PROPERTIES OF THE FLOW AROUND TWO ROTATING CIRCULAR CYLINDERS IN SIDE-BY-SIDE ARRANGEMENT WITH DIFFERENT ROTATION TYPES

by

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The field characteristics of two side-by-side rotating circular cylinders in a cross-flow is investigated under different rotation types, at T/D = 1.11,1.6, and 3, respectively (T is the center spacing between the cylinders, and D is the cylinder diameter). A similar flow pattern which is the most efficient to narrow the low-pressure area is identified for rotation type A, independent of T/D ratio, and two typical flow patterns are found under different spacings for rotation type B and type C, respectively. It is confirmed that there is an optimal rotational speed of 1.7-2, under rotation type A to attenuate the vortices, velocity drop, and turbulence intensity tremendously. As rotational speed increases to the optimal value, both the velocity drop and turbulence intensity decrease and their distributions are smooth. The results indicate that the shear layers which are accelerated following the free-stream direction would have significant influence on the flow modification, and different rotation types actually arrange these shear layers in diverse ways to change the flow pattern. Pitch ratio is capable to transform the gap flow, which is usually including the shear layers referred, thus this parameter can modify the wake of the two cylinders at different rotation types.

Key words: *rotating circular cylinders, rotation type, flow modification*

Introduction

Relative movement of fluid and cylinders is very common in many applications [1-4]. Fluid flow around two or more circular cylinders is a classical problem and has been studied extensively. The most basic multiple-cylinder configurations are tandem, side-by-side and staggered configurations.

The flow around stationary circular cylinders in a side-by-side arrangement has been well investigated. However, the problem of flow passing rotating circular cylinders in a side-by-side arrangement has not been investigated widely. Yoon *et al.* [5] found that as rotational speed increases, flow becomes stabilized and finally reaches a steady state beyond the critical rotational speed depending on *T/D*. Later, Hasan *et al.* [6] provided detailed quantitative information about the flow variables. Nemati *et al.* [7] also indicated that as rotational speed increases, the flow changes its condition from periodic to steady after arriving a critical rotational speed. Guo *et al.* [8] showed that the flow becomes stabilized and finally steady beyond the critical rotational speed regardless of the variation in Reynolds number and *T/D*. In the literatures of [5-8], the upper and lower cylinders rotate as shown in fig. 1(a). While the investi-

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gations on the flow as shown in figs. 1(b) and (c) have not been found so far. Therefore, the present work is to study the modification of flow by the combined effects of the rotation and the spacing between two cylinders on the flow with different rotation types by providing detailed quantitative information about the flow variables.

