Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia Engineering 56 (2013) 173 – 178

Procedia Engineering

www.elsevier.com/locate/procedia

5th BSME International Conference on Thermal Engineering

Suppression of fluid forces on two staggered cylinders

Md. Mahbub Alam[1*] and Y. Zhou[1,2]

[1]Shenzhen Graduate School, Harbin Institute of Technology, Shenzhen, China
[2]Mechanical Engineering Department, The Hong Kong Polytechnic University, Hong Kong.

Abstract

An investigation is conducted to suppress flow-induced forces on two identical cylinders (diameter D = 49 mm) at stagger angle $\alpha = 0^{\circ} \sim 180^{\circ}$ and gap spacing ratio $T/D = 0.1 \sim 5$, where T is the gap width between the cylinders. In order to suppress fluid forces, two tripwires, each of 5 mm, were attached on each cylinder at azimuthal angle $\beta = \pm 30^{\circ}$. Time-mean drag (C_D) and fluctuating drag (C_{Df}) and lift (C_{Lf}) on two tripped cylinders were measured and compared with those on plain cylinders. Flow visualization test was also conducted to observe flow structures around the cylinders. C_D, C_{Df} and C_{Lf} all for the plain cylinders are strong function of α and T/D due to six different interaction mechanisms. On the other hand, the tripped cylinders interfere weakly each other, resulting in insignificant variation in forces with α and T/D. Tripwires suppress forces on the cylinders remarkably.

Selection and peer review under responsibility of the Bangladesh Society of Mechanical Engineers

Keywords: Two cylinders; drag; lift; trip wires; supression; interaction

Nomenclature

u_θ	velocity in the direction of (m/s)
A	radius of (m)
B	position of
C	further nomenclature continues down the page inside the text box
Greek symbols	
γ	stoichiometric coefficient
δ	boundary layer thicknesses(m)
Subscripts	
r	radial coordinate

* Corresponding author: Tel: +8675526623472
Email: alamm28@yahoo.com; alam@hitsz.edu.cn

1877-7058
Selection and peer review under responsibility of the Bangladesh Society of Mechanical Engineers
doi:10.1016/j.proeng.2013.03.104

1. Introduction

The alternate shedding of vortices in the near wake leads to fluctuating forces on the structures and may cause structural vibrations, acoustic noise, or resonance, which in some cases can trigger failure. In a real life architectural environment, most buildings and structures are in close proximity of each other, such as chimney stacks, tube bundles in heat exchangers, overhead power-line bundles, bridge piers, stays, masts, chemical-reaction towers, offshore platforms and adjacent skyscrapers. Aerodynamics of two closely separated structures is of both fundamental and practical significance. Two cylinders are considered as the basic model to understand the physics of flow around multiple structures. Fluid forces, Strouhal numbers (*St*) and flow structures are the major factors considered in the design of multiple slender structures subjected to cross flow. The flow around two cylinders is apparently more complicated than that around a single one.

Based on the interference effect between two cylinders, Zdravkovich [1] divided the whole region of possible arrangements of two cylinders into four; (i) the proximity interference region, where the flow around one cylinder affects the other; (ii) wake interference region, the near-wake flow of the upstream cylinder is unaffected by the downstream one; however, the downstream one is significantly affected by the upstream cylinder; (iii) the proximity and wake interference region includes the combination of the proximity and wake interferences; (iv) the no interference region, where the wake of one cylinder does not affect the other. This classification is useful from the engineering design point of view, though providing little information on the flow structure around the cylinders.

Time-averaged drag and lift forces acting on two staggered cylinders have been examined in literatures (e.g., [2, 3]). However, data in the literatures are mostly concerned with the downstream cylinder. A review of literature indicated that due to interference between the cylinders, fluctuating lift and drag forces on two staggered circular cylinders are intensified depending on T/D and α, where T is the gap spacing between the cylinders, D is the cylinder diameter and α is the stagger angle between the free-stream flow and the line connecting the centers of the cylinders. No method has however been established to suppress the intensified forces. Use of tripwires to control boundary layer on a cylinder is interesting and effective [4]. Alam et al. [5] used tripwires as control objects to suppress forces on two cylinders in tandem and side-by-side configurations.

