Interference between Two Tripped Cylinders in a Cross Flow

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ABSTRACT

Flow interference is investigated between two tripped cylinders of identical diameter $D$ at stagger angle $\alpha = 0^\circ \sim 180^\circ$ and gap spacing ratio $P' (= P/D) = 0.1 \sim 5$, where $P$ is the gap width between the cylinders and $\alpha$ is the angle between the freestream velocity and the line connecting the cylinder centers. Two tripwires, each of diameter $0.1D$, were attached on each cylinder at azimuthal angle $\beta = \pm 30^\circ$, respectively. Time-mean drag ($C_D$) and fluctuating drag ($C_{Df}$) and lift ($C_{Lf}$) on the two tripped cylinders were measured and compared with those on plain cylinders. Surface pressure measurements were also carried out to assimilate the fluid dynamics around the cylinders. $C_D$, $C_{Df}$ and $C_{Lf}$ all for the plain cylinders are strong function of $\alpha$ and $P'$ due to strong mutual interference between the cylinders, connected to six interactions, namely boundary layer and cylinder, shear-layer/wake and cylinder, shear layer and shear layer, vortex and cylinder, vortex and shear layer, and vortex and vortex interactions. $C_D$, $C_{Df}$ and $C_{Lf}$ are very large for vortex and cylinder, vortex and shear layer, and vortex and vortex interactions, i.e., the interactions where vortex is involved. On the other hand, the interference as well as the strong interactions involving vortex are suppressed for the tripped cylinders, resulting in insignificant variations in $C_D$, $C_{Df}$ and $C_{Lf}$ with $\alpha$ and $P'$. In most of the ($\alpha$, $P'$) region, the suppressions in $C_D$, $C_{Df}$ and $C_{Lf}$ are about 58%, 65% and 85%, respectively, with maximum suppressions 60%, 80% and 90%.

Keywords: interactions; aerodynamics; two cylinders; tripped cylinders; trip wires; wake; forces; vortex; shear layer; staggered arrangement.

1. INTRODUCTION

1) Professor
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. Fluid forces, Strouhal numbers ($St$) and flow structures are the major factors considered in the design of multiple slender structures subjected to cross flow. Alternate vortex shedding and vortex impingement may produce a large fluctuating pressure on the structures, causing structural vibrations, acoustic noise, and even resonance, which can trigger structural failure. Numerous failures in the practical applications of cylinder-like structures in cross flow have been illustrated in Chen (1987), Paidoussis (1981, 1993) and Blevins (1990). The cost associated with a typical engineering structural failure can easily reach the order of million dollars and even billions of dollars. Naturally, a concentrated effort is required to study and assimilate the fluid dynamics associated with multiple cylindrical structures in cross flow. Fluid-dynamic interference between two cylinders may give rise to flow separation, gap flow switching, shear-layer development, reattachment, vortex impingement, recirculation, quasi-periodic vortices and vortex street interaction, involving most of the generic flow features associated with multiple structures. Thus, flow around two cylinders provides an excellent model for gaining insight into the underlying flow physics around more structures.