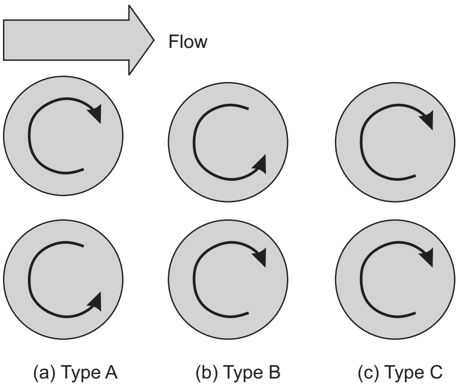


Figure 1. Different rotation types

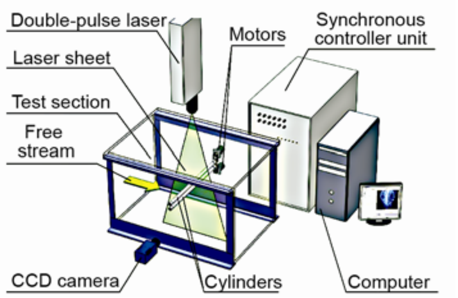


Figure 2. Experimental arrangement

Experimental details

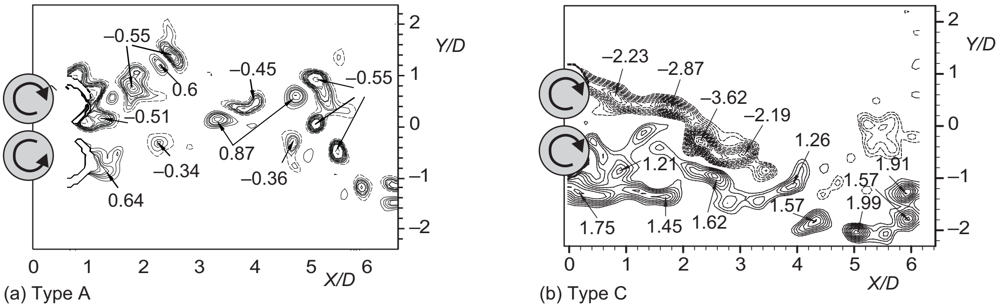
Experiments are conducted in a low speed wind tunnel with its test section is 2 m long and a 600 mm × 600 mm square cross-section. The speed of the wind in the test section can be adjusted from 0.5 to 50 m/s with turbulence intensity less than 0.5%. The experimental setup is shown schematically in fig. 2. A pair of identical aluminum alloy round rods with a diameter of D = 25 mm are mounted. The rods are driven to rotate by two motors. The Reynolds number under this setting is 950. Both particle image velocimetry (PIV) and hot-wire anemometry (HWA) are used. The PIV system has a maximum sampling frequency of 15 Hz, and the space resolution of the velocity fields is about 2.4 mm in our experiments. The sampling frequency of HWA, with one-dimensional probe, is set to 1000 Hz and the sampling time is kept at 10 s. PIV is used to measure instantaneous velocity and HWA to obtain the high time-resolution flow information in large area from the near-wake to the far-wake.

Effect of rotation type on the flow pattern under different gap spacing

Vortex fields

For T/D = 1.11, the wake appears as a single-bluff-body regime, but there is a small-scale biased gap flow upward. However, vortex formation and shedding occurs only from the outside shear layers owing to the "near-wall effect" [9]. The most intensive vorticities of the upper and lower outside shear layers are –2.3 and 2, respectively. For the rotation type A, the outside shear layers are forced to interact in the nearer wake. As $|\alpha|$ increases to 1.74 (α is the rotational speed which is the ratio of the linear velocity speed at the cylinders wall to the free-stream velocity) as shown in fig. 3, the largest vorticity has been reduced weaker than 1 s^{-1}. For type B, the gap between the two cylinders is too small to form a gap flow like a planar jet and the rotation extends the low-pressure area. The vorticity of the intense vortices which are stronger than 2 s^{-1} can be maintained to the downstream boundary of the test area. For the type C, the upper outside layer deflects to the lower outside layer.

For T/D = 1.6, the biased flow pattern is obviously observed with two pairs of high-vorticity shear layers. Once the two cylinders are rotated in type A, both the outside shear layers deflect to Y/D = 0. Thus the vorticity is sharply attenuated. The inner shear layers are accelerated by type B that results in the transformation of biased gap flow into planar-jet-like flow with unbiased potential core. Furthermore, the potential core separates the two wakes of the cylinder pair, and consequently the vortices can keep their strength without interaction. While the type C rotation of the cylinders deflects the wakes of both cylinders downward, and the wakes of cylinders appear parallel to each other. Since the lower inner shear layer is attenuated and moves downwards, the gap flow is dominated by the upper inner shear layer and the strength of the vortices hardly changes even as $|\alpha|$ increases to 1.74.



