

Properties of wake excitation in tandem circular cylinders with several kinds of surface roughness

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ABSTRACT: Properties of wake excitation of circular cylinders in the tandem arrangement of central distance of three diameters were experimentally investigated. In order to investigate the influence of Reynolds number on the wake excitation, the effects of surface roughness of circular cylinders on it were examined. For circular cylinders with smooth surface, two types of stable limit cycles in transverse responses were measured. Effects of surface roughness on the wake excitation were quite large and the complicated interaction between the separated shear flow from the windward cylinder and the leeward cylinder were observed by flow visualization tests.

KEYWORDS: Wake excitation, Surface roughness of circular cylinder, Tandem arrangement, Vibration of leeward circular cylinder.

1 INTRODUCTION

Properties of wake excitation for tandem and staggered circular cylinders have been studied by lots of researchers, for example, Cooper & Wardlaw [1], Simpson [2], and so on. It is well known that the wake excitation vibrations of circular cylinders are deeply depended on the arrangement of the circular cylinders and Reynolds number, Re . Furthermore, for the wake excitation of tandem and staggered circular cylinders, the interaction between the leeward circular cylinder and the wake flow of the windward circular cylinder plays an important role.

Authors also investigated the instability of closely spaced triple circular cylinders [3], where the effect of Reynolds number, Re , was found in the onset velocity of wake galloping. In order to reduce the effects of the Re , the wake excitation of a circular cylinder in the wake of several shapes of rectangular cylinders was also tested and some interesting results were reported [4, 5].

In the paper, the effects of surface roughness of the circular cylinder on the wake excitation were experimentally investigated and a part of the results achieved here has already been reported in References [6, 7].

2 EXPERIMENTAL SETTING

A wind tunnel with a semi-closed circuit was used and its working section was 1m wide, 1.5m high and 4m long. Two stainless steel circular cylinders were used. Their diameter, D , was 42mm and their length was 900mm, respectively. The central distance between both circular cylinders in tandem arrangement was three times of their diameter, $3D$, where the windward cylinder was fixed to side walls. The responses of the leeward circular cylinder were measured under longitudinal and transverse freedoms (2DOF). The Scruton number, $Sc=2m\delta\rho D^2$, in which m is the mass, δ is the logarithmic damping and ρ is the air density, was changed from 6.8 to 35.1. Natural frequencies for longitudinal direction, f_x and transverse direction, f_y of the leeward cylinder were almost the same and also changed from 1.7 Hz to 2.7Hz. However, the results obtained un-

der the conditions of $Sc=16.4$ and $f=2.2\text{Hz}$ were only focused on the paper for the lack of space. Properties of the wake of the windward circular cylinder were investigated by I-type hot wire anemometer. Flow visualizing tests were carried out by using the high speed camcorder, where five hundred frames were recorder in a second. The experimental conditions examined here were summarized in Table 1.

The surface roughness of the cylinders was changed by rough plastic meshes, parallel and helical wires whose diameter, d , was 2mm. The interval of helical wires set $2\pi/3$ (three wires were installed), $\pi/3$ (six wires) and $\pi/6$ (twelve wires), respectively. For twelve wires, the inclination from cylinder axis, θ , was changed from 0 to 30 degrees at ten-degree intervals. Moreover, the roughness lengths of surface roughness materials were also measured by I-type hot wire anemometer and summarized in Table 2.

Table 1 Experimental conditions

Diameter, D (mm)	42
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, $b=1\text{mm}$, thickness, $t=1\text{mm}$, central distance, $B=4\text{mm}$, Mesh B; $b=2\text{mm}$, $t=1.85\text{mm}$, $B=10\text{mm}$), Parallel wires (diameter, $d=2\text{mm}$, interval of wires, $\pi/6$) Helical wires (inclination from cylinder axis, $\theta=\pi/18, \pi/9, \pi/6$, $d=2\text{mm}$, interval of wires, $2\pi/3, \pi/3, \pi/6$)

