PROPERTIES OF WAKE EXCITATION OF CIRCULAR CYLINDER

Fumiaki Nagao[+1], Minoru Noda[+2], Masahiro Inoue[+3], Shota Matsukawa[+4], and Akihiro Shitamori[+5]
[+1,+2] Institute of Technology and Science, Tokushima University, Tokushima, Japan
[+3]Chuden Plant Co., Ltd., Hiroshima, Japan
[+4]Anan Technical High School, Anan, Japan
[+5]Graduate School of Tokushima University, Tokushima, Japan

The wake excitation of close-spaced tandem or staggered circular cylinders is known to develop from the interaction between the leeward circular cylinder and wake flow of the windward circular cylinder. However, this phenomenon is strongly influenced by the Reynolds number, which controls the flow around the cylinders, and by the arrangement of the circular cylinders. Experiments were performed to investigate the wake-induced vibrations of circular cylinders arranged in tandem with a central distance of three diameters and having several kinds of surface roughness. For smooth circular cylinders, two types of stable limit cycles for the transverse response were measured. The larger response, which had a double amplitude of about three diameters ($2Y/D \approx 3$), was much more sensitive to the Scruton number and surface roughness of the cylinders. The smaller response ($2Y/D$ = 1–1.25) was closely related to the separated flow from the windward cylinder. The Reynolds number was found to have a relatively large effect on wake galloping. The surface roughness of the leeward circular cylinder played a more important role in wake galloping than that of the windward circular cylinder. However, installing helical wires on both cylinders produced a synergistic stabilizing effect. The effect of the Reynolds number on the wake excitation was investigated over the critical *Re* range.

Keyword: Wake excitation, Surface roughness of circular cylinder, Critical Reynolds number

1. INTRODUCTION

Many studies have focused on the aerodynamic instabilities of tandem or staggered circular cylinders such as sub-conductors, chimneys, towers, antennas, and the twin cables of cable-stayed bridges[1,2)]. The wake-induced vibrations of the leeward cylinder in tandem or staggered circular cylinders are known to develop from the interaction between the leeward circular cylinder and the wake flow of the windward circular cylinder. The present authors previously investigated the instability of closely spaced triple circular cylinders[3)] and found that the Reynolds number *Re* affects the onset velocity of wake galloping. In order to reduce the effects of *Re*, the wake excitation properties of a circular cylinder in the wake of several kinds of rectangular cylinders were tested with interesting results[4), 5)]. The properties of unsteady pressures on the leeward circular cylinder in the wake of a square cylinder with free vibrations were experimentally measured to understand the excitation mechanism of the leeward circular cylinder[5)]. Using the ensemble-averaged fluctuating pressures during one period, it was clarified that the timing of the leeward circular cylinder across the shear flow of the windward square cylinder played an important role in the formation of the wake excitation force.

This paper presents an experimental investigation on the effects of the surface roughness on the wake galloping of tandem circular cylinders; some of the results have already been reported elsewhere[6)-8)]. Moreover, the responses of wake galloping were also examined beyond the critical *Re* range.

2. EXPERIMENTAL PROCEDURE

Two kinds of wind tunnels were used here. One was used to investigate the effects of the surface roughness of the circular cylinder on wake galloping. The other was used to examine the response of the wake galloping over the critical *Re* range. The tandem circular cylinders were set at a central interval of three

[+1]fumi@ce.tokushima-u.ac.jp, [+2]noda@ce.tokushima-u.ac.jp

diameters for both wind tunnel tests.