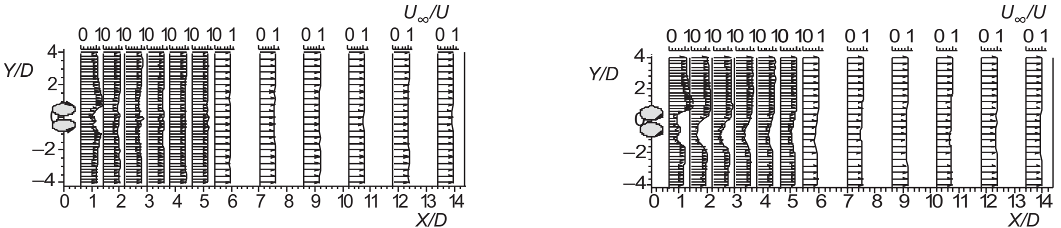
(a) Type A (b) Type C

Figure 3. Vorticity contours (*T/D* = 1.11, |*α*| = 1.74)

For $T/D = 3$, type A rotation of cylinders also can reduce the vorticity in the wake efficiently. For type B, the flow pattern is similar as that for $T/D = 1.6$, however, the interaction between the two wakes of cylinders becomes negligible and both wakes behave closer to that of single-rotating-cylinder. As the cylinders rotate in type C, both wakes of the two side-by-side cylinders deflect downward, however, the wake of the lower cylinder is attenuated faster than that of the upper cylinder.

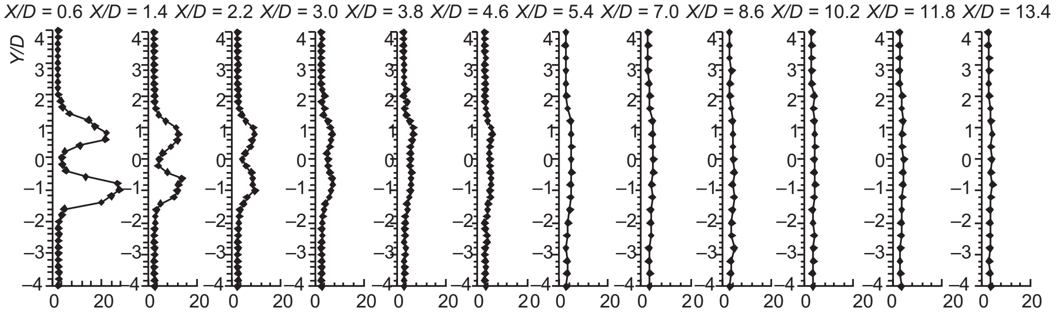
Velocity profile and turbulence intensity

As shown in figs. 4 and 5, there are three remarkable features could be observed from the velocity profiles and turbulence intensity for $T/D = 1.11$: (1) the velocity fluctuation drops and turbulence intensity is well symmetric from $X/D = 1.4$ to $X/D = 13.4$ against the center plane except the asymmetric type C, furthermore, and all the velocity drop and turbulence intensity higher than 5% distribute only is restricted in a continuous area; (2) Both rotations of type A and C could obviously weaken the velocity drop and turbulence intensity and narrow their distributions. The type A rotation has the highest efficiency for the flow modification, while type B rotation enlarges the velocity drop and turbulence intensity ($Tu > 10\%$); (3) there is an optimal velocity ratio (denoted as $|\alpha|_p$) for rotation type A to suppress the

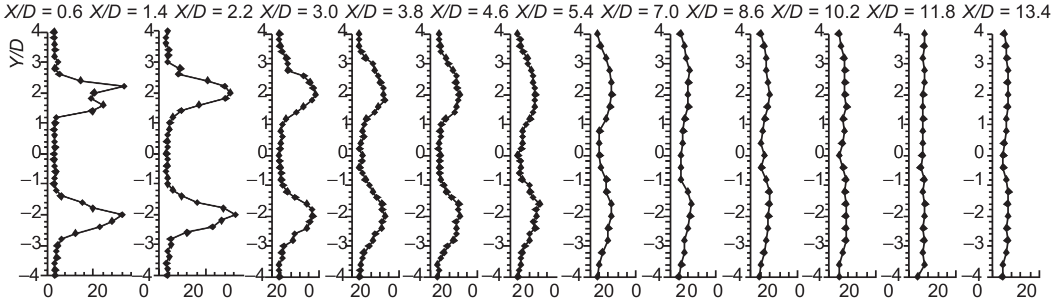


(a) Type A, $|\alpha| = 1.74$ (b) Type C, $|\alpha| = 1.74$

Figure 4. Time-averaged velocity profiles (*T/D* = 1.11)



(a) Type A



(b) Type B

Figure 5. Profiles of turbulence intensity (T/D = 3, $|\alpha|$ = 1.96)

low-pressure area best and attained the lowest level of turbulence, which is consistent with the numerical results given by Yoon *et al.* [5, 10] about the critical rotational speed at Re = 100. If $|\alpha|>|\alpha|_p$, the turbulence intensity would be strengthened near the center plane in the near-wake and over the larger traverse area in the far-wake.