3 RESULTS AND DISCUSSION

3.1 Responses of Smooth Surface Cylinders

Figures 1(a) and (b) show the typical longitudinal and transverse responses and the static displacements, l/D , of leeward circular cylinder in tandem arrangement, $Sc=16.4$ and $f=2.2\text{Hz}$, in 2DOF. From Figure 1(a), two different transverse responses were measured; the first stable limit cycle (1-SLC) had almost the same amplitude, $2Y/D \approx 1.2$, which closely related to the formation of wake of the windward circular cylinder. On the contrary, the second one (2-SLC) vibrated beyond the separated shear flow of windward cylinder and also developed from $2Y/D=2.25$ to 3.0 with the increase of wind speed. Furthermore, two unstable limit cycles were also measured. Longitudinal responses were quite small.

From Figure 1(b), under the same wind speed, the static displacements, l/D , of 2-SLC were much larger than those of 1-SLC and at rest. However, somewhat large l/D of the rest condition for the higher V/fD , larger than 75, was introduced by the longitudinal vibration. Furthermore, the longitudinal vibration in the wake of a square cylinder was not generated at all [4]. Therefore, properties of the wake of the square cylinder and those of the circular cylinder were much different each other.

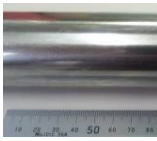
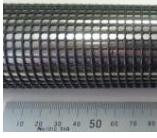
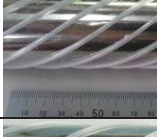
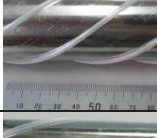
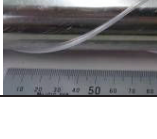
Effects of damping and natural frequencies on the responses of the wake excitation were reported in References [6, 7]

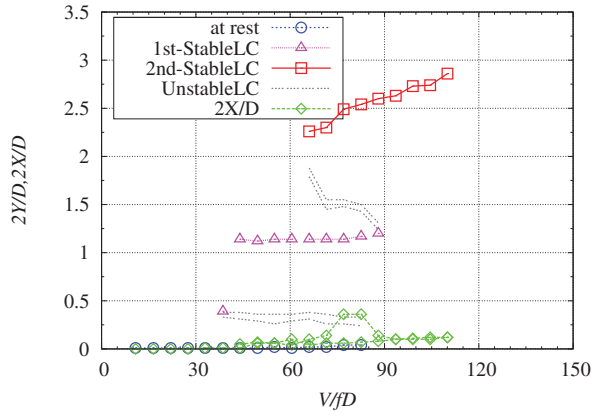
3.2 Wind speeds distribution behind a smooth cylinder

The distribution of the mean wind speed and the turbulence intensity of the wake at the distance of $3D$ from the center of the windward circular cylinder were given in Figures 2 (a) and (b), re-

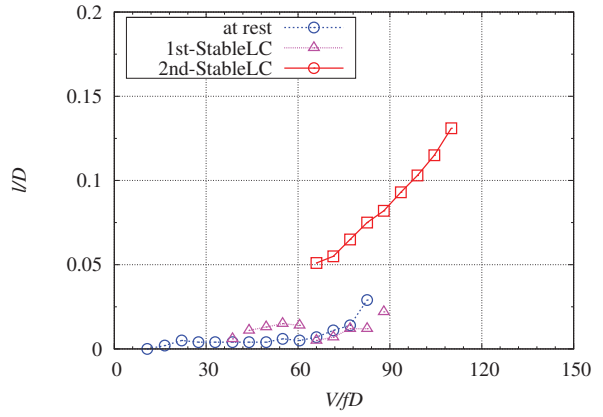
spectively. The amplitudes of second stable limit cycle (2-SLC) correspond to the just outside of separated shear flow where wind speeds return to the approaching mean wind speed, V_0 . On the contrary, around the amplitude of the first one (1-SLC), the largest turbulence intensity induced by Kármán Vortex was measured, where the mean wind speeds recovered to 80% of the approaching wind speed. Therefore, 1-SLC and 2-SLC occurred inside and outside of the wake of the windward circular cylinder, respectively.