One semi-closed circuit wind tunnel had a working section of 1 m wide, 1.5 m high, and 4 m long and was used to investigate the effects of the surface roughness of the circular cylinder on the wake galloping of the tandem circular cylinders. The circular cylinders were made of stainless steel and had a diameter of D = 42 mm and length of 900 mm. The windward cylinder was fixed to the sidewalls. The responses of the leeward circular cylinder were measured for two degrees of freedom (2DOF), longitudinal and transverse. The Scruton number $Sc = 2m\delta/\rho D^2$, where m is the mass, δ is the logarithmic damping, and ρ is the air density, was changed from 6.8 to 35.1. The natural frequencies for the longitudinal direction f_x and transverse direction f_y of the leeward cylinder were almost the same and changed from 1.7 to 2.7 Hz. However, only the results obtained under the conditions of Sc = 16.4 and f = 2.2 Hz are explained in this paper. Table 1 summarizes the experimental conditions examined here. The surface roughness of the cylinders was changed by rough plastic meshes and helical wires with a pitch of 229 mm (π/6 inclination from the cylinder axis) and intervals of 2π/3 (three wires were installed), π/3 (six wires), or π/6 (12 wires), respectively. For 12 wires, the inclination from the cylinder axis θ was changed from 0° to 30° at 10° intervals. Table 2 summarizes the roughness lengths for the surface roughness of the materials; these were measured with an I-type hot wire anemometer.

Table 1: Experimental conditions for investigating the surface roughness.

Working section (m)	1 (width) × 1.5 (height) × 4 (length)
Diameter and length of model, D (m), L (m)	0.042, 0.9
Reynolds number, Re	2800–30,700
Mass, m (kg/m)	2.58
Scruton numbers, $Sc = 2m\delta/\rho D^2$	6.8, 16.4, 35.1
Degrees of freedom	Two (longitudinal and transverse directions)
Natural frequency, f (Hz)	1.7, 2.2, 2.7
Surface roughness of cylinders	Plain (smooth), rough plastic meshes (Mesh A: width b = 1 mm, thickness t = 1 mm, central distance B = 4 mm; Mesh B: b = 2 mm, t = 1.85 mm, B = 10 mm), parallel wires (diameter d = 2 mm, interval of wires = π/6), and helical wires (inclination from cylinder axis θ = π/18, π/9, π/6; d = 2 mm; interval of wires = 2π/3, π/3, and π/6)

Table 2: Roughness length and appearance of surface materials.

Surface material	Plain	Mesh A (M-A)	Mesh B (M-B)	12 parallel wires	12 helical wires $\theta = \pi/18$	12 helical wires $\theta = \pi/9$	12 helical wires $\theta = \pi/6$	6 helical wires $\theta = \pi/6$	3 helical wires $\theta = \pi/6$
Roughness length (mm)	0.0025	0.20	0.52	0.51	0.43	0.40	0.25	0.19	0.06
Solidity ratio (%)	-	43.8	36	18.1	185.5	19.3	20.9	9.2	4.6
Appearance									

The other semi-closed circuit wind tunnel had a maximum wind speed of 50 m/s and was used to investigate the effects of extremely high Re exceeding the critical Re on the wake galloping of tandem circular cylinders. The working section was 0.5 m wide, 2 m high, and 4.5 m long, respectively. Polyvinyl chloride circular cylinders with a diameter of D = 216 mm and length of 400 mm were used. The windward cylinder was fixed to the sidewalls. The responses of the leeward circular cylinder were also measured for 2DOF with a very small Scruton number of Sc = 6. The natural frequencies (longitudinal direction: f_x = 1.47 Hz, transverse direction: f_y = 1.45 Hz) of the leeward cylinder were almost the same. Table 3 summarizes the experimental conditions examined here.

In order to confirm the critical Re for the circular cylinder, the drag acting on the cylinder and fluctuating wind speed in the wake of the cylinder were measured with a load cell and I-type hot wire anemometer, respectively. Fig. 1 shows the drag coefficient of the circular cylinder for D = 100 mm. The drag coefficient for D = 216 mm decreased suddenly around $Re = 3.4 \times 10^5$. However, no drag crisis was observed for the circular cylinder with D = 100 mm. Beyond the critical Re, an almost constant value of Cd was measured for the circular cylinder with D = 216 mm. As shown in the figure, Schewe[9)] obtained almost the same tendency. Figure 2 shows the power spectral densities of fluctuating wind velocities around the critical Re in the wake of the circular cylinder with D = 216. At $Re = 3.31 \times 10^5$, the apparent peak fluctuating frequency was present, and the frequency coincided with the Strouhal number of the circular cylinder St = 0.2 in the region of subcritical Re. On the other hand, a clear fluctuation peak was not detected at $Re = 3.46 \times 10^5$. As shown in these figures, the circular cylinder with D = 216 mm reached the critical and supercritical Re regions.