At T/D = 1.6 and $|\alpha|$ = 0, the two side-by-side circular cylinders exhibit a bistable or biased flow pattern owing to the intermediate value of T/D. The time-averaged velocity and turbulence intensity profiles indicate that (1) all the rotation types can observably change the initial biased flow pattern of the side-by-side circular cylinders, and the symmetrical types A and B force the biased flow to translate into two parallel vortex streets, but the asymmetrical rotation type C aggravates the deflection of the near-wake through extending the wider near-wake and the contraction of the narrow near-wake; (2) The rotation accelerates the combination of the wider and narrow near-wake; (3) As same as T/D = 1.11, type A has the highest efficiency to the modification of the wake, especially for the attenuation of the velocity drop and turbulence intensity, that can be observed from the strongly smooth of velocity and turbulence intensity profiles.

As the pitch ratio is increased to 3, two parallel vortex streets are built in the wake and the gap flow is generally along streamwise in the wake. When the cylinders are rotating as type A, the increase of the velocity drop and turbulence intensity in the near-wake implies that the outer shear layers begin to concentrate into the center plane and have a chance to interact. Meanwhile, the formation and shedding of the inner shear layers are limited to a small area which is bounded by the outside shear layers. As long as the type A executing, both outer shear layers could gain stronger momentum and shear velocity gradient in the reverse direction, then the forced interaction between the outer shear layers presented and they would counteract each other. The other point to notice is that the forced interaction mentioned occurs before the shedding of the outer shear layers even prior to their intensifying. Because of the flow modification above, the velocity drops and turbulence intensity in the wake are reduced efficiently as the rotation type A is performed. Even in the far-wake, the turbulence intensity decreases from more than 10% at $|\alpha| = 0$ to about 5% at $|\alpha| = 1.96$. Under type B of rotation, the gap flow has been accelerated by the inner shear layers, thus the two parallel vortex streets have been further separated, and meanwhile the velocity drops and the turbulence of the wake have been suppressed to a certain extent. However, the velocity drops and turbulence intensity profiles remain distinguishable bi-modal even in the downstream boundary of the test area. For rotation type C, the upper shear layers of both the cylinders which acquire larger momentum from rotating wall have deflected the two parallel wakes downwards. Since the lower shear layer of the upper cylinder can obtain enough momentum from large-spacing gap flow to deflect, the interaction between the upper and lower shear layers of the upper cylinder is lagged and larger streamwise-span low-pressure area formed. In contrast, the shear layers of the lower cylinder would interact each other and are shed in advance, because the lower shear layer generally maintains its initial direction, while the upper shear layer deflects to the former.