The objectives of this study were to (i) find the possible interaction mechanisms between two plain cylinders and (ii) reduce flow-induced forces on and inference between the cylinders using tripwires, where T is the gap width between the cylinders, D is the diameter of a cylinder and α is the stagger angle. Measurements were conducted at $\alpha = 0^\circ \sim 180^\circ$, $T/D = 0.1 \sim 5.0$. The linkage between force and flow structure and the interactions between the cylinders are discussed in details.

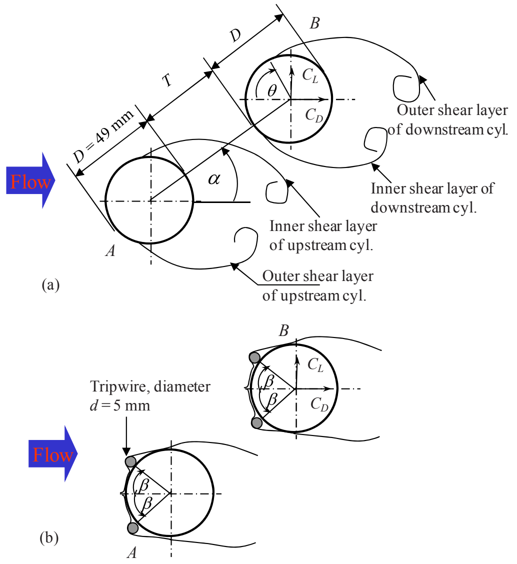

Fig. 1. Definitions of symbols and arrangement of cylinder (a) without tripwires, (b) with tripwires.

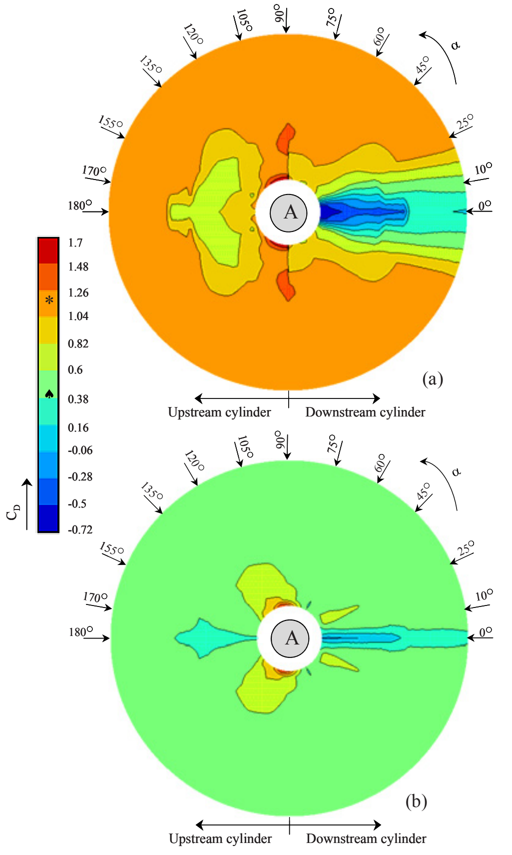

Fig. 2. Contour plot of time averaged drag coefficient, C_D: (a) plain cylinders, (b) tripped cylinders. '*' and '♠' denotes C_D values of a single cylinder plain and tripped, respectively.

2. Experimental detail

Measurements were done in a closed-circuit wind tunnel with a test section of 1.20×0.30 m at the fluid mechanics laboratory of Kitami Institute of Technology, Japan. The Reynolds number (*Re*) based on the diameter of a single cylinder was 5.52×10^4 and the turbulent intensity was 0.5%. C_D, C_{Df} and C_{Lf} were measured using two load cells installed inside a circular cylinder of diameter D = 49 mm. See Alam et al. [6] for details of the load cell. Two tripwires, each of 5 mm were placed at azimuthal angle $\beta = \pm30^{\circ}$ measured from front stagnation point. The β was decided based on optimum suppression of forces on a single cylinder [5]. Experiments were performed at $\alpha = 0^{\circ}$, 10°, 25°, 45°, 60°, 75°, 90°, 105°, 120°, 135°, 155°, 170°, and 180°, for $T/D = 0.1 \sim 5$. Flow visualization was carried out at Re = 350 in a water channel with a 250 mm × 350 mm working section and 1.5 m long. In the flow visualization test, two circular cylinders with identical diameter of 20 mm were used.