Table 3: Experimental conditions for investigating higher Re.

Maximum wind speed (m/s)	50
Working section (m)	0.5 (width) × 2.0 (height) × 4.5(length)
Diameter D (m) and length L (m) of model	0.216, 0.4
Reynolds number, Re	14,400–72,000
Mass, m (kg/m)	50
Scruton number, $Sc = 2m\delta/\rho D^2$	6
Degrees of freedom	Two (longitudinal and transverse directions)
Natural frequency, f (Hz)	1.47 (longitudinal), 1.45 (transverse)

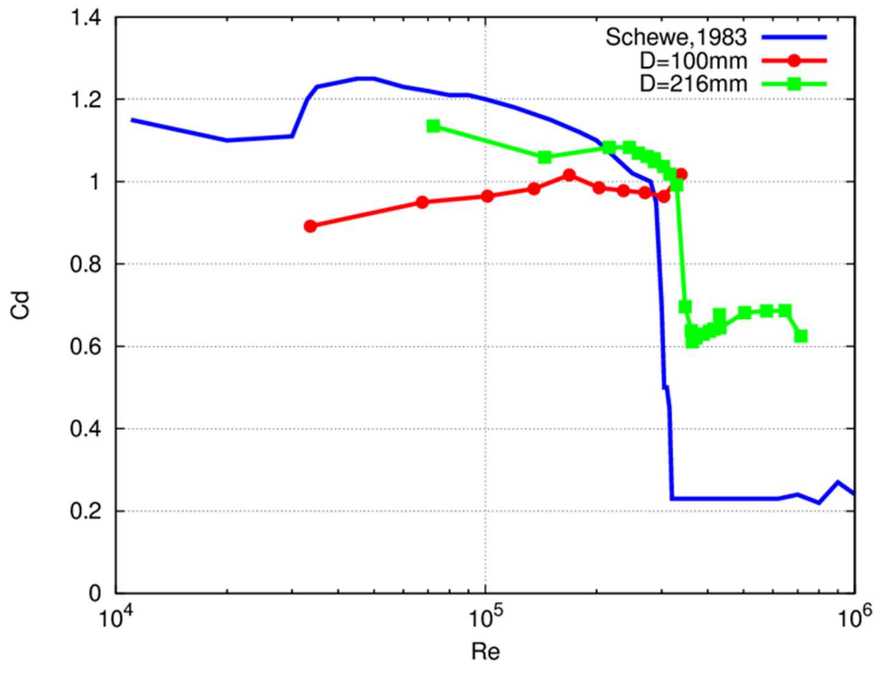


Figure 1: Effects of Re on the drag coefficient of the circular cylinder Cd.