Table 2 Roughness length and appearance of surface materials

Surface material	Roughness length (mm)	Solidity ratio (%)	Appearance
Plain (smooth)	0.0025		
Rough plastic mesh A (Mesh A)	0.20	43.8	
Rough plastic mesh B (Mesh B)	0.52	36	
Twelve parallel wires	0.51	18.1	
Twelve helical wires $\theta=\pi/18$	0.43	18.5	
Twelve helical wires $\theta=\pi/12$	0.40	19.3	
Twelve helical wires $\theta=\pi/6$	0.25	20.9	
Six helical wires $\theta=\pi/6$	0.19	9.2	
Three helical wires $\theta=\pi/6$	0.06	4.6	

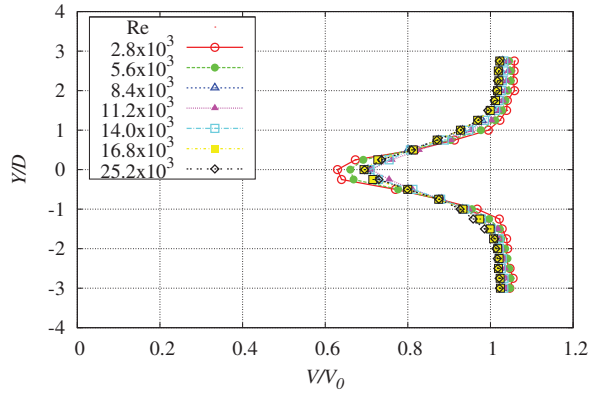


(a) 2DOF responses (transverse and longitudinal modes)

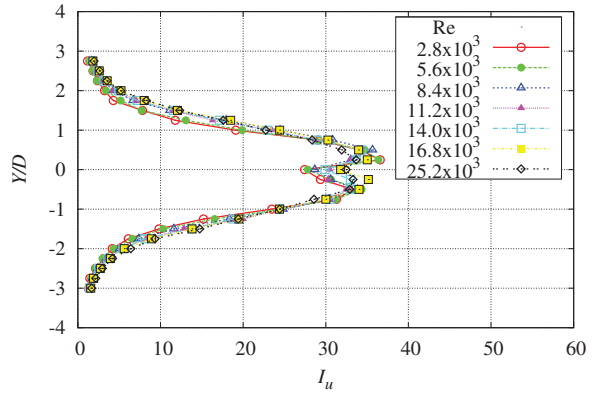


(b) Static displacements (l/D)

Figure 1 Responses and static displacements of the leeward circular cylinder in tandem arrangement, for the central distance of $3D$, $Sc=16.4$, $f=2.2\text{Hz}$.



(a). Mean wind speed ratio to approaching wind speed



(b). Turbulence intensity (%)

Figure 2 Wind profiles at $3D$ downstream from the center of the windward circular cylinder.

3.3 Responses with Surface Roughness

3.3.1 Rough plastic mesh

Figure 3 shows the effects of the installation of meshes to circular cylinders on the wake excitation, where amplitudes and wind speeds were normalized by the relative diameter of circular cylinder taking into account of the thickness, t , of meshes, $D'=D+2t$. Effects of meshes only installed on the windward circular cylinder were summarized in Figure (a), inversely, Figure (b) showed responses with meshes only attached to the leeward circular cylinder; furthermore, Figure (c) gave the results with meshes on both circular cylinders. From Figure (a), due to the installation of meshes on the windward cylinder, the larger transverse responses, 2-SLC, developed in the lower wind speeds in comparison with those of the smooth surface circular cylinder, where the installation of rougher mesh started the vibration in the lower wind speed. From Figure (b), due to the installation of meshes only on the leeward cylinder, the larger transverse responses of 2-SLC were only measured in the lower wind speeds, on the contrary, in the higher wind speeds, more than 60 for Mesh B, more than 70 for Mesh A, the smaller amplitudes of the 1-SLC were only measured and the larger responses of the 2-SLC were disappeared. For the installation of

meshes on the both circular cylinders as shown in Figure (c), the responses closed to those of the installation of meshes only on the leeward cylinder.