Depending on the interference effect between two cylinders, Zdravkovich (1988) and Mederios & Zdravkovich (1992) divided the whole region of possible arrangements of two cylinders into four regions. (i) *Proximity interference region*: the flow around either cylinder affects the other, occurring in both side-by-side and staggered cylinders at large $\alpha$. The interference includes two wakes coupled each other, or narrow and wide wakes, and single combined wake. (ii) *Wake interference region*: it occurs in tandem and slightly staggered arrangements where the downstream cylinder influence on the upstream cylinder is insignificant, but the opposite is significant. It corresponds to coshedding flow. (iii) *Proximity and wake interference region*: in essence, it is the combination of the proximity and wake interference, occurring in tandem and staggered arrangements for small $P^*$ and $\alpha$ at which the near wake of the upstream cylinder is disrupted by the downstream cylinder. Gu and Sun (1999) classified the proximity and wake interference into wake interference, shear layer interference, and proximity interference. (iv) *No interference region*: the flow of the either 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.
Extensive investigations have been conducted on the wake of two staggered cylinders in light of measurements of velocity field or flow structure (e.g., Sumner et al. 2000; Alam et al. 2005), Strouhal number $St$ (e.g., Kiya et al. 1980; Alam and Sakamoto 2005), time-averaged pressure coefficient $C_p$ (e.g., Igarashi 1981; Sun et al. 1992; Alam et al. 2005), fluctuating (rms) pressure coefficient $C_p'$ (e.g., Alam et al. 2005), time-averaged drag $C_D$ (e.g., Price and Paidoussis 1984; Alam and Meyer 2011), fluctuating drag $C_D'$ (e.g., Price and Paidoussis 1984; Alam and Meyer 2011), time-averaged lift $C_L$ (e.g., Gu et al. 1993; Alam and Meyer 2011) and fluctuating lift $C_L'$ (e.g., Alam et al. 2005; Alam and Meyer 2011). Detailed measurements of flow field, $St$ and forces enabled classifications of flow prevailing for two staggered cylinders (e.g., Kiya et al. 1980; Sumner et al. 2000; Alam and Meyer 2011). At Reynolds number $Re = 1.58 \times 10^4$ based on free-stream velocity $U_\infty$ and $D$, Kiya et al. (1980) measured $St$ in the wake of two staggered circular cylinders for spacing ratio $P^* = 0 - 4$ and $\alpha = 0 - 90^\circ$, where $P$ is the gap distance between the two cylinders, and $\alpha$ is the angle between the oncoming flow direction and the line connecting the cylinder centres. Depending on whether $St$ was greater than or less than an isolated single cylinder Strouhal number $St_0$, they divided the $P^*_\alpha$ plane into five regions (region 1, $St > St_0$; region 2, $St < St_0$; region 3, bistable flow; region 4, single-body flow; region 4, weak or no vortex shedding; see Kiya et al. 1980 for the details of the regions).

With a very detailed measurement of $C_D$, $C_L$, $C_L'$ and $St$, Alam and Meyer (2011) observed that $C_D$, $C_L$, $C_D'$, $C_L'$ and $St$ are highly sensitive to $P^*$ and $\alpha$, and simply flow classification based on interference are not enough to explain the variations in $C_D$, $C_L$, $C_D'$, $C_L'$ and $St$. Alam and Meyer (2011) therefore classified the whole $\alpha$ and $P^*$ region based on individual cylinders and identified 19 distinct flow regimes. Each of them had different influences on the forces and $St$. There were two island-like regimes ($\alpha = 10^\circ - 25^\circ$, $P^* = 2.2 - 4.0$; $\alpha = 18^\circ - 32^\circ$, $P^* = 2.1 - 5$) where the values of $C_D$ and $C_L$ were extensively high, about 2.35 and 1.58 times the single cylinder values. Maximum $C_D$ of 1.75 acts on the cylinders in the regime of $\alpha = 90^\circ$, $P^* = 2.2 - 2.6$, which is about 1.56 times the single cylinder value. The information suggests that finding a flow control technique to reduce forces is necessary.

The use of spanswise tripping wires to trip the boundary layer is very interesting, bringing about a delayed separation, weaker shedding, and hence a reduction in forces. Previous researches showed that $St$ and $C_D$ characteristics strongly depend on the wire size, wire location and $Re$ (e.g., James and Truong 1972; Nebres and Batill 1993; Aydin et al. 2014). James and Truong (1972) at $Re = 10^4 \sim 10^5$ investigated experimentally the
dependence of a cylinder wake on the tripwire diameter (0.006 ~ 0.063D) and position \( \beta = 0^\circ \) to 180\(^\circ \), where \( \beta \) is the angular position of a tripwire measured from the forward stagnation point. They found that a larger tripwire diameter results in the transition of the boundary layer to turbulence occurring at an earlier \( \text{Re} \) and/or a smaller \( \beta \). Nebres and Batill (1993) studied the effect of a single wire of diameter 0.007D ~ 0.14D on the pressure distribution, \( St \) and \( C_D \) at \( \text{Re} = 2 \times 10^4 \sim 4 \times 10^4 \) and \( \beta = 0^\circ \sim 180^\circ \). The tripwire had a considerable effect on the wake at \( \beta = 20^\circ \sim 70^\circ \) where a small change in \( \beta \) leads to large variation in both \( St \) and \( C_D \). On the other hand, the tripwire had no effect on the wake when positioned near the forward stagnation point (\( \beta < 20^\circ \)) or the base region.