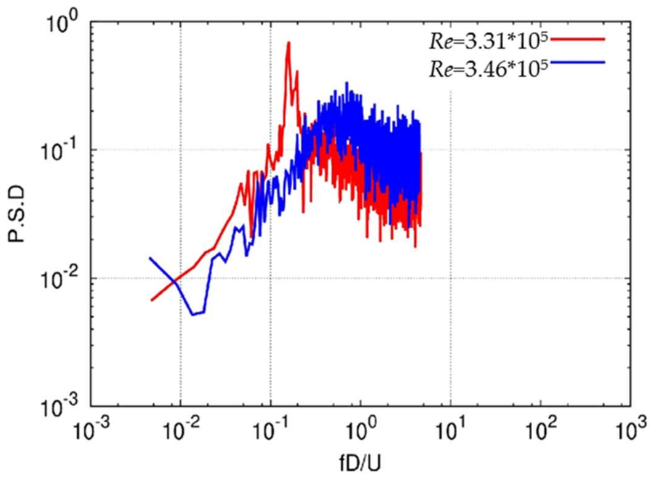
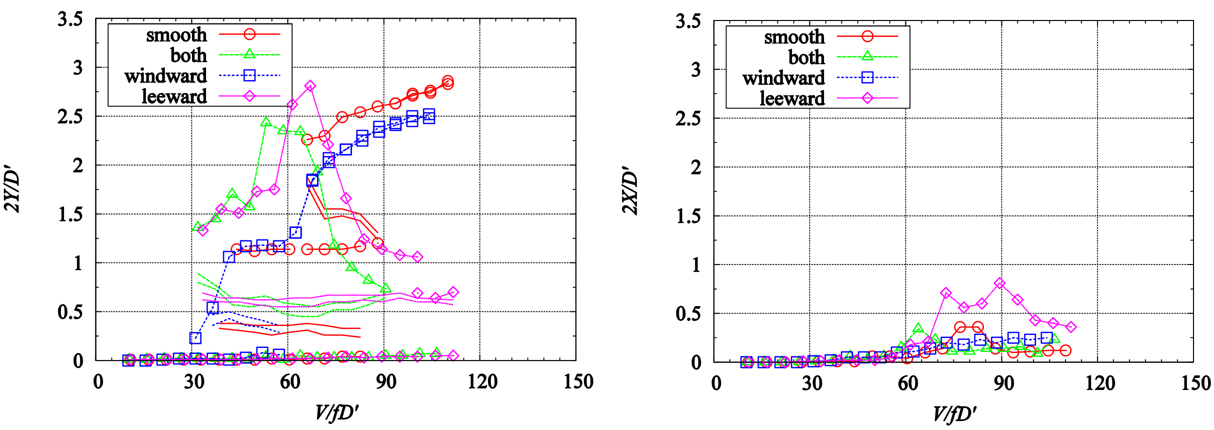


Figure 2: Power spectral densities of the fluctuating wind in the wake of the circular cylinder.

3. EFFECTS OF THE SURFACE ROUGHNESS OF THE CIRCULAR CYLINDER ON THE WAKE EXCITATION

(1) Effects of the rough plastic Mesh A (M-A)

Figure 3 shows the effects on the wake excitation of installing Mesh A (M-A) on the circular cylinders. The amplitudes and wind speeds were normalized by the relative diameter of the circular cylinders accounting for the thickness t of the meshes: $D' = D + 2t$. Figure 3(a) summarizes the effects of M-A on the transverse responses, and Figure 3(b) shows the longitudinal responses. The responses of the circular cylinder with the smooth surface are given in the figure for comparison. As shown in Figure 3(a), two different transverse responses were measured. The first stable limit cycle (1-SLC) had an almost constant amplitude of $2Y/D \approx 1.2$, which was closely related to the formation of a wake for the windward circular cylinder. In contrast, the second cycle (2-SLC) vibrated beyond the separated shear flow of the windward cylinder and developed from $2Y/D$ = 2.25 to $2Y/D = 3.0$ with increasing wind speed. With installation of M-A on the windward cylinder, the transverse responses developed at lower wind speeds, and smaller amplitudes of 2-SLC were measured at higher wind speeds in comparison with those of the smooth surface circular cylinder. On the contrary, when M-A was installed on the leeward cylinder, larger transverse responses were measured at lower wind speeds. However, the responses decreased suddenly at higher wind speeds of more than 70. When M-A was installed on both cylinders, the responses converged to those of installation on the leeward cylinder.