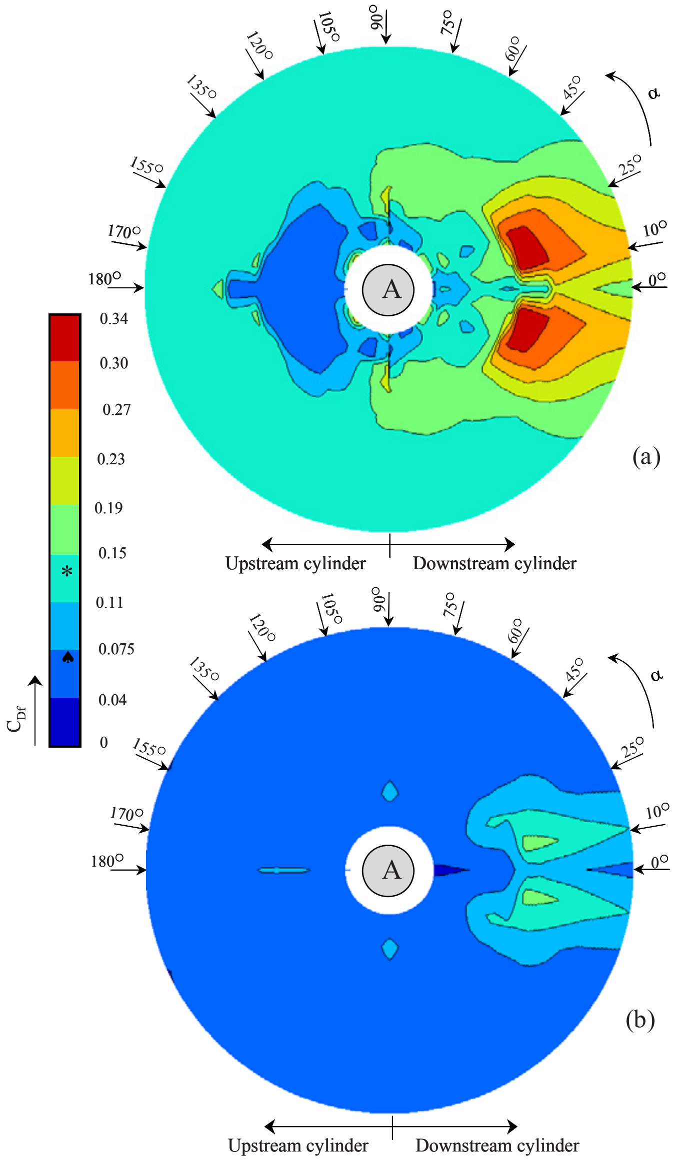

Fig. 3. Contour plot of fluctuating drag coefficient, C_{Df}: (a) plain cylinders, (b) tripped cylinders. '*' and '♠' denotes C_{Df} values of a single cylinder plain and tripped, respectively.

3. Results and discussion

3.1. Fluid forces on the cylinders

Contours of C_D, C_{Df} and C_{Lf} on a T/D-α plane are shown in Figs. 2-4 for the cases of the plain and tripped cylinders. Here tripped cylinders mean cylinders with tripwires. In the scale bars, the color or the range marked by '*' and '♠' indicates the value of a single isolated plain and tripped cylinders, respectively. For the purpose of simplicity, the result can be described with reference to Fig. 1, in which the cylinder *A* is tentatively assumed to be fixed, and thus the two parameters *T/D* and α suffice to determine the arrangement of the two cylinders. It may be noted that the cylinder *B* is the downstream cylinder for $-90^{\circ} < \alpha < 90^{\circ}$ and it becomes the upstream cylinder for $90^{\circ} < \alpha < -90^{\circ}$, i.e., the left and right sides of a contour map show the values of coefficient of the upstream and downstream cylinders, respectively. At the peripheries of the inner and outer circles, the values of *T/D* are 0 and *T/D* = 5.0, respectively. Note that the values of C_D, C_{Df}, and C_{Lf} of a single plain cylinder are 1.12, 0.14, and 0.48, respectively. Repulsive (upward directed) C_L is considered as positive (Fig. 1).