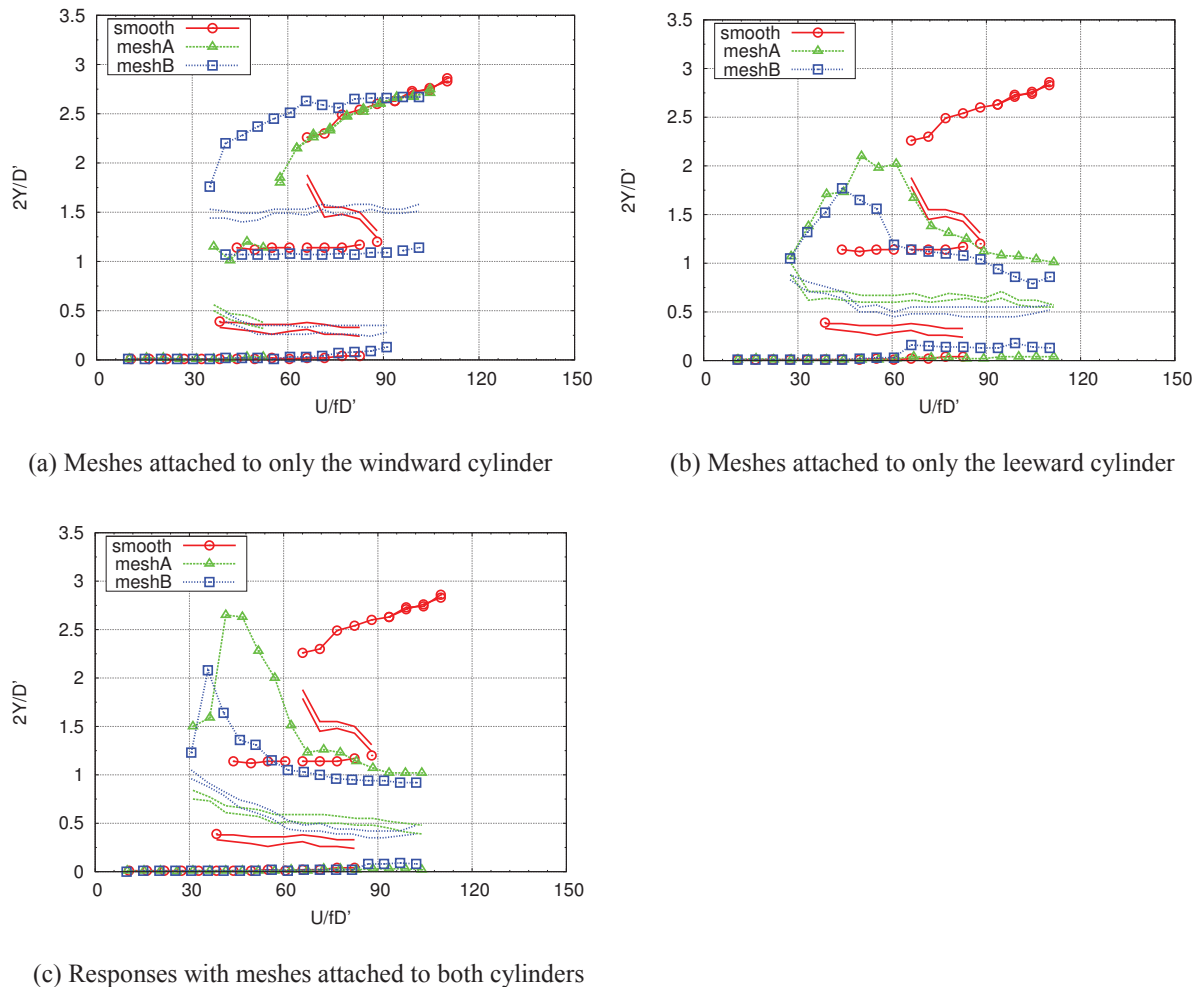


Figure 3 Effects of the installation of meshes on the wake excitations.