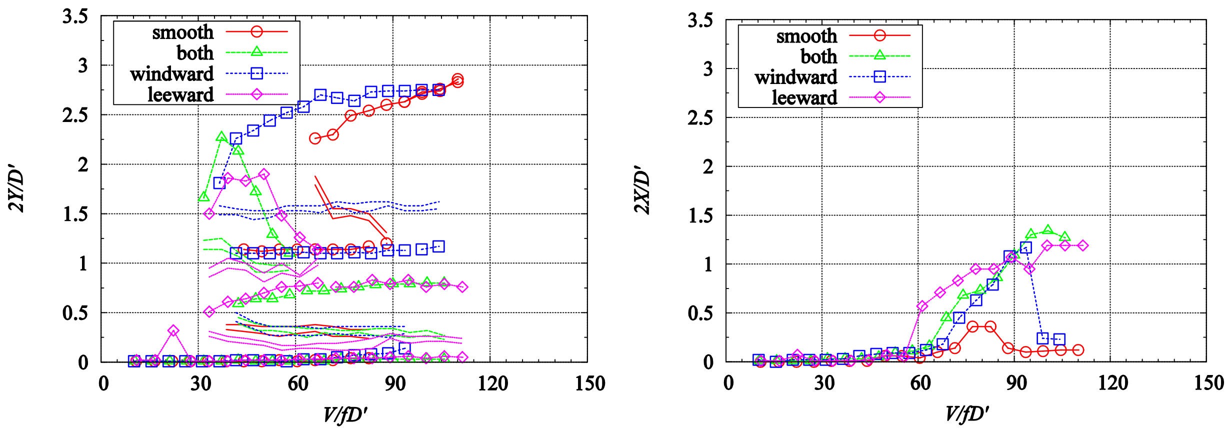
(a) Transverse responses (b) Longitudinal responses

Figure 3: Effect of installing Mesh A on the wake excitation.

These changes in responses were led by the relative increase in *Re* due to the increase in surface roughness of the circular cylinders by the installation of M-A. For the longitudinal direction shown in Figure 3(b), comparatively large amplitudes were only measured when M-A was installed on the leeward cylinder.

(2) Effects of the rough plastic Mesh B (M-B)

Figures 4 (a) and (b) show the transverse and longitudinal responses of the leeward cylinder with and without Mesh B (M-B). M-B was installed on the windward cylinder, the leeward cylinder, or both cylinders, respectively. As shown in Figure 4 (a), when M-B was installed on the windward cylinder, the large transverse responses of 2-SLC developed at lower wind speeds relative to those of the smooth surface circular cylinder and when M-A was installed on the windward cylinder as given in Figure 3 (a). In contrast, when M-B was installed on the leeward cylinder, the larger transverse responses of 2-SLC were only measured at lower wind speeds of less than 70, and the amplitudes of 1-SLC decreased. When M-B was installed on both cylinders, the responses also converged to those of installation on the leeward cylinder, similar to M-A. For the longitudinal direction, which is shown in Figure 4 (b), comparatively large amplitudes were measured in the high wind speed region for all cases of M-B installation when the transverse responses were held down by the unstable limit cycles.



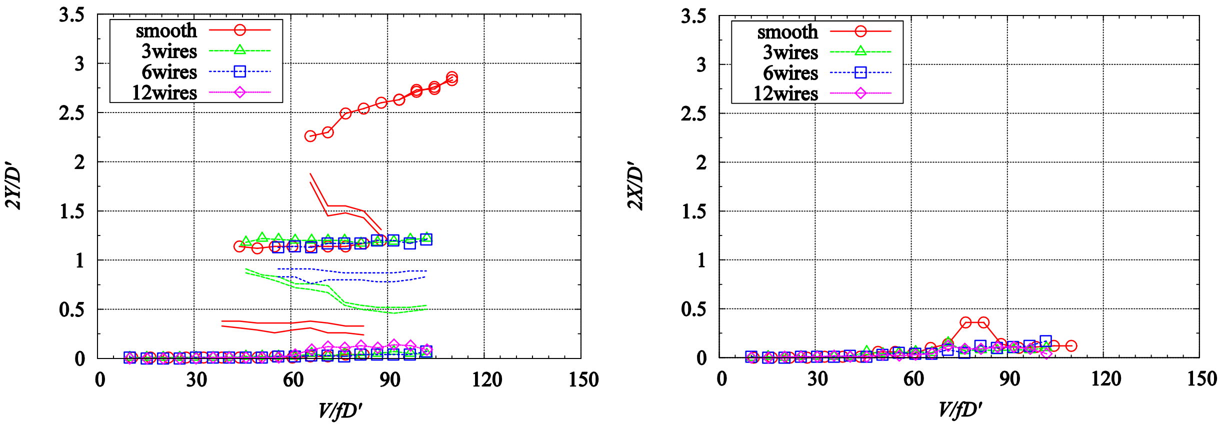
(a) Transverse responses (b) Longitudinal responses

Figure 4: Effect of installing Mesh B on the wake excitations.