The contour maps show that C_D, C_{Df} and C_{Lf} of the plain cylinders briskly vary with change in *T/D* and α (Figs. 2a, 3a, 4a). However, those of the tripped cylinders vary rather mildly. The observation suggests that interference between the plain cylinders is much strong but that between the tripped cylinders is weak. For the case of plain cylinders, it is seen that the upstream cylinder experiences somewhat lower C_D at $\alpha = -120^{\circ} \sim 120^{\circ}$, $T/D < 3.0$ than a single isolated cylinder (Fig. 2a). The downstream cylinder experiences highly negative C_D at $\alpha = -10^{\circ} \sim 10^{\circ}$, $T/D < 3.0$, with a maximum negative value of -

0.72 when it is in contact with the upstream cylinder at $\alpha = 0^\circ$. Maximum C_D acts on the two cylinders when they are arranged in side-by-side with $T/D = 1.2 \sim 2.0$ in which an enhanced antiphase vortex shedding occurs from the cylinders. A significantly higher C_D acts on the upstream cylinder at $\pm 90^\circ < \alpha < \pm 120^\circ$, $T/D < 0.2$. For the case of tripped cylinders, a significant reduction in C_D is observed over the whole region except the region bounded by $T/D < 0.2$, $\alpha = 90^\circ \sim 105^\circ$ where color is still red. In this region, however, C_D can be reduced by changing the positions of the outer tripping wires toward the forward. Value of C_D on the most of the region is 1.04 ~ 1.26 (Fig. 2a) which have been suppressed to 0.38~0.6 by using tripping wires (Fig. 2b). On average, the suppression in C_D is about 58%. Figure 2(b) indicates that mutual interference between the cylinders is greatly weakened when tripping wires are used on the cylinders, which was an objective of this study.

For the case of plain cylinders, significantly higher magnitudes of C_{Lf} and C_{Df} act on the downstream cylinder at $\alpha = -35^\circ \sim 35^\circ$, $T/D > 2.5$ (Figs. 3a, 4a). C_{Lf} and C_{Df} on the upstream cylinder become extremely small for $\alpha = -120^\circ \sim 120^\circ$, $T/D < 3.0$ and on both cylinders in the vicinity of side-by-side arrangement at small T/D. In the first region, they become very small because formation of fully developed Karman vortex behind the upstream cylinder is retarded by the presence of the downstream cylinder [6]. In the second region, the gap flow between the cylinders acts as a base bleed, propelling the rolling positions of the outer shear layers downstream, causing small C_{Lf} and C_{Df}.

C_{Df} of the tripped cylinders is suppressed to very small value for the whole region, compared that of the plain cylinders. The value of C_{Df} in the region $\alpha = 10^\circ \sim 25^\circ$, $T/D = 2.5 \sim 3.5$ is maximum 0.30 ~ 0.34 for the plain cylinders and reduces to 0.15~0.19 when tripping wires are used. Here also mutual interference effect between the tripped cylinders is very small. A dramatic decrease in C_{Lf} is self-evident for tripped cylinders compared to plain cylinders (Fig. 4b). C_{Lf} in the red region (maximum values of C_{Lf}) of the plain cylinders has been reduced to significantly small value by the tripping wires on the cylinders. Thus use of tripping wires on two cylinders is an effective means for suppressing interference between and forces acting on two cylinders in any arrangements.