3.3.2 Helical wires

Figure 4 shows transverse responses of the leeward circular cylinder with zero, three, six and twelve helical wires, whose diameter, d , was $0.048D$, and the inclination from cylinder axis, θ , was $\pi/6$, in the condition of $Sc=16.4$, $f=2.2\text{Hz}$, 2DOF, where the helical wires were installed on both cylinders. Due to the installation of three helical wires, the large amplitudes of 2-SLC were completely disappeared. For the installation of six helical wires, 1-SLC was moved toward the higher wind speed and unstable limit cycle was also enlarged in comparison with the results of the installation of three helical wires. In the case of twelve helical wires, the wake excitation was completely disappeared. Therefore, even though the roughness length of twelve helical wires was shorter than that of the rough plastic mesh, Mesh B, the increase of helical wires attached to the cylinders improved the wake excitation efficiently. The efficiency of helical wire on the wake galloping was also reported by Fujino et al. [8] by using the full-size models for parallel cables.

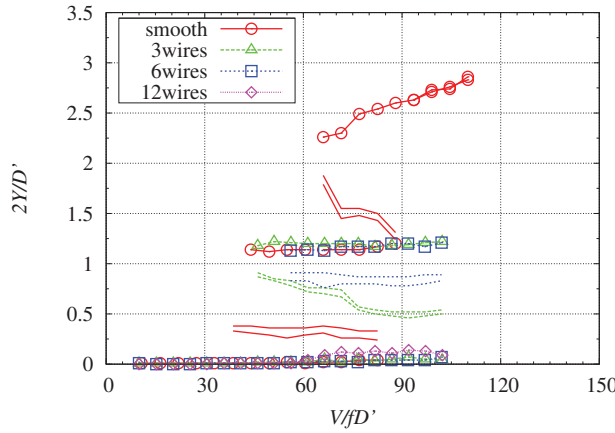


Figure 4 Transverse responses of the leeward cylinder with and without the helical wires, $Sc=16.4$, $f=2.2\text{Hz}$.

The effects of the inclination of wires, θ , on transverse responses of the leeward cylinder in the condition of $Sc=16.4$, $f=2.2\text{Hz}$, 2DOF were summarized in Figure 5, where twelve wires were installed on both cylinders. For the installation of parallel wires to the cylinder axis, $\theta=0$, the larger amplitudes of 2-SLC were observed in the lower wind speeds, around $V/fD'=30$, as same as the responses with meshes installed on both cylinders. Due to the installation of helical wires, the large amplitudes of 2-SLC were completely disappeared even if the small inclination of wires such as $\theta=10$ degrees. Furthermore, for the case of the smallest inclination of wires, $\theta=10$ degrees, 1-SLC was moved toward the higher wind speed. The larger inclination of the helical wires removed the wake excitation completely. Therefore it is clear that the increase of the inclination of wires reduced the transverse responses of the leeward cylinder.

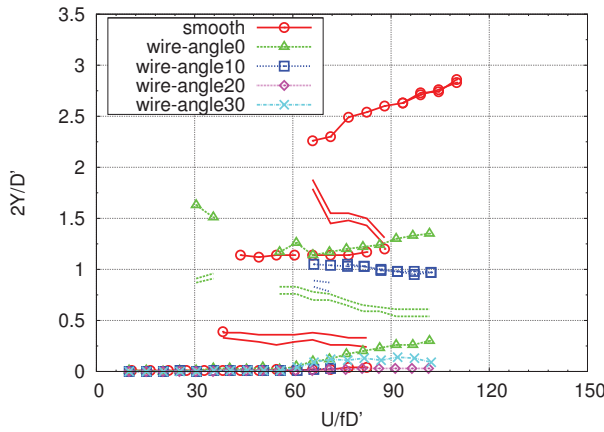


Figure 5 Effects of the inclination of wires from cylinder axis, θ , on the transverse responses, $Sc=16.4$, $f=2.2\text{Hz}$.

Figure 6 shows the transverse responses with twelve helical wires attached to the windward cylinder or the leeward cylinder or both cylinders, in the condition of $Sc=16.4$, $f=2.2\text{Hz}$, 2DOF. For the installation of twelve wires on only the leeward cylinder, the amplitudes of 1-SLC were

decreased. However, the occurrence of 1-SLC moved toward the lower wind speed and 1-SLC developed from the rest condition without 1-USLC. On the other hand, the amplitudes of 1-USLC were increased by the installation of wires on only the windward cylinder; furthermore, the amplitudes of 1-USLC due to the installation of the windward cylinder were almost the same as that of the 1-SLC of the installation of them on only the leeward cylinder. For the installation of wires on both cylinders, the stabilizing effects for the windward cylinder and the leeward cylinder should act together.