(3) Effects of helical wires

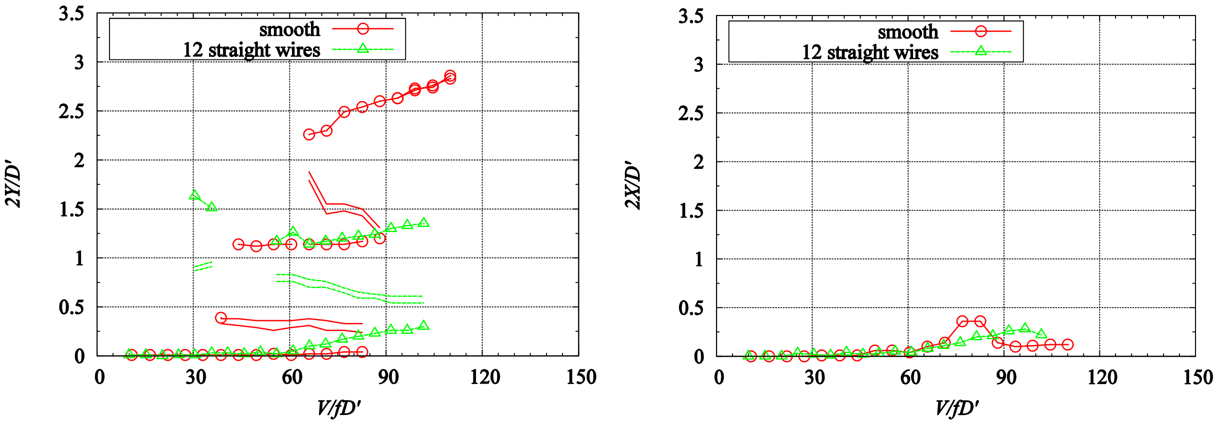
Figures 5 (a) and (b) show the transverse and longitudinal responses, respectively, of the leeward cylinder with zero, three, six, and twelve helical wires under the conditions of $Sc = 16.4$, $f = 2.2$ Hz, and 2DOF. The helical wires were installed on both cylinders, and the amplitudes and wind speeds were normalized by the relative diameter with helical wires $D' = D + 2d$. As shown in Figure 5 (a), when three helical wires were installed, the large amplitudes of 2-SLC completely disappeared. When six helical wires were installed, 1-SLC moved toward higher wind speeds, and 1-USLC was also larger in comparison with the results of installing three helical wires. When twelve helical wires were installed, the wake excitation completely disappeared. Therefore, even though the roughness length of the twelve helical wires was shorter than that of the rough plastic M-B, increasing the number of helical wires on the cylinders efficiently improved the wake excitation. For the longitudinal direction as shown in Figure 5 (b), no vibrations were observed for all helical wire installation cases, even when the transverse responses were held down.

Figures 6 (a) and (b) show the transverse and longitudinal responses, respectively, with and without twelve straight wires under the conditions of $Sc = 16.4$, $f = 2.2$ Hz, and 2DOF. The straight wires were installed on both cylinders. When the straight wires, as shown in Figure 6 (a) were installed, the large amplitudes of 2-SLC were suppressed. However, 1-SLC and large amplitudes at lower wind speeds were observed, similar to the results for M-A and M-B. Therefore, when helical wires are installed, the reduced uniformity of the flow properties in the axial direction should play an important role in suppressing wake galloping. From Figure 6 (b), small amplitudes were measured in the longitudinal mode.