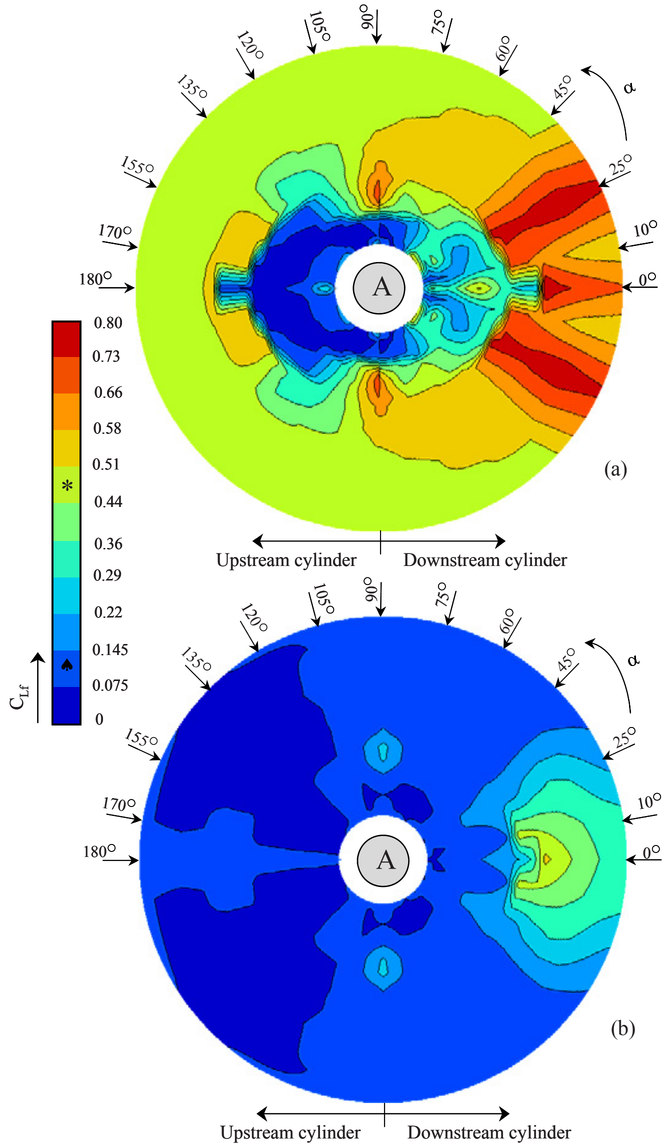

Fig. 4. Contour plot of fluctuating lift coefficient, C_{Lf}: (a) plain cylinders, (b) tripped cylinders. '*' and '♠' denotes C_{Lf} values of a single cylinder plain and tripped, respectively.

3.2. Interaction mechanisms

A single cylinder in cross-flow in general generates boundary layers, shear layers, alternating vortices and wake. When two cylinders are in close proximity, boundary layers, shear layer, vortex and wake are therefore four physical interacting parameters. A scrupulous observation of flow structures reveals the interactions of the six types. They are interaction between (i) boundary-layer and cylinder, (ii) shear-layer/wake and cylinder, (iii) shear layer and shear layer, (iv) vortex and cylinder, (v) vortex and shear layer, and (vi) vortex and vortex. Their regimes are given in Fig. 5. The details of the interactions are given as follows.

Boundary-layer and cylinder interaction: this interaction occurs when T/D is small, $T/D < 0.3$ - 0.6 depending on α. Interacting with the other cylinder, boundary-layer of a cylinder may form separation bubbles, delay to separate, reattach, etc. See Fig. 5c. The interaction therefore intensifies C_D and C_L but weakens C_{Df} and C_{Lf}. The two cylinders being very close behave like a combined cylinder.

Shear-layer/wake and cylinder interaction: this happens when shear layer(s) from one cylinder interacts on the other cylinder surface by reattaching, impinging, forming separation bubble, etc. (Fig. 5d, e). Naturally, one of the cylinders is completely (Fig. 5d) or partially (Fig. 5e) submerged in the wake of the other, hence it can also be termed as wake and cylinder interaction. The shear layer interacted by the cylinder loses its strength to shed alternating Karman vortex, hence forces wane significantly. Being completely submerged in the wake of the other, the cylinder acting as a stabilizer suppresses the flow unsteadiness between the cylinders. The interaction occurs when two cylinders are nearly in-line, $|\alpha| \approx 0^\circ \sim 20^\circ$, $0.3 < T/D < 2.3$ - 3.