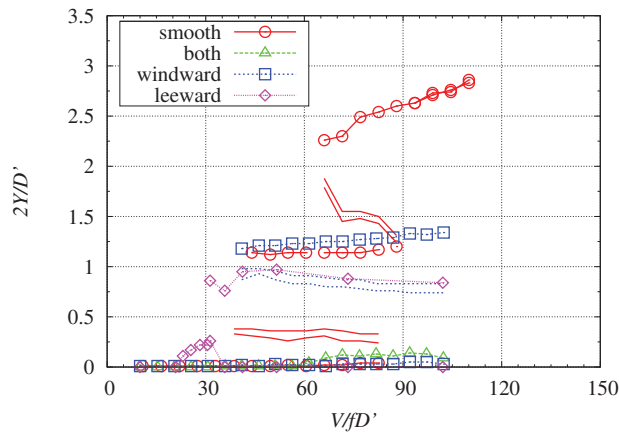


Figure 6 Responses of the leeward circular cylinder with and without the twelve helical wires, $Sc=16.4$, $f=2.2\text{Hz}$

3.4 Flow visualization

Figures 7 and 8 show the results of flow visualization tests for smooth surface circular cylinders during free vibrations in 1-SLC and 2-SLC under the same reduced wind speed, $V/fD=65$, respectively, where phase angles of the sinusoidal vibration of leeward circular cylinder were changed from the neutral position of 0 (Figure (a)) to $11\pi/6$ (Figure (l)) with the interval of $\pi/6$. In the figures, representative streak lines were also shown by solid arrows. As shown in Figure 7, the smaller amplitude of vibration of 1-SLC was restricted by the separated shear flow formed by the windward circular cylinder, where the leeward cylinder was completely included in it. As shown in Figures 6 (d), (e), (j), (k), the wake excitation of 1-SLC was induced by the gap flow into the wake region as detected in previous papers [8, 9]. On the contrary, under the larger amplitude of 2-SLC, Karman vortices were developed behind the windward circular cylinder during all vibration phases as shown in Figure 8. As given in Figure 2 (a), the amplitudes of second stable limit cycle (2-SLC) almost correspond to the separated shear flow formed behind the single circular cylinder, on the other hand, the amplitudes of first stable limit cycle (1-SLC) restricted by the separated shear flow formed behind the windward cylinder in tandem arrangement of circular cylinders. Therefore, taking into an account of the time integrated mean flow situation, the larger amplitude of 2-SLC could be excited by the similar flow properties for the smaller amplitude of 1-SLC.

As shown in Figures 3 (b) and (c), due to the installation of meshes only on the leeward cylinder or both cylinders, the larger transverse responses of 2-SLC were measured in the restricted lower wind speeds, where flow patterns around cylinders were also similar to those under the larger amplitude of 2-SLC for smooth surface circular cylinders as given in Figure 8. Furthermore, during smaller responses for the installation of meshes or helical wires to the cylinder, flow pat-

terns around cylinders were almost the same to those for smooth surface circular cylinders under the smaller amplitude of 1-SLC as given in Figure 7.

4 CONCLUSIONS

From the experimental investigation of the tandem circular cylinders of central distance of three diameters with several kinds of surface roughness, following results were obtained:

In the range of tested Scruton number, Sc , two types of stable limit cycles were occurred in transverse responses. The amplitude of larger responses (2-SLC) almost correspond to the separated shear flow formed behind the single circular cylinder, on the other hand, the smaller amplitudes of first stable limit cycle (1-SLC) restricted by the separated shear flow formed behind the windward cylinder in tandem arrangement of circular cylinders.

Effects of Reynolds number on the wake galloping were quite large. The surface roughness installed on the leeward circular cylinder played a more important role in the wake galloping in comparison with that installed on the windward circular cylinder, however, the stabilizing effects of the installation of helical wires on both cylinders have been accomplished by the mutual effect achieved with the windward cylinder and the leeward cylinder.