(a) Transverse responses (b) Longitudinal responses

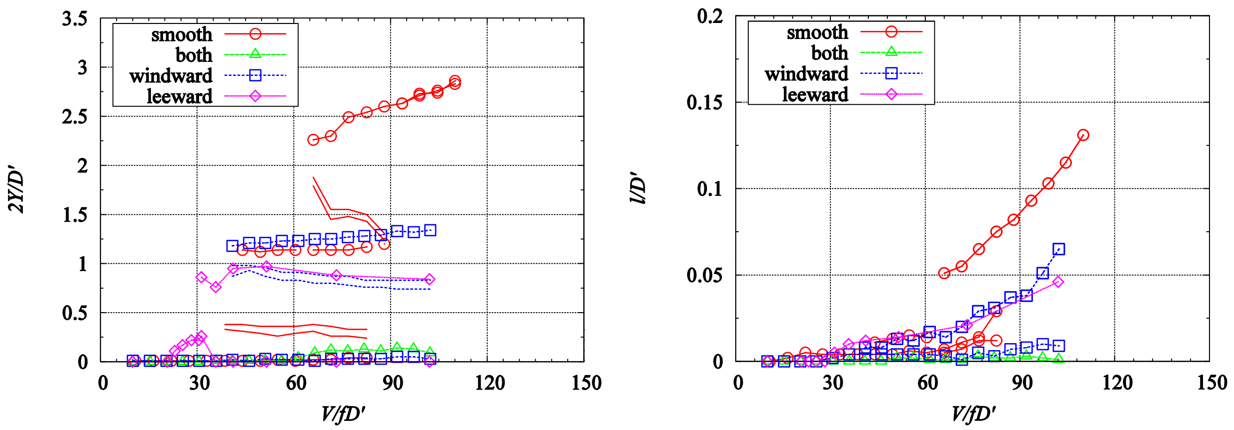
Figure 5: Responses of the leeward circular cylinder with and without the helical wires: *Sc* = 16.4, *f* = 2.2 Hz.



(a) Transverse responses (b) Longitudinal responses

Figure 6: Responses of the leeward circular cylinder with and without 12 straight wires: *Sc* = 16.4, *f* = 2.2 Hz.

Figure 7 (a) and (b) represent the transverse responses and static displacements, respectively, with twelve helical wires attached to the windward cylinder, the leeward cylinder, or both cylinders under the conditions of *Sc* = 16.4, *f* = 2.2 Hz, and 2DOF. As shown in Figure 7 (a), when wires were installed on only the leeward cylinder, the amplitudes of 1-SLC decreased. However, 1-SLC occurred at lower wind speeds and developed from the rest condition without 1-USLC. On the other hand, the amplitudes of 1-USLC increased when wires were installed on only the windward cylinder. Furthermore, the amplitudes of 1-USLC when wires were installed on the windward cylinder were almost the same as that of 1-SLC when the wires were installed on only the leeward cylinder. When wires were installed on both cylinders, the stabilizing effects of the windward and leeward cylinders acted together. No longitudinal response was observed at all. As shown in Figure 7 (b), the static displacements when helical wires were installed on the windward or leeward cylinder increased at higher wind speeds.



(a) Transverse responses (b) Static displacements

Figure 7: Responses of the leeward circular cylinder with and without the 12 helical wires, *S*c=16.4, *f*=2.2 Hz.

4. EFFECTS OF THE REYNOLDS NUMBER ON WAKE EXCITATION

Figure 8 (a) and (b) show the transverse and longitudinal responses with the larger diameter model (D = 0.216 m), including the high *Re* numbers. As shown in Figure 8 (a), large transverse responses occurred when the wind velocity V/fD was reduced to about 29, which is consistent with the onset velocity of the small *Sc* circular cylinder model Sc = 6. However, when compared with the responses of the smooth surface shown in the previous figures, the first stable limit cycle (1-SLC) having an almost constant amplitude of $2Y/D \approx 1.2$, which is closely related to the formation of the wake of the windward circular cylinder, disappeared. The second stable limit cycle (2-SLC) vibrated beyond the separated shear flow of windward cylinder with increasing amplitudes from $2Y/D$ = 2.25 to $2Y/D$ = 3.0 and was the only one measured. The unstable limit cycle also appeared at the same subcritical *Re*. As shown in Figure 8 (b), the longitudinal responses were also measured with large transverse responses. However, the longitudinal amplitude demonstrated quite large fluctuations. Beyond the critical *Re* of around $Re = 3.5 \times 10^5$, the large transverse responses decreased with increasing *Re*. Finally, at supercritical *Re* of greater than $Re = 4.2 \times 10^5$, the wake galloping varnished.