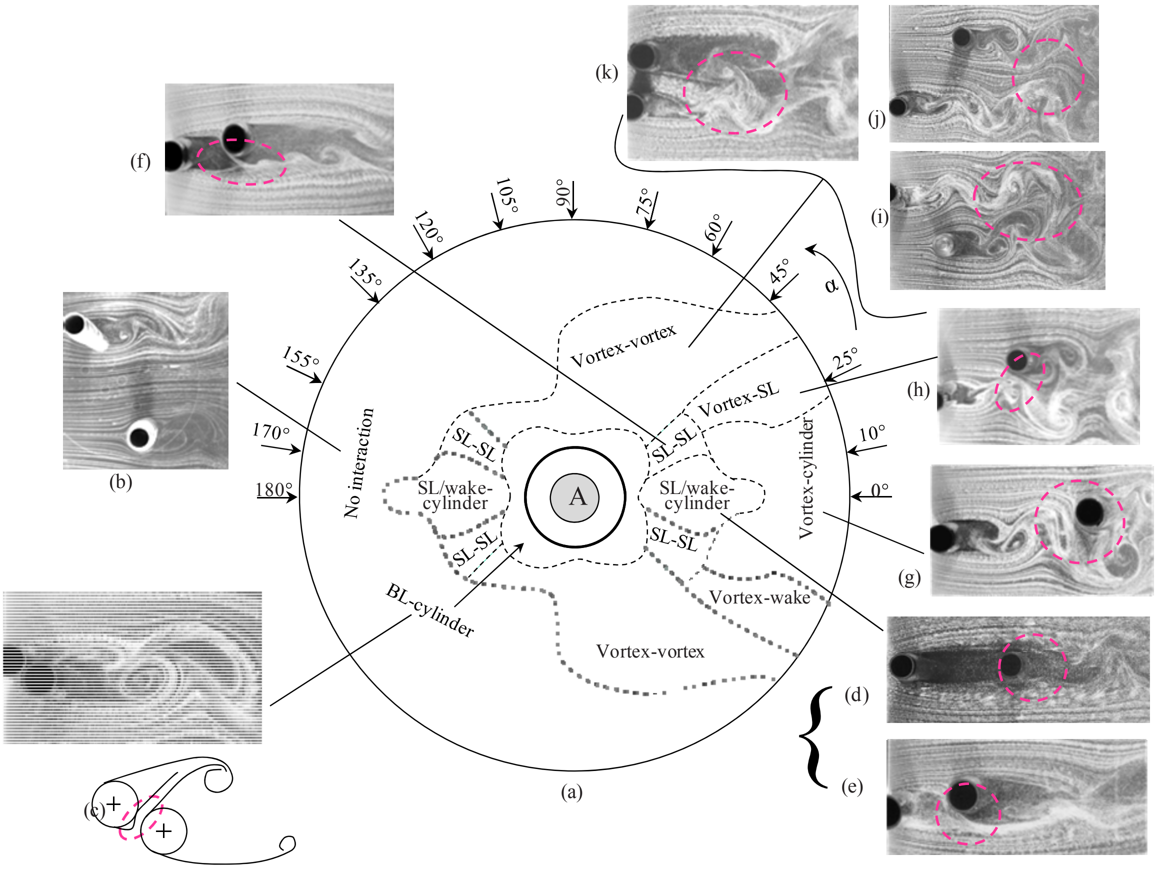

Fig. 5. Interaction regimes in T/D - α plane. SL : shear layer, BL : boundary layer.

Shear layer and shear layer interaction: here the shear layer(s) of a cylinder directly interacts with that of the other. The interaction causes intermittent interlock-in of the shear layers, hence generates vortices at more than one frequency (Fig. 5f), and reduces forces on the cylinders. Since α of this interaction regime is higher than that of shear layer/wake and cylinder interaction regime, generation of two shear layers through the gap is possible. The two shear layers interact with themselves and the outer-shear layers.

Vortex and cylinder interaction: when T/D is greater than the critical spacing of two nearly in-line cylinders, the shear layers of the upstream cylinder cannot reach the downstream cylinder, hence roll between the cylinders, forming alternate vortices. Thus the alternate vortices from the upstream cylinder strike on the downstream cylinder and embrace the side surface during passing on the cylinder (Fig. 5g). This interaction is generally very strong, intensifying C_{Df} significantly. Gursul and Rockwell [7] investigated the interaction of oncoming two rows of vortices on an elliptical leading edge and observed very high fluctuating pressure on the surface where vortices reached.

Vortex and shear-layer interaction: for a larger α, the downstream cylinder becomes offset from the inner row of vortices from the upstream cylinder, hence the vortices cannot interact with the downstream cylinder, but can interact with the inner-shear layer. Interacting with the shear layer while it is growing, the vortices force the shear layer to form a synchronized coupled vortex (Fig. 5h). This interaction renders a very high C_{Lf}, as alternate interaction between vortex and shear layer intervenes.