Alam et al. (2003a) used tripwires with a diameter of 0.081D ~ 0.13D. The angular position of the tripping wire was varied from 20° to 60°. The optimum angular position of tripping rods for suppressing fluid forces was found to be 30° with \( C_D \), \( C_{Df} \) and \( C_{Lf} \) were suppressed by 67%, 61% and 87%, respectively. Alam et al. (2010) conducted an experimental investigation in the wake of a circular cylinder with two tripwires (each of diameter 0.045D) attached at \( \beta = \pm 10^\circ \sim \pm 70^\circ \) at \( \text{Re} = 2.5 \times 10^3 \sim 6 \times 10^4 \). They identified five flow regimes based on forces, \( St \) and flow structure in the wake. Placing one tripwire of diameter varying from 0.029D to 0.059D at \( \text{Re} = 5 \times 10^3 \sim 3 \times 10^4 \), Aydin et al. (2014) observed two critical locations of the wire where Karman instability attenuates and amplified, respectively.

While two staggered cylinders interact strongly each other and amplify forces, no methods have been developed to reduce forces or to weaken the interaction between them. The objective of this study is to reduce forces and interference between two staggered cylinders. Two tripwires are used on each cylinder at \( \beta = \pm 30^\circ \) that is the optimum position obtained for a single isolated cylinder by Alam et al. (2003a). \( C_D \), \( C_{Df} \) and \( C_{Lf} \) are measured for both cylinders with \( \alpha \) varying from 0° to 180° and \( P^* \) from 0.1 and 5.0. The measured forces on the tripped cylinders are compared with those on plain cylinders and reductions of forces are estimated. Pressure measurements are also conducted for both plain and tripped cylinders.

2. EXPERIMENTAL DETAILS

Experiments were done in a closed-circuit wind tunnel with a 2.5-m-long rectangular test section of 1.20×0.30 m at the fluid mechanics laboratory of Kitami Institute of Technology, Japan. See Alam et al. (2005) for the details of the wind tunnel. The cylinders spanned the horizontal 0.3-m dimension of the tunnel. In the test section side walls, two circular holes of 0.5 m diameter, one opposite to the other, were made
where two circular disks, each included a slit for cylinders, marked $0^\circ - 360^\circ$ with a resolution of $1^\circ$, were placed (Fig. 1c). The disks were rotatable to adjust the stagger angle $\alpha$ (Fig. 1a). Two circular cylinders of a diameter $D = 49$ mm, made of brass, spanned horizontally the 0.3-m dimension. The free-stream velocity, $U_\infty$, was 17 m/s, resulting in $Re \equiv \frac{\mu}{DU_\infty} \equiv 5.5 \times 10^4$, where $\nu$ is the kinematic viscosity of air. In order to check the spanwise uniformity of flow as well as spanwise separation of flow over a single cylinder for fluid forces being measured by a load cell (which will be discussed next), circumferential time-averaged and fluctuating pressures on the surface of the cylinder at the mid-section, and at $\pm 35$ mm and $\pm 80$ mm (from the mid-section), were measured. The results showed that the time-averaged and fluctuating pressure distributions at the five different sections were the same within the accuracy of measurement. The geometric blockage ratio was 4% based on single cylinder; total blockage for the cylinder pair was 8%. Based on their measurements, West and Apelt (1982) suggested that the blockage had virtually no effect on forces if less than 6% and could have a very small effect if between 6% and 9%. Therefore, the present blockage (8%) is expected to have a negligible effect on $C_D$. The cylinder aspect ratio at the test section was 6.1. West and Apelt (1993) established that the forces on an elemental section are independent of spanwise location for aspect ratios greater than 10, i.e., ‘long’ cylinder conditions occur. From the result published by Szepessy and Bearman (1992), it was found that the force was about 3% higher for an aspect ratio of 6 than that for the aspect ratio of 10. More details of the tunnel and blockage and aspect ratio effects can be found in Alam et al. (2003b, 2005).