The interaction of wake properties and the responses of the leeward circular cylinder should be investigated in detail.

5 ACKNOWLEDGEMENTS

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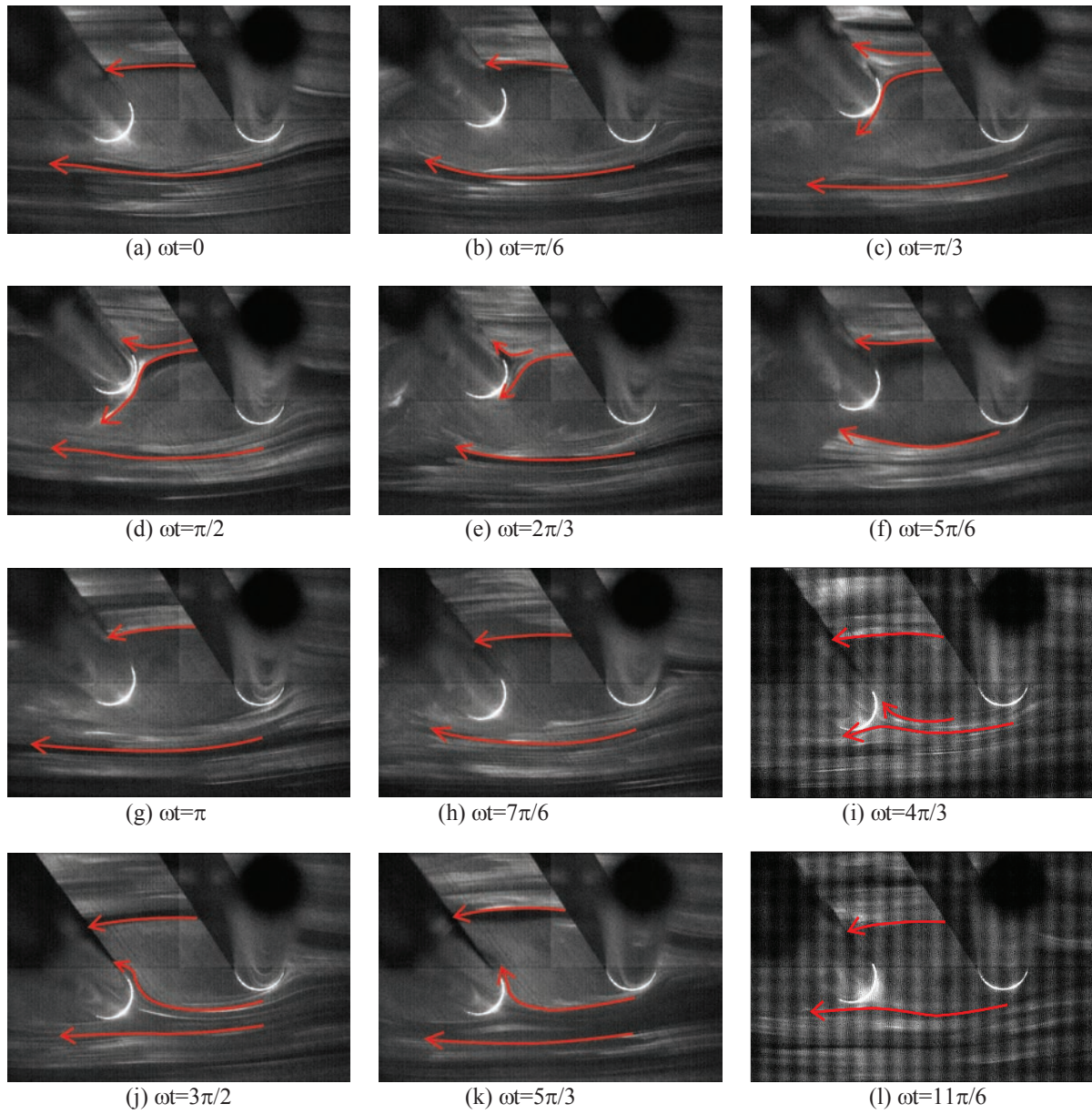


Figure 7 Flow around cylinders in free vibration of 1-SLC at $V/fD=65$.

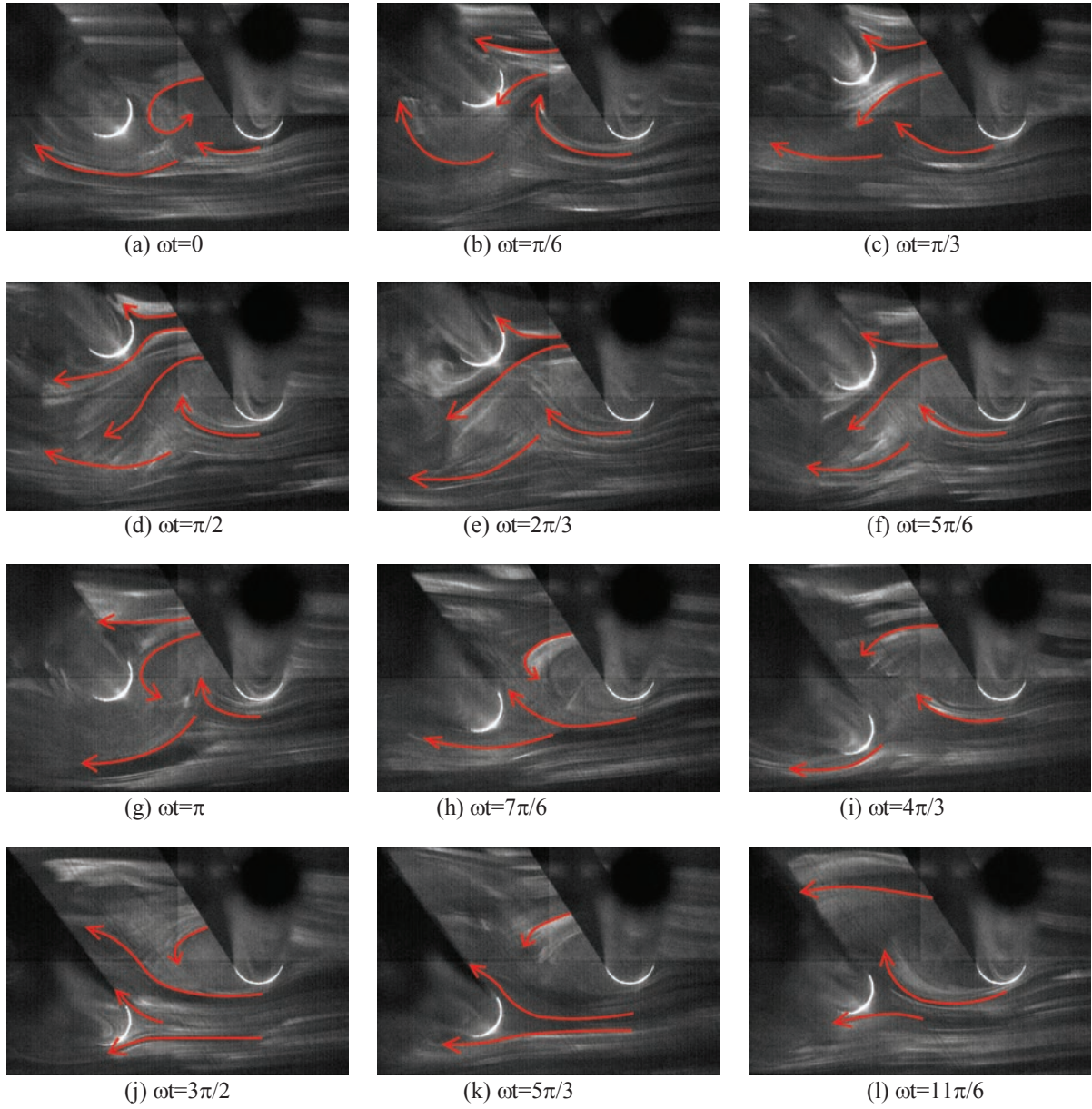


Figure 8 Flow around cylinders in free vibration of 2-SLC at $V/fD=65$.