Vortex and vortex interaction: for a further increase in α, the transverse distance between the cylinders becomes large, hence each cylinder forms a separate wake immediately behind them. The vortices on the two inner rows interact with each other and combines the two wakes into a wider one (Fig. 5i, j, k), which results in a slightly higher C_D, C_{Df} and C_{Lf}.

For the case of tripped cylinders, flow around the cylinders over the entire region is almost the same except -25° < α < 25°. The actions of all the possible interactions are reduced. Mutual interference effect between the cylinders is reduced significantly; as a result, C_D, C_{Df} and C_{Lf} are almost insensitive to *T/D* and α.

As sketched in Fig. 1(b), the flow structure on the tripped cylinders has the following features: (i) shear layer separating from the tripwires reattach on the cylinder surface, (ii) the eventual separation is postponed, (iii) wake narrows, and (iv) vortex shedding is almost suppressed from the cylinders. A cylinder with these features do not interfere the other. However, for α < 25°, the downstream cylinder is submerged in the wake of the upstream cylinder, hence interfered weakly.

4. Conclusions

The results can be summarized as follows.

Fluctuating drag coefficient (C_{Df}) and Fluctuating lift coefficient (C_{Lf}) on the downstream cylinder are extensively high in two island-like regions $\alpha = \pm (10° \sim 30°)$, $T/D = 2.5 \sim 5$, where the inner shear layer of the downstream cylinder sheds vortices in synchronization with the convective inner vortices from the upstream cylinder, generating a coupled vortex. Tripping wires suppress C_{Df}, and C_{Lf} by about 55% and 70%, respectively in these regions.

While the plain cylinders each other intervene extensively, tripped cylinders do not; hence C_{Df} and C_{Lf} are almost insensitive to *T/D* and α. Compared to the plain cylinders, the tripped cylinders eperience smaller forces in the entire *T/D* and α ranges examined.

Six different interaction mechanisms between the cylinders were observed: boundary-layer and cylinder interaction, shear-layer/wake and cylinder interaction, shear layer and shear layer interaction, vortex and cylinder interaction, vortex and shear-layer interaction, and vortex and vortex interaction. Each of them had different influences on the induced forces. Both shear-layer/wake and cylinder, and boundary-layer and cylinder interactions weaken C_{Df}, C_{Lf} and flow unsteadiness. While the former interaction stabilizes the wake or shear layers, the latter one forms a separation bubble, delays boundary layer separation, or causes reattachment. The separation bubble formation results in maximum repulsive C_L of +0.86 at $|\alpha| = 135^{\circ}$, $T/D = 0.1 \sim 0.2$. Maximum C_D of 1.75 acts on the cylinders in the regime of $|\alpha| = 90^{\circ}$, $T/D = 2.2 \sim 2.6$ caused by a strong vortex and vortex interaction, which is about 1.56 times the single cylinder value.

References

[1] Zdravkovich MM. The effects of interference between circular cylinders in cross flow. J Fluids and Structures 1987; 1: 239-261.

[2] Zdravkovich MM. Pridden DL. Interference between two circular cylinders; series of unexpected discontinuities. J Industrial Aerodynamics 1977;. 2: 255-270.

[3] Price,SJ, Paidoussis MP. The aerodynamic forces acting on groups of two and three circular cylinders when subject to a cross-flow. J Wind Engineering and Industrial Aerodynamics 1984; 17: 329-347.

[4] Nebres J, Batill S. Flow about a circular cylinder with single large-scale surface perturbation. Exp. in Fluids 1993; 15: 369-379.

[5] Alam MM, Sakamoto H, Moriya M. Reduction of fluid forces acting on a single circular cylinder and two circular cylinders by using tripping rods. J Fluids and Structures 2003;18: 347-366.

[6] Alam MM, Sakamoto H, Zhou Y. Determination of flow configurations and fluid forces acting on fwo staggered cylinders of equal diameter in cross-flow. Journal of Fluids and Structures 2005; 21: 363-394.

[7] Gursul I, Rockwell D. Vortex-street impinging upon an elliptical leading edge. J Fluid Mechanics. 1990; 211, 211–242.