Figure 1(b) shows a symmetrical arrangement of two tripping rods, each $5$-mm diameter, on a cylinder and the coordinate system. $\beta$ is the angular position of a tripping wire (Fig. 1b) and $\theta$ is the azimuthal angle measured from the nominal front stagnation point (Fig. 1a). As fluid forces were measured using load cell, a gap between a tripping wire and the cylinder was required. To understand the influence of the gap on forces, the gap ratio was varied from $\delta/D = 0.008$ to $0.22$ ($\delta = 0.4 \sim 12$ mm) and it was found that fluid force coefficients all were almost independent of the gap ratio for $\delta/D < 0.15$. See Alam et al. (2003a) for more details.

Two pairs of square blocks, as shown in Fig. 1(d), were used to hold the tripping wires and the cylinder to the tunnel wall. Each block has two holes at $\beta = \pm 30^\circ$ with $\delta/D = 0.008$ mm, where the tripping wires were placed precisely. The diameters of the holes for the tripping wires were the same as the diameters of the tripping wires, and each hole was 35 mm in length. As a result, fluid forces acting on the tripping wires did not
cause any vibration or rotation of the tripping rods.

Fluid forces were measured over a small spanwise length of the cylinders, using load cells (Fig. 1e). The cylinder to be measured was built in with an active ('live') section of a spanwise 45 mm (0.92D) length and two dummy sections. This size was determined taking into account the cross-correlation length of fluctuating pressure in the spanwise direction of the cylinder. The active section, placed between the two dummy sections, corresponded to the midspan of the cylinder and was installed with a load cell that consisted of four semiconductor strain gauges.
One of the dummy sections was also instrumented with another load cell of the same configuration. The load cell inside the active section measured a combination of fluid forces and forces due to vibration transmitted from outside through the cylinder support, whilst that inside the dummy section measured the latter forces only. Hence the fluid forces acting on the active section could be calculated by subtracting the output of the load cell inside the dummy section from that of the load cell inside the active section. The sensitivity of the load cells was 11.311 mV/g. See Sakamoto et al. (1994) or Alam et al. (2005) for the load details.

A semiconductor pressure transducer (Toyoda PD104K) with a range of ±10 kPa was used to measure the surface pressure during experiments. The transducer output was calibrated to give a reading of 6.22 V for 1 kPa of applied pressure. The pressure transducer responded to pressure fluctuation up to 500 Hz with a gain factor of 1±0.06, the phase lag being negligible.

3. FLOW AROUND A SINGLE CYLINDER WITH TRIPWIRES
Here we will provide an overall picture of the flow structures around a single isolated tripped cylinder. Here a tripped cylinder means the cylinder with tripwires. Fig. 2 shows surface oil-flow pattern, the corresponding flow sketch and fluctuating pressure $C_{p_f}$ distribution on a tripped and a plain cylinder. For the plain cylinder, the boundary layers separate at about $\theta = 75^\circ$ and $285^\circ$ (Fig. 2a) corresponding to the maximum $C_{p_f}$ in the distribution (Fig. 2c). On the other hand, the surface oil-flow pattern (Fig. 2b) shows that the two boundary layers separating from the tripping wires reattach on the cylinder surface behind the wires at $\theta = 52^\circ$ and $308^\circ$, respectively. The reattachments are followed by laminar separations at $\theta = 87^\circ$ and $273^\circ$. These reattachment and separation positions correspond to the sharp and small peaks, respectively, in $C_{p_f}$ distribution (solid circle symbol). The magnitude of $C_{p_f}$ on the whole surface is considerably smaller for the tripped cylinder than the plain cylinder, inferring that the alternating Karman type vortex is almost suppressed or very weak. For more details, refer to Alam et al. (2003a).

4. INTERACTION BETWEEN PLAIN CYLINDERS

Based on mechanisms of interactions between the cylinders, Alam and Meyer (2011) classified the whole region of $\alpha = 0^\circ$ - $180^\circ$ and $P^* = 0.0 - 5.0$ into six interaction regimes, namely boundary layer and cylinder interaction; shear-layer/wake and cylinder interaction; shear layer (SL) and shear layer (SL) interaction; vortex and cylinder interaction; vortex and shear layer (SL) interaction; and vortex and vortex interaction. The regimes of the interactions in $P^* - \alpha$ are shown in Fig. 3.

