequency of the cylinder distance 3d; (f) non-dimensional frequency of the cylinder distance 4d (colors of the symbols in Fig. 8(a)～(c) have the same meaning as in Fig. 4).

(a) (b)

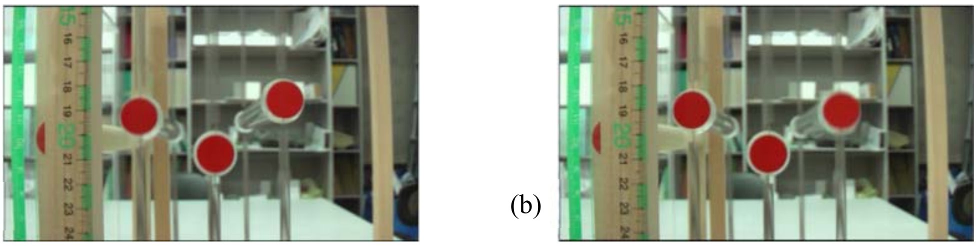


Fig. 9 Snapshots of the cylinder vibration of the cases of three spring-supported cylinders: (a) the center distance 2d at wind speed 4 m/s (vertical translational vibration); (b) the center distance 3d at wind speed 4 m/s (vertical translational vibration).

Fig. 6(c), at the distance 4d the vibration amplitude of the second cylinder is relatively small. Based on these results, we may lead to an understanding that, at longer distance between cylinders, the fluctuating streams from the fixed cylinder lost their energy by shaking the upstream cylinders. However, as shown in Fig. 8(c), the third cylinder vibrates at larger amplitude than the other two at wind speed 10 m/s. We should make further effort to investigate the mechanism of these phenomena.

As shown in Fig. 8(a), at the distance 2d, the vertical translational vibration occurs over the wind range of wind speed, and at fairly high wind speed the vertical rotational vibration begins to occur. This is different from the case of two cylinders at distance 2d of Fig. 6(a) where the vertical rotational vibration dominates for most of wind speeds. In addition, the wind speed to initiate vibration is smaller for the distance 3d than 2d. These differences between the different number of vibrating cylinder are uncertain. In the present study, both translational and rotational vibrations are allowed. We should conduct further experiment by restricting vibration mode.

4. CONCLUDING REMARKS

In this study, a series of wind tunnel experiments are conducted in which one or more spring-supported circular cylinders are aligned straightly in the wake of a fixed circular cylinder of the same diameter. The purpose of the present experiments is to acquire fundamental idea that in what situation these cylinders vibrate and how they vibrate. The number of the vibrating cylinders in the present experiment is one, two and three. The following results are obtained.

[1] In case of the single vibrating cylinder, the wake galloping occurred in the cases that the distance between the center of the fixed cylinder and the vibrating cylinder is 3d or 4d. In the case that the center distance is 2d, the vibration amplitude is relatively small. These results of wake galloping are consistent with the observation in literature.

[2] In the cases of two or three vibrating cylinders, all the spring-supported cylinders vibrate. Basically, they vibrate in the vertical translational mode at the phase opposite to the next cylinder.

[3] In the cases of two or three vibrating cylinders, on the contrary to the case of single vibrating cylinder, vibration occurred even at the center distance 2d as well as the amplitude are larger than the distance 3d and 4d. It should be future work to clarify the mechanism of these phenomena, but it may be inferred that the closer the vibrating cylinders the more intensified the interaction between the cylinder motion and the surrounding streams.

Further investigation should be conducted on the cases that more numbers of vibrating cylinders or other cylinder distances. Especially, the vibration mode should be restricted. In addition, investigation from the view point of fluid-structure interaction mechanism is essentially important.

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