In order to suppress the wake galloping of tandem circular cylinders in the subcritical *Re* region, countermeasures such as relative increases of *Re* of the circular cylinder may be efficient approaches.

5. CONCLUSIONS

Two wind tunnel were used to investigate the wake excitation of tandem circular cylinders having a central distance of three diameters:

Installing surface roughness on the leeward circular cylinder has a more important effect on wake galloping than installing it on the windward circular cylinder. However, installing helical wires on both cylinders achieved a synergistic stabilizing effect.

The Reynolds number has a relatively large effect on wake galloping. Above the critical *Re*, wake galloping disappears. Countermeasures such as relative increases of *Re* for the circular cylinder may efficiently suppress wake galloping.

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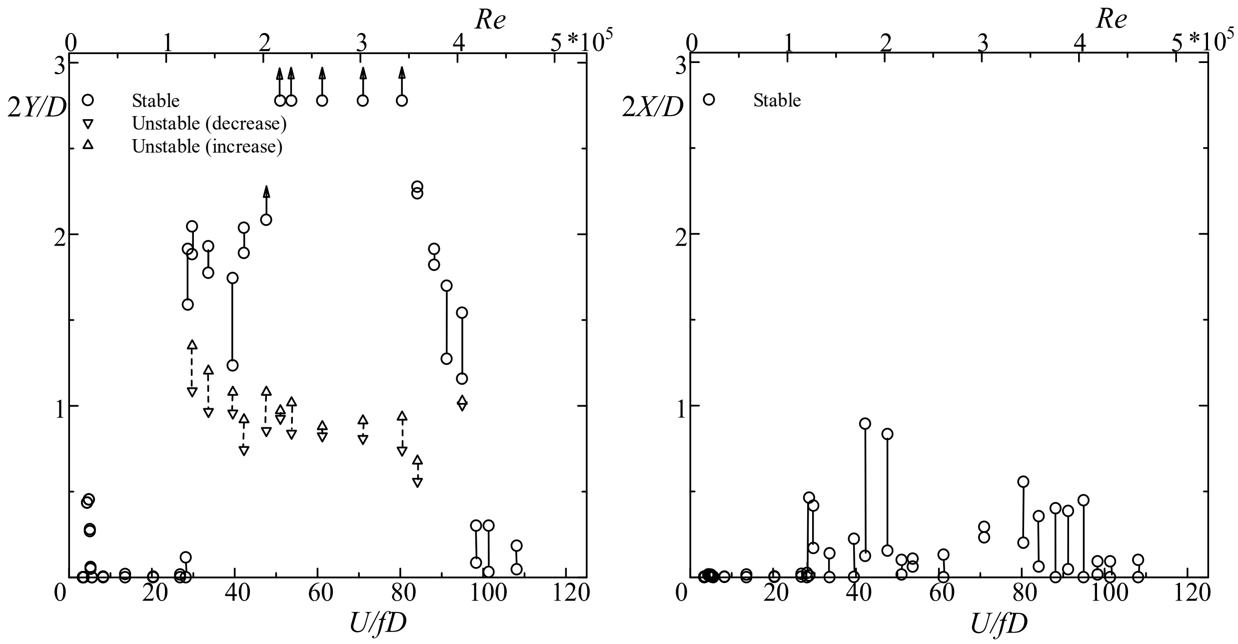

(a) Transverse responses (b) Longitudinal responses

Figure 8: Responses of the leeward circular cylinder with the large-diameter model: D = 0.216 m, Sc = 6, f = 1.45 Hz.

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