Conclusions

This study has firstly investigated the influence of rotation type on the flow characteristics of two side-by-side circular cylinders in cross-flow under different spacing at Re = 950. For rotation type A, under the typical spacing $T/D = 1.11$, 1.6, and 3, the outer shear layers are all accelerated and the flow is deflected to the center plane of the test area where the strength of the vortices is attenuated by interaction, and then the inner shear layers are constricted in a narrower area which is enclosed by the formers. Therefore, this flow mechanism could account for the easier attenuation of velocity drop and turbulence intensity in the whole test area in rotation type A than other rotation types. The biased flow pattern would change into two parallel wakes, since the inner shear layers are pushed to the center plane by the outer ones. A remarkable feature to be noticed is that an optimal rotational speed $|\alpha|_p$ exists, which approximately ranges from 1.7 to 2, to tremendously reduce and smooth the velocity drop and turbulence intensity best, under type A. When type B of rotation initiates, the pitch ratio could affect the flow pattern significantly: (1) for $T/D = 1.11$, the gap between the two side-by-side cylinders is too small to form a large-scale inner shear layer, thus the single bluff-body behavior keeps going even if $|\alpha|$ increases to 2.83; (2) for $T/D = 1.6$ and 3, the high-momentum fluid of the gap flow further intensified the separation of the two vortex streets and forces the inner shear layers to be symmetry along the free-stream. The velocity drop and the turbulence intensity hardly decrease with their expanding distribution range. Once type C of rotation being executed, the wakes of the two cylinders present strong asymmetry and deflect to one side of the transverse, according to the rotational direction. Under this condition, the effect of the spacing between the two circular cylinders on the flow pattern can be divided into two main regimes: (1) At very small pitch ratio $T/D = 1.11$, the two cylinders behave as a single rotating circular cylinder that the upper outer shear layer with high-momentum deflects downwards and the lower shear layer generally maintains in streamwise direction; (2) For the larger pitch ratios $T/D = 1.6$ and 3, the gap flow could deflect, because of the powerful shear velocity gradient which is formed between the inner shear layers and the high kinetic energy is mainly from the lower inner shear layer. Thus the unbiased lower outer shear layer is apt to be involved in the gap flow that is why the lower wake is prior to be dissipated.

The main flow mechanism of the above detailed results can be concluded as follows: firstly, the shear layers accelerated by the rotating cylinders wall which are following the free-stream would have significant influences on the flow pattern of the two cylinders in cross-flow. Secondly, the effect of pitch ratio on the flow pattern could be attributed to the adjustment of gap flow with suppression or non-interference. Finally, different rotation types would yield diverse arrangement of the accelerated shear layers that is the real reason why rotation type plays a very important role in the flow modification as discussed.

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References

[1] Sumner, D., Two Circular Cylinders in Cross-Flow: a Review, *Journal of Fluids and Structures*, *26* (2010), 6, pp. 849-899

[2] Lin, J. Z. *et al*., The Motion of Fibers in an Evolving Mixing Layer, *International Journal of Multiphase Flow*, *29* (2003), 8, pp. 1355-1372

[3] Lin, J. Z. *et al.*, Numerical Research on the Orientation Distribution of Fibers Immersed in Laminar and Turbulent Pipe Flows, *Journal of Aerosol Science*, *35* (2004), 1, pp. 63-82

[4] Lin, J. Z. *et al.*, Effects of the Aspect Ratio on the Sedimentation of a Fiber in Newtonian Fluids, *Journal of Aerosol Science*, *34* (2003), 7, pp. 909-921

[5] Yoon, H. S. *et al.*, Flow Characteristics of Two Rotating Side-by-Side Circular Cylinder, *Computers & Fluids*, *38* (2009), 2, pp. 466-474

[6] Hasan, N. *et al.*, Numerical Simulation of Fluid Flow of Two Rotating Side-by-Side Circular Cylinders by Lattice Boltzmann Method, *International Journal of Computational Fluid Dynamics*, *24* (2010), 3-4, pp. 83-94

[7] Guo, X. H. *et al.*, Vortex Structures and Behavior of Flow Past Two Rotating Circular Cylinders Arranged Side-by-Side, *Chinese Physics Letter*, *26* (2009), 8, pp. 4701-1-4

[8] Guo, X. H. *et al.*, New Formula for the Drag Coefficient of Cylindrical Particles, *Particuology*, 9 (2011), 2, pp. 114-120

[9] Xu, S. J. *et al.*, Reynolds Number Effects on the Flow Structure behind Two Side-by-Side Cylinders, *Physics of Fluids*, *15* (2003), 5, pp. 1214-1219

[10] Yoon, H. S. *et al.*, Laminar Flow Past Two Rotating Circular Cylinders in a Side-by-Side Arrangement, *Physics of Fluids*, *19* (2007), 12, pp. 128103-1-4

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