Fig. 3 Possible interactions and their regimes in $P^* - \alpha$ plane for plain cylinders. SL: shear layer.
For the purpose of simplicity, it can be described with reference to Fig. 1(a), in which the cylinder A is tentatively assumed to be fixed, and thus the two parameters $P^*$ and $\alpha$ suffice to determine the arrangement of the two cylinders. It may be noted that the cylinder B is the downstream cylinder for $\alpha < 90^\circ$ and it becomes the upstream cylinder for $\alpha > 90^\circ$. At the peripheries of the inner and outer half-circles, the values of $P^*$ are 0.0 and 5.0, respectively. How these interactions are connected to $C_D$, $C_{Df}$ and $C_{Lf}$ can be observed in contours of $C_D$, $C_{Df}$ and $C_{Lf}$ on a $P^*$ - $\alpha$ plane shown in Figs. 4(a), 5(a) and 6(a). While vortex and cylinder, and vortex and shear layer interactions enhance $C_{Df}$ and $C_{Lf}$, both shear-layer/wake and cylinder, and boundary-layer and cylinder interactions weaken $C_{Df}$ and $C_{Lf}$ (Figs. 3, 5a, 6a). Vortex and vortex interaction results in high $C_D$ and $C_{Lf}$ (Figs. 3, 4a, 6a). Shear layer and shear layer brought about the multiple frequencies in the wake (Alam and Meyer 2011). It is interesting from the above observation that $C_D$, $C_{Df}$ and $C_{Lf}$ are amplified for the interactions where vortex is involved. Thus, it is worth examining how $C_D$, $C_{Df}$ and $C_{Lf}$ behave when sheddings of vortices are suppressed or weakened using tripwires.

5. TRIPPED CYLINDERS

Figs. 4, 5 and 6 display a comparison of $C_D$, $C_{Df}$ and $C_{Lf}$ on a $P^*$ - $\alpha$ plane between the plain and tripped cylinders. In the scale bars, the color or the range marked by '*' and '▲' indicates the value of a single isolated plain and tripped cylinders, respectively. As mentioned above, the left and right sides of a contour map show the values of coefficient of the upstream and downstream cylinders, 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 and those of a single tripped cylinder are 0.38, 0.05 and 0.07.

5.1. Steady fluid force

For the case of plain cylinders, it is seen that the upstream cylinder experiences somewhat lower $C_D$ at $\alpha = 120^\circ$-180$^\circ$, $P^* < 3.0$ than a single isolated cylinder (Fig. 4a). The downstream cylinder experiences highly negative $C_D$ at $\alpha < 10^\circ$, $P^* < 3.0$, with a maximum negative value of -0.72 when it is in contact with the upstream cylinder at $\alpha = 0^\circ$. Both are connected to shear-layer/wake and cylinder interactions. Maximum $C_D$ acts on the two cylinders at $\alpha = 90^\circ$, $P^* = 1.2$ - 2.0, where an enhanced antiphase vortex shedding occurs from the cylinders (Fig. 4c), associated with vortex and vortex interactions. A significantly higher $C_D$ acts on the upstream cylinder at $\alpha = 90^\circ$ - 120$^\circ$, $P^* < 0.2$ due to formation of separation bubble (Alam et al. 2005) resulted from boundary layer and cylinder interaction. For the tripped cylinders (Fig. 4b), a significant reduction
in $C_D$ in comparison with the plain cylinders is observed over the whole region except at $\alpha = 90^\circ \sim 120^\circ$, $P^* < 0.2$ that nestles in the boundary layer and cylinder interaction. The maximum $C_D$ ($\alpha = 90^\circ$, $P^* = 1.2 \sim 2.0$) appearing in vortex and vortex interaction is suppressed for the tripped cylinders, by about 60%. The $C_D$ on the most of the region for the plain cylinders is 1.04 $\sim$ 1.26 (Fig. 4a) which have been suppressed to 0.38 $\sim$ 0.6 for the tripped cylinders (Fig. 4b). On an average, the suppression in $C_D$ is about 58%.

Figure 4(b) indicates that mutual interference between the cylinders greatly weakens when the tripping wires are used on the cylinders. This is because now the sheddings from the two tripped cylinders is very weak.

Fig. 4 Contour plot of time averaged drag coefficient, $C_D$: (a) plain cylinders (Alam and Meyer 2011), (b) tripped cylinders. ‘*’ and ‘▲’ denotes $C_D$ values of a single cylinder plain and tripped, respectively. (c) The flow structure corresponding to the maximum $C_D$. 
5.2. Fluctuating fluid force

For the case of plain cylinders, significantly higher magnitudes of $C_{Df}$ and $C_{Lf}$ act on the downstream cylinder at $\alpha = 5^\circ \sim 25^\circ$ ($P^* > 2.5$) and $\alpha = 15^\circ \sim 35^\circ$ ($P^* > 2.5$), respectively (Figs. 5a, 6a), connected to vortex and cylinder (Fig. 5c) and vortex and shear layer (Fig. 6c) interactions. The mechanisms of producing the maximum $C_{Df}$ and $C_{Lf}$ are different. The large magnitude of $C_{Df}$ is caused by the alternate strike of the upstream cylinder vortices on the front surface of the downstream cylinder (Fig. 5c). On other hand, that of $C_{Lf}$ results from the alternate vortices passing over the lower surface of the downstream cylinder (Fig. 6c). $C_{Lf}$ and $C_{Df}$ on the upstream cylinder become extremely small for $\alpha = 120^\circ \sim 180^\circ$, $P^* < 3.0$ and on both cylinders in the vicinity of side-by-side arrangement at small $P^*$. In the former 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 (Alam et al. 2005). In the latter 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 to that of the plain cylinders. The value of $C_{Df}$ in the region $\alpha = 10^\circ \sim 25^\circ$, $P^* = 2.5 \sim 3.5$ is maximum, 0.30 ~ 0.34, for the plain cylinders and 0.15 ~ 0.19 for the tripped cylinders. The reduction is indeed due to the absence of interaction between vortex and cylinder as the vortices are suppressed for the tripped cylinders. Here also the mutual interference between the tripped cylinders is very small. A dramatic decrease in $C_{Lf}$ is self-evident for the tripped cylinders compared to the plain cylinders (Fig. 6b). $C_{Lf}$ in the red region (maximum values of $C_{Lf}$) of the plain cylinders reduces to a significantly small value with the tripping wires added on the cylinders; the reduction is about 70%. Again while the large value of $C_{Lf}$ is ascribed to the vortex and shear layer interaction in the plain cylinder case, $C_{Lf}$ is small for tripped cylinders as there is no significant vortex and shear layer interaction. Thus the use of tripping wires on two cylinders is an effective means for suppressing interactions associated with vortex.

$C_{Df}$, $C_{Df}$ and $C_{Lf}$ of the plain cylinders briskly vary with change in $P^*$ and $\alpha$ (Figs. 4a, 5a, 6a) due to emergence of many flow features including shear layer reattachment, vortex impingement, triggering, vortex coupling, shear layer instability, etc, engendered by the six interactions (Alam and Meyer 2011). 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 very weak. For the case of tripped cylinders, the flow around the cylinders over the entire region is almost
the same except $\alpha < 25^\circ$. In other words, the mentioned features appearing for the plain cylinders are suppressed or their actions are insignificant for the tripped cylinders; mutual interference effect between the cylinders is reduced significantly; as a result, $C_D$, $C_{Df}$ and $C_{Lf}$ are almost insensitive to $P^*$ and $\alpha$.

Fig. 5 Contour plot of fluctuating drag coefficient, $C_{Df}$: (a) plain cylinders (Alam and Meyer 2011), (b) tripped cylinders. ‘*’ and ‘▲’ denotes $C_{Df}$ values of a single cylinder plain and tripped, respectively. (c) The flow structure corresponding to the maximum $C_{Df}$. 
As sketched in Fig. 2(b), the flow structure on the tripped cylinders has the following features: (i) the shear layer separating from the tripwires reattaches 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 could not interfere the other. However, for $\alpha < 25^\circ$, the downstream cylinder is submerged in the wake of the upstream cylinder, hence interfered weakly.

5.3. Quantitative suppression

As seen in Figs. 5 and 6, quantitative magnitudes of suppression in $C_{Df}$ and $C_{Lf}$
are not the same at all over the region, but dependent on $P^*$ and $\alpha$. For the plain cylinders, there are some regions where $C_{Df}$ and $C_{Lf}$ are very small, such as $\alpha = 135^\circ \sim 180^\circ$, $P^* < 2$. In these regions, considerable suppression in $C_{Df}$ and $C_{Lf}$ cannot be expected because values $C_{Df}$ and $C_{Lf}$ in those regions are already small. So it may also be an important point to quantify local suppressions in $C_{Df}$ and $C_{Lf}$.

Fig. 7 Percent of local suppression in $C_{Df}$ and $C_{Lf}$ in $\alpha - P^*$. (a) $C_{Df,R}$ and (b) $C_{Lf,R}$. 
The local suppressions in $C_{Df}$ or $C_{Lf}$ can be estimated as,

$$\% \text{ local suppression in } C_{Df} = \frac{C_{Df, PC}(\alpha, P^*) - C_{Df, TC}(\alpha, P^*)}{C_{Df, PC}(\alpha, P^*)} \times 100,$$

and

$$\% \text{ local suppression in } C_{Lf} = \frac{C_{Lf, PC}(\alpha, P^*) - C_{Lf, TC}(\alpha, P^*)}{C_{Lf, PC}(\alpha, P^*)} \times 100,$$

where the suffixes $PC$ and $TC$ refer to plain cylinders and tripped cylinders, respectively.

Local suppression in $C_{Df}$ and $C_{Lf}$ is presented in Fig. 7. Maximum values in the scale bar are presented as 80% and 90% for $C_{Df,R}$ and $C_{Lf,R}$, respectively; suppressions of the coefficients more than those were not occurred. It is clear from the figures that, in most of the region, $C_{Df}$ and $C_{Lf}$ are suppressed by about 65% and 85%, respectively. There are some regions where $C_{Df,R}$ and $C_{Lf,R}$ negative (0 ~ -10%). Negative suppression means the values of coefficient for the tripped cylinders are greater than those of the plain cylinders, i.e., $C_{Df}$ and $C_{Lf}$ are not suppressed by using tripping rods. Indeed, these are the regions where values of $C_{Df}$ and $C_{Lf}$ of the plain cylinder are very small.

![Fluctuating (rms) pressure coefficient distributions on the surface of the cylinder at $\alpha = 0^\circ$, $P^* = 1.4$. Plain cylinders: ○, upstream cylinder; ●, downstream cylinder. Tripped cylinders: △, upstream cylinder; ▲ downstream cylinder. - - - -, single plain cylinder.](image-url)
5.4. Fluctuating pressure on the cylinder surface

Figure 8 displays $C_{Pf}$ measured for the upstream and downstream cylinders at $\alpha = 0^\circ$, $P^* = 1.4$ lying in the shear-layer/wake and cylinder interaction regime (Fig. 3). The circular and triangular symbols represent the plain and tripped cylinders, respectively. For the case of the plain cylinders, due to the interaction between the upstream-cylinder shear layer and the downstream cylinder, $C_{Pf}$ over the whole surface of the downstream cylinder is very large, while that on the upstream cylinder is very small as the downstream cylinder acts as a wake stabilizer of the upstream cylinder. On the other hand, for the tripped cylinders, the upstream cylinder $C_{Pf}$ is comparable to that for the plain cylinder, except two peaks at $\theta \approx 50^\circ$ and $310^\circ$ caused by the shear layer reattachment behind the tripwires as observed for the single tripped cylinder (Fig. 2). That of the downstream cylinder is slightly higher, yet insignificant compared to that of the single plain cylinder or plain downstream cylinder.

![Fluctuating (rms) pressure coefficient distributions on the surface of the cylinder at $\alpha = 25^\circ$, $P^* = 2.6$. Plain cylinders: $\bigcirc$, upstream cylinder; $\bullet$, downstream cylinder. Tripped cylinders: $\bigtriangleup$, upstream cylinder; $\blacktriangle$, downstream cylinder. - - - -, single plain cylinder.](image)

Figure 9 shows $C_{Pf}$ measured for the upstream and downstream cylinders at $\alpha = 25^\circ$, $P^* = 2.6$ where $C_{Lf}$ on the plain downstream cylinder is the largest (i.e, vortex and
shear layer interaction). For the plain cylinders, while $C_{Pf}$ distributions of the upstream cylinder resembles that of the single cylinder, $C_{Pf}$ is very large on the lower surface ($\theta \approx 200^\circ$-$320^\circ$) of the downstream cylinder, due to the incoming vortices from the upstream cylinder (Lee & Smith, 1991; Rockwell, 1998). The flow structure corresponds to that presented in Fig. 6(c). For the tripped cylinders, the upstream cylinder undergoes very small magnitude of $C_{Pf}$, having very similar $C_{Pf}$ distribution to that for single tripped cylinder (Fig. 2b). $C_{Pf}$ on the downstream cylinder is also small. A slightly increased $C_{Pf}$ at $\theta \approx 200^\circ$-$330^\circ$ for the tripped downstream cylinder is due to the upstream cylinder wake disturbance. The observation suggests that the tripped wires have effectively suppressed alternating sheddings from both cylinders. At $\alpha = 10^\circ$, $P^* = 2.6$ where $C_{Di}$ is the largest for the plain cylinders, $C_{Pf}$ distributions (not shown) revealed that a large fluctuation in pressure occurring on the front surface of the downstream cylinder results in the large magnitude of $C_{Di}$. The large fluctuation in pressure suppressed for the tripped cylinders.

6. CONCLUSIONS

An investigation is conducted on the flow interference between two tripped identical cylinders at $\alpha = 0^\circ$-$180^\circ$ and $P^* = 0.1$-$5$. Two tripwires, each of diameter $0.1D$, were attached on each cylinder at azimuthal angle $\beta = \pm 30^\circ$. $C_D$, $C_{Di}$ and $C_{Li}$ on the tripped cylinders were measured and compared with those on the plain cylinders at $Re = 5.5 \times 10^4$. Pressure measurements on the surface of the cylinder were also carried out.

$C_D$, $C_{Di}$ and $C_{Li}$ of the plain cylinders are strong function of $\alpha$ and $P^*$, connected to interaction between boundary layer and cylinder, shear-layer/wake and cylinder, shear layer and shear layer, vortex and cylinder, vortex and shear layer, and vortex and vortex. $C_D$, $C_{Di}$ and $C_{Li}$ are very large for the interactions where vortex is involved (i.e., vortex and cylinder, vortex and shear layer, and vortex and vortex). The addition of tripwires suppresses the vortex sheddings from the cylinders, resulting in the suppression of the interactions involving vortex. The large magnitudes of $C_D$, $C_{Di}$ and $C_{Li}$ thus reduce to very small values. While the plain cylinders intervene each other extensively, the tripped cylinders do not; hence $C_D$, $C_{Di}$ and $C_{Li}$ of the tripped cylinders are almost insensitive to $P^*$ and $\alpha$. Compared to the plain cylinders, the tripped cylinders experience smaller forces in the entire $P^*$ and $\alpha$ ranges examined. While in most of the region the suppressions in $C_D$, $C_{Di}$ and $C_{Li}$ are about 58%, 65% and 85%, respectively, maximum suppressions are 60%, 80% and 90%, respectively.

For the case of the plain cylinders, vortex and shear layer interaction and vortex
and cylinder interaction result in a large $C_{Pf}$ respectively on the lower side and front surface of the downstream cylinder. $C_{Pf}$ distribution of the upstream cylinder is comparable to that of a single cylinder. The shear-layer/wake and cylinder interaction brings about a small $C_{Pf}$ on the upstream cylinder and a high $C_{Pf}$ on the downstream cylinder. On the other hand, both tripped cylinders for the all interactions undergo very small $C_{Pf}$ over the whole